

Holocene coastal change at Luce Bay, South West Scotland

DAVID E. SMITH,^{1*} RICHARD M. TIPPING,² JASON T. JORDAN³ and MATHEW BLACKETT³

¹School of Geography and the Environment, Oxford University, Oxford, UK

²Environmental Science, University of Stirling, Stirling, UK

³School of Energy, Construction and Environment, Coventry University, Coventry, UK

Received 29 January 2019; Revised 27 May 2020; Accepted 9 June 2020

ABSTRACT: Coastal change during the Mid- to Late Holocene at Luce Bay, South West Scotland, is examined using morphological, stratigraphic and biostratigraphical techniques supported by radiocarbon dating. Deglaciation left extensive sediments, providing a source for depositional coastal landforms. Glacio-isostatic uplift resulted in the registration of evidence for former relative sea levels (RSLs), which support the pattern of Holocene RSL change for the northern Irish Sea as determined by shoreline-based Gaussian trend surface models. The rate of RSL rise was rapid from before ca. 8600 to ca. 7800 cal a BP, but then slowed, changing by <3 m over the next 3000 years, a pattern reflected in the convergence of shorelines predicted in the models. By ca. 4400 cal a BP RSL was falling towards present levels. As these changes were taking place, coastal barriers developed and dunes formed across them. In the West of the Bay, a lagoon forming to landward of the barriers and dunes acted as a sediment sink for dune sand. Changes in the coastal landscape influenced the occupation of the area by early human societies. This study illustrates the value of combining an understanding of process geomorphology, RSL and archaeology in studies of coastal change. © 2020 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons, Ltd.

KEYWORDS: archaeology; coastal change; Holocene; microfossils; radiocarbon.

Introduction

Luce Bay is a 20-km-wide macro-tidal marine embayment on the northern coast of the outer Solway Firth in SW Scotland (Fig. 1) with clear but complex inter-relations between Holocene sediment bodies of contrasting depositional environments (Single and Hansom, 1994). Its detailed evolution is bound up with new archaeological insights into the role coastal landscapes played in Neolithic-Bronze Age society (Cowie, 1996; Thomas, 2015; Bradley *et al.*, 2016) yet few local empirical data exist to underpin these insights. The objectives of the work were thus to (i) identify the nature, causes and rates of change of Holocene coastal processes using field and laboratory analyses, (ii) compare relative sea levels (RSLs) at Luce Bay with evidence from neighbouring areas and (iii) examine the intricate effect of coastal changes at Luce Bay on the early human occupation of the area.

Methodology and techniques

Morphological mapping at a scale of 1: 10 000 (cf. Smith *et al.*, 2003a, 2003b) was integrated with >300 levelled altitudinal points to Ordnance Datum Newlyn (OD) on closed traverses with accuracies < ±0.05 m. Sediment stratigraphies were recorded from 2.5-cm-diameter Eijelkamp gouge boreholes surveyed to OD (see Supplementary Information) and from the British Geological Survey (NERC) National Geoscience Data Centre (2017) boreholes: the altitudes of some commercial boreholes had to be obtained from LIDAR data with accuracies ±0.05 m. Samples for microfossil analysis and radiocarbon dating were obtained using a 'Russian' closed-chambered corer (Jowsey, 1966) at boreholes

previously investigated using an Eijelkamp gouge (thus reducing the possibility of vertical errors in the recorded stratigraphy). Comparison between surveyed altitudes at Luce Bay and the tidal record is facilitated by the availability of tidal values for Luce Bay Platform (Table 1).

Diatom analyses, undertaken using standard preparation techniques, paid close attention to sediment-stratigraphic boundaries where environmental changes occurred. Identification followed Hustedt (1930–1991), Patrick and Reimer (1966), Hendey (1964–1976), Van der Werff and Huls (1957–1974, 1976), and Krammer and Lange-Bertalot (1986–1991). Diatom nomenclature follows Denys (1991/2) and the halobian classification for diatoms follows Hustedt (1930–1991) and Vos and De Wolf (1993). Frequencies are expressed in figures as percentages of a minimum of 200 diatom valves per level.

Radiocarbon (¹⁴C) dating was undertaken on samples of peat from transgressive or regressive overlaps, with the exception of one date (from No. 2 Holdings) given below. All dates were obtained by the accelerator mass spectrometry (AMS) method and were calibrated using Calib 7.1 (Stuiver and Reimer, 1993; Reimer *et al.*, 2009). In the text, dates are given as sidereal (calibrated) age ranges BP (before 1950) to two standard deviations, with their radiocarbon date to one standard deviation in parentheses, thus 8602–8973 cal (7910 ± 30 ¹⁴C) a BP: approximate dates are indicated by 'ca.'. The Early Holocene is defined as having occurred 11 700–8200 cal a BP, the Middle Holocene 8200–4200 BP cal a BP and the Late Holocene 4200 cal a BP to present (following Walker *et al.*, 2019).

The coastal marine sediments studied at Luce Bay are considered evidence of former RSLs, and the methodology used in the present investigation follows that used in previous work undertaken by the authors at similar locations in South West Scotland (e.g. Smith *et al.*, 2003a, 2003b, 2006), to enable comparisons to be drawn. Recently, Hijma *et al.* (2015)

*Correspondence: D. E. Smith, as above.

E-mail: david.smith@ouce.ox.ac.uk

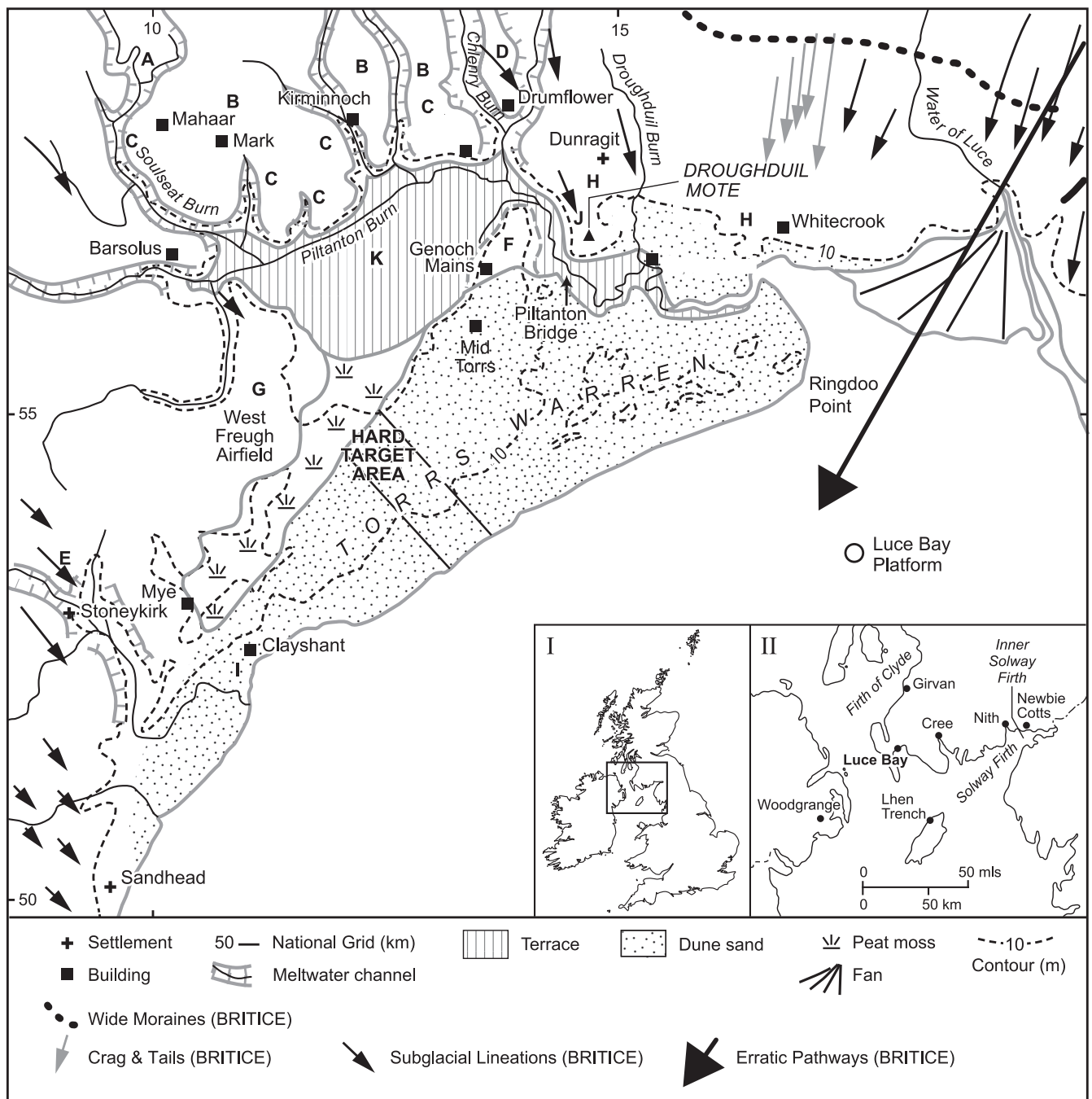


Figure 1. The head of Luce bay, South West Scotland, showing places discussed in this paper together with the morphology of glacial and coastal features based on mapping by the authors with additions from BRITICE. Inset: location of the area and nearby sites mentioned in the text.

have recommended standard protocols for studies of RSL change. In Table 2, the approach used in the present study in measuring RSL change is compared with that of Hijma *et al.* (2015). Values for the former levels according to the different approaches are given in Table 3, and graphs of the levels determined in the two approaches are shown in Fig. 11. Note that the values for RSL change above Mean High Water Spring Tides (MHWS) in the method used here are closely comparable to the values for RSL change above Reference Water Level in the Hijma *et al.* (2015) method.

Sea level index points (SLIP) and limiting points (SLLP) in the present work are from former saltmarsh (locally termed merse) and mudflat environments. The error range is based on the measurement of contemporary features and follows the approach of Smith *et al.* (2003a). Full details of each borehole from which samples were taken are given in Supporting Information (tables prefixed by S in this text).

In determining regional patterns of glacio-isostatic uplift involving estuarine areas, tidal effects can result in an increase in elevation of comparable index points towards the head of an estuary. In the Solway Firth, altitudes of both mudflat inner margin and saltmarsh inner margin clearly exhibit a rise with the increase in MHWS and Mean High Water Neap Tides (MHWN) towards the head of the estuary. In this area, had OD alone been considered, the tidal factors could have masked or modified evidence of glacio-isostatic or other crustal effects. Figure 2 illustrates the change in tidal parameters from four tidal stations compared with mudflat and saltmarsh heights along the northern shore of the Solway Firth, from Luce Bay in the SW to Redkirk Point in the NE, based on 188 mudflat and 475 saltmarsh inner margin altitudes, taken at 50-m intervals using data for Luce Bay and adjacent areas (Smith *et al.*, 2003a, 2003b, and new data obtained for this study). These observations support the choice of MHWS for comparative studies of RSL

Table 1. Tidal values (m OD) for Luce Bay Platform (UK Hydrographic Office, 2010), based upon Drummore Chart Datum (Admiralty Tide Tables, 1996)

Tidal Station	MHWS	MHWN	MLWN	MLWS	HAT	LAT	Mean tidal level	Mean high water	Location
Luce Bay Platform	3.4	2.0	-1.0	-2.3	4.1	-3.0	0.53	2.7	54°50'N, 4°53'W

change in Scotland by the authors (e.g. Smith *et al.*, 2000). In the same way, reference to the Indicative Meaning as outlined by Hijma *et al.* (2015) also provides the opportunity to take account of spatial variations in tidal and other effects.

Results

Morphology and stratigraphy

The area studied contains widespread evidence of deglaciation. During the Last Glacial Maximum (LGM), the area was occupied by an ice sheet flowing broadly southward or south-south-westward into the Irish Sea basin (e.g. McMillan *et al.*, 2011). Decay of this ice sheet left a landscape of extensive glacial deposits. Recent work has indicated that a Late Devensian readvance occurred in the Luce Bay area (McCabe *et al.*, 1998, 2005; McCabe and Dunlop, 2006), correlated with the Killard Point Stadial, dated at between 17 000 and 18 200 cal a BP. McCabe *et al.* (1998, 2005) correlated this readvance with Heinrich event I. More recently, BRITICE (Clark *et al.*, 2017) mapping has provided information on patterns of ice flow across the area.

In Fig. 1 the morphological features discussed and the location of the stratigraphical evidence examined are shown. West of Dunragit and landward of Torrs Warren a broad lowland (K) surrounds the Piltanton Burn. To the north, dead-ice hollows (A) and outwash surfaces (B) surround proglacial meltwater channels (C, D, E). Dissected fragments of a surface of sand and gravel at F

and G reach consistent altitudes of 15–20 m OD and may indicate a former RSL into which the meltwaters deployed, although exposures in the surface at F and in the extensive gravel pits at I are largely of outwash gravels, the latter exhibiting southward-dipping bedding, with rapid changes in the dominant particle size. The lower reaches of the channels lead into a broad lowland surrounding the Piltanton Burn. The lowland (K) is occupied by silty fine sand, up to 8 m thick in places according to boreholes undertaken by the authors and commercial boreholes, sometimes with silty clay. Along the margins of the lowland, the sand surface is covered in a thin veneer of peat except in the south, where greater thicknesses of peat, in places up to 2 m, occur (Newell in Cowie, 1996 and commercial boreholes). Survey of the sand surface (Fig. 3) at over 200 levelled points discloses altitudes which rise from ca. 6 m OD (2.6 m MHWS) below Piltanton Bridge, to over 10 m OD (6.6 m MHWS) where the Souseat and Piltanton Burns enter the lowland. The lowland is lowest in the centre and downstream beyond Piltanton Bridge, but rises along the lower reaches of the burns draining into it. The lowland acted as a sediment sink for blown sand as Torrs Warren dunes formed.

East of Dunragit the landscape is one of glaciofluvial deposits (H) locally mantled by blown sand and overlooking a basin area in the west, the Whitcrook Basin (M). Along the northern side of the basin at L, a terrace in silty clay occurs at 8.5–9.5 m OD. To the south, the basin opens out to a terrace in sands and silts along the Piltanton Burn at 6–6.5 m OD, continuing the lowest level in the Piltanton Burn lowland beyond Piltanton Bridge. The Droughduil Motte, a late

Table 2. Comparison between the approaches of the authors and that recommended by Hijma *et al.* (2015), with the error margins upon which the graphs in Fig. 11 are based. For detailed measurements see Fig. 3

Source of error	Value (based on Smith <i>et al.</i> , 2003a)	Hijma <i>et al.</i> (2015) recommendation
Sediment consolidation	Only based upon peat or silty peat. At transgressive overlap: for sediment underlying the point measured an addition of 68% (maximum) or 40% (minimum) consolidation. At regressive overlap: where there is biogenic sediment in layer(s) beneath of up to 0.51 m thickness, the same additions of 68 and 40% are made but are reduced proportionately and progressively up to 2.10 m transgressive sediment thickness.	Half the thickness of the 'sample' (assumed here to be half the thickness of the layer). Sample described as 'organic and mud-rich'. In Fig. 11B, the values for sediment consolidation used in the present paper are used.
Elevation	Correction of ± 0.021 m for survey plus ± 0.20 m for benchmark error. DGPS not used.	Survey ± 0.03 m; benchmark error ± 0.10 m; DGPS error ± 0.04 m. Given the similarity with values given in the present paper, these values are used.
Dating	All dates from Beta or SURRC. Calibration by Calib 7.1. All dates from peat. All calibrated errors given at 2σ and $^{13}\text{C}/^{12}\text{C}$ ratio given.	2σ range for ^{14}C AMS dating recommended. Calibration by OxCal. The Calib 7.1 values in the present paper are used here.
Drilling (coring)	Not estimated. 'Russian' corer used for sampled boreholes and checked for core shortening with Eijklekamp corer. No error estimated.	± 0.01 m for 'Russian' corer. Non-vertical drilling error up to ± 0.21 m. Given that the 'Russian' cores are supported by the Eijklekamp record, no modification is made here.
Tidal parameters	Nearest tide gauge (Luce Bay Platform) used.	Nearby tide gauge.
Morphology	Surveyed surface of the high marsh and underlying mudflat ± 0.63 m based upon the inner margin of presently forming features in the local area.	Not estimated.
Indicative range error	High marsh and underlying mudflat surface range in the present paper is used (see above).	Half the elevational range of an indicator. The indicative range at Luce Bay is the range between HAT and MHW, and thus 1.4 m. The indicative meaning – half the indicative range – is ± 0.70 m

Table 3. Radiocarbon dates obtained in this study. The following errors applied for all contacts: survey error ± 0.021 m; benchmark error ± 0.20 m; altitude range of surface of morphological feature (present work) 0.63 m; indicative range (Hijma *et al.*, 2015) 0.7 m (see Table 2)

Sampl code	RSL index (I) or limiting-point (L)	Location	National Grid Reference	Conventional ^{14}C age (BP)	$^{13}\text{C}/^{12}\text{C}$ ratio (‰)	Laboratory code	Cal. BP range, 2σ	Surveyed altitude at contact (m OD)	Sediment consolidation (m)	RSL (m), based on methodology in this paper		RSL (m), based on Hijma <i>et al.</i> methodology, with Reference Water Level at 3.4 m OD (mid-point HAT-MHW) and Indicative range ± 0.7 m. (see HAT-MHW, Table 1)	Regressive (R) or transgressive (T) RSL overlap	Horizon dated
										Above OD	Above present MHS (Table 1)			
BA1	I	Barsolus	NX1055.5690	7910 \pm 30	-26.9	SUERC-38782	8603-8975	4.85	+0.19 - +0.12	4.12-5.89	0.72-2.49	1.605 \pm 0.956 (0.649-2.561)	T	Top of peat below laminated silty clay
BA2	L	Barsolus	NX1055.5690	7240 \pm 35	-28.9	SUERC-38783	7981-8162	7.04	+0.51 - +0.33	6.52-8.40	3.12-5.00	4.060 \pm 1.341(2.719-5.401)	T	Top of peat below laminated silty clay
BA3	L	Barsolus	NX1056.5692	945 \pm 30	-29.3	SUERC-38784	794-925	8.39	+0.29 - +0.19	7.73-9.53	4.33-6.13	5.23 \pm 1.161 (4.069-6.391)	R	Base of peat above laminated silty clay
KH1	I	Kirminnoch	NX1215.5802	7160 \pm 30	-28.2	Beta-431217	7820-7975	8.99	+0.41 - +0.24	8.38-10.25	4.98-6.85	5.915 \pm 1.246 (4.669-7.161)	T	Top of peat below laminated silt
KH2	I	Kirminnoch	NX1215.5802	5640 \pm 30	-28.1	Beta-431218	6305-6410	9.90	+0.41 - +0.24	9.289-11.1-6	5.89-7.76	6.825 \pm 1.246 (5.579-8.071)	R	Base of peat above laminated silt
MP	I?	Mineral Plantation	NX1263.5753	2320 \pm 25	-29.0	SUERC-39067	2313-2358	6.36	+0.03 - +0.02	5.53-7.24	2.13-3.84	2.985 \pm 0.926 (2.059-3.911)	R?	Base of organic sediment above estuarine clay
P	L	No. 2 Holdings	NX1490.5715	3497 \pm 33	-28.9	SUERC-44834	3649-3858	8.8	+0.07 - +0.05	8.00-9.72	4.603-6.32	5.460 \pm 0.951 (4.509-6.411)	No indicative RSL trend	Organic-rich clay under thin, bleached, well-sorted medium sand
WB1	I	Whitecrook Basin	NX1527.5715	7430 \pm 30	-27.2	SUERC-38788	8184-8332	4.67	+0.02 - +0.01	3.83-5.54	0.43-2.14	1.285 \pm 0.951 (0.334-2.236)	T	Top of peat below well sorted fine-medium sand
WB2	I	Whitecrook Basin	NX1527.5715	3930 \pm 30	-28.5	SUERC-38789	4300-4560	7.51	0	6.66-8.36	3.26-4.96	4.110 \pm 0.921(3.189-5.031)	R	Base of peat above structureless sands and silts
MA1	I	Mahaar	N- X10003.57425	6839 \pm 30	-29.6	SUERC-75536	7610-7731	8.37	+0.06 - +0.03	7.55-9.28	4.15-5.88	5.015 \pm 0.966 (4.049-5.981)	T	Top of peat below silt
MA2	I?	Mahaar	N- X10003.57425	6052 \pm 30	-29.2	SUERC-75532	6798-6990	8.69	+0.09 - +0.07	7.91-9.63	4.51-6.23	5.370 \pm 0.961(4.409-6.331)	T?	Top of peat beneath silt and clay
MA3	I	Mahaar	N- X10003.57425	4618 \pm 30	-29.1	SUERC-75531	5298-5462	9.03	+0.09 - +0.07	8.27-10.03	4.87-6.63	5.750 \pm 0.921(4.829-6.671)	R	Base of peat above silt and clay

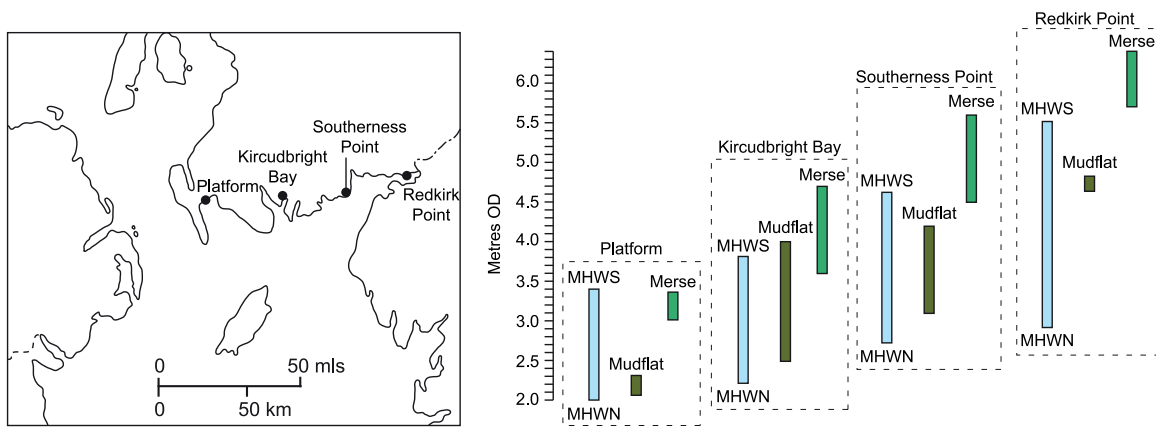


Figure 2. Tidal range for the north side of the Solway Firth from four tidal stations compared with surveyed altitudes of the inner margins of the merse (saltmarsh) and mudflats. Note the rise in the altitudes of tidal values compared with the ranges of merse (saltmarsh) and mudflat values towards the head of the Firth. The number of values for Luce Bay are less than in the other areas because relatively few locations are available for these measurements in the area. [Color figure can be viewed at wileyonlinelibrary.com]

Neolithic artificial mound (Thomas, 2015), underlain by blown sand, overlooks the Whitecrook Basin at the southern end of a ridge (J) extending south from Dunragit. The basin is drained by a narrow incised channel to the Piltanton Burn.

More than 120 commercial boreholes, supplemented by our boreholes, record the stratigraphy beneath the Whitecrook Basin. Till widely occurs at the base, overlain by glaciofluvial sands and gravels. Above the sands and gravels, peat, up to 0.6 m thick, is sometimes present, overlain at the margins of the area by dune sand, or by colluvium. Away from the margins, the peat is overlain by up to 0.75 m of clay or silt and then by up to 1.5 m of sands and gravels, which are in turn

overlain by one or more horizons of clay or silt, sometimes laminated, which reach a maximum recorded altitude of 10.37 m OD. Dune sand may overlie the highest clay or silt layer, although in some locations the clay or silt is present at the surface (as in terrace L).

A borehole transect (Fig. 4) in the Whitecrook Basin discloses details of the stratigraphy. Commercial borehole NX15NE1031/01, in the west, reached to over 20.42 m depth (reaching -11.69 m OD), disclosing at the base fine to coarse gravel and sand overlain at -9.17 m OD by laminated clay with horizons of fine sand then at 5.01 m OD by structureless sands and silts to the surface. Eastwards, boreholes undertaken in the present study

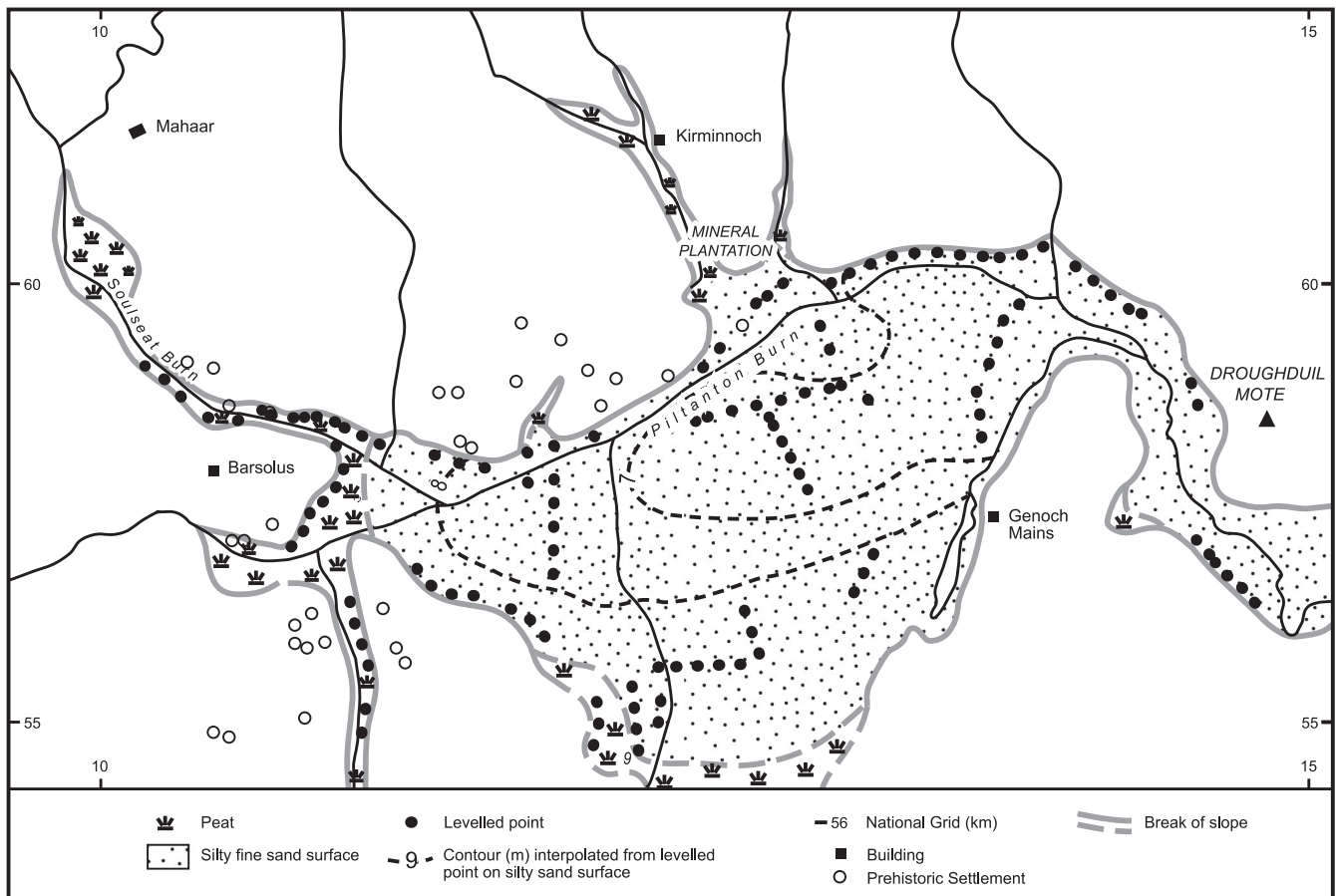


Figure 3. Location of surveyed altitudes and interpolated contours (m OD) for the Piltanton Burn lowland. Also shown are the locations of prehistoric settlement sites in the lowland from the Canmore database, Historic Environment Scotland.

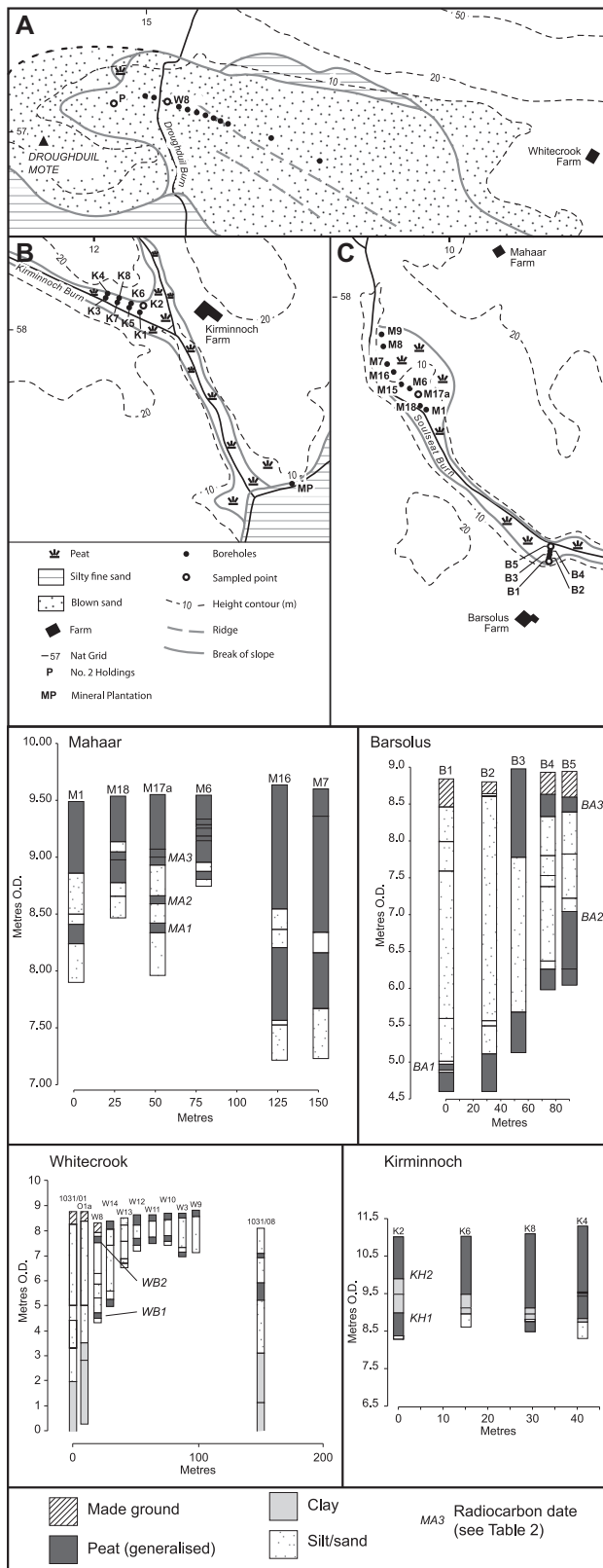


Figure 4. Sites at Whitecrook Basin (A) (including No. 2 Holdings), Kirminnoch (B) (including Mineral Plantation), Mahaar and Barsolus (C), showing locations of boreholes and generalized borehole stratigraphies.

(prefix W, Fig. 4) reveal horizons of peat and in borehole W8 peat horizons occur at 4.62 m OD and 7.5 m OD, both sampled for radiocarbon dating (see Table 3 and Table S6). Commercial borehole transects elsewhere in this area are interpreted as disclosing coastal barriers with marine/estuarine deposits in the intervening swales. The alignment of each barrier is not clear

from available borehole locations. The exceptional depth of silty clay in the Whitecrook Basin may be because this area was in a low-energy environment, protected from high-energy coastal processes by barrier development to the south-east, thus receiving fine sediment during Early–Middle Holocene RSL rise.

Holocene relative sea levels

Evidence for RSLs at Luce Bay is largely provided by stratigraphy. The sites studied are indicated in Fig. 1: Mahaar and Barsolus, in the Souleat Burn valley at the head of the Piltanton Burn Lowland; Kirminnoch and Mineral Plantation, in a proglacial meltwater channel at the centre of the Piltanton Burn Lowland; and Whitecrook Basin (Including No. 2 Holdings), east of Dunragit.

At Mahaar (Figs 1, 4 and 5), in the peat-filled valley of the Souleat Burn, sand with some gravel at the base is overlain by peat above which there is a horizon of silts and sands. Within the silts and sands a noticeable horizon of peat is found, while the silts and sands are in turn overlain by surface peat. The detailed stratigraphy at the sampled borehole, 17a, is shown in Table S1. The sediments at Mahaar yielded mixed brackish–marine to brackish–freshwater diatom assemblages (Fig. 5). The assemblages were sparse (there were no diatoms present between 8.50 and 8.82 m OD and counts elsewhere were to 100 total valves) but show a clear brackish–marine component dominated by the benthic *Diploneis interrupta* and *Caloneis westii* and a constant brackish–freshwater component of *Fragilaria* sp. Mahaar represents the most extreme landward extent of estuarine sediments in the Piltanton Burn lowland. The sediment and diatom records and three AMS radiocarbon dates (MA1–MA3, Table 3) indicate that RSL began to rise as peat was replaced by silt at 7609–7729 cal (6839 ± 30 ^{14}C) a BP. RSL then fell as peat developed upon the silt surface. This peat was then replaced by silt at 6797–6987 cal (6052 ± 30 ^{14}C) a BP, although the lack of any diatom assemblage at this point cannot confirm that this is an RSL index point. Nevertheless the presence of brackish–marine to brackish–freshwater diatoms higher in this same silt layer supports it as being of estuarine origin. RSL subsequently fell as peat began to accumulate on this silt at 5296–5461 cal (4618 ± 30 ^{14}C) a BP.

At Barsolus (Figs 1, 4, 6 and 7), 2 km downstream from Mahaar, sediment stratigraphies disclose peat overlain by laminated silt and sandy silt in turn overlain by peat to the surface (Fig. 4). Diatom analyses (Figs 6 and 7) were undertaken at boreholes 1 and 5 (Tables S2 and S3). Radiocarbon dates (BA1–BA3) are listed in Table 3. From borehole 1 at 4.85 m depth where the laminated silt overlies peat, the peat yielded a mixed brackish to freshwater assemblage of *Nitzschia navicularis*, *D. interrupta*, *Fragilaria virescens* and *Pinnularia intermedia*, while overlying laminated silt yielded a marine to brackish assemblage with *Paralia sulcata*, *Podosira montagnei*, *D. smithii*, *N. navicularis* and *D. interrupta*. A gradual change in environmental conditions from freshwater to marine/estuarine is indicated, and a date of 8602–8973 cal (7910 ± 30 ^{14}C) a BP was obtained from the top of the peat. Higher in the stratigraphy at 1.5 m depth in borehole 5, a date of 7980–8160 cal (7240 ± 35 ^{14}C) a BP was obtained from the top of peat beneath laminated silt (no diatoms were present). The laminated silt and sandy silt is gradually overlain by herb-rich peat, the minerogenic sediments containing mostly freshwater and brackish–fresh diatoms but with small amounts of marine and marine–brackish diatoms, changing to predominantly fresh and brackish–fresh diatoms in the peat, dominated by *Cyclostephanos dubius* and

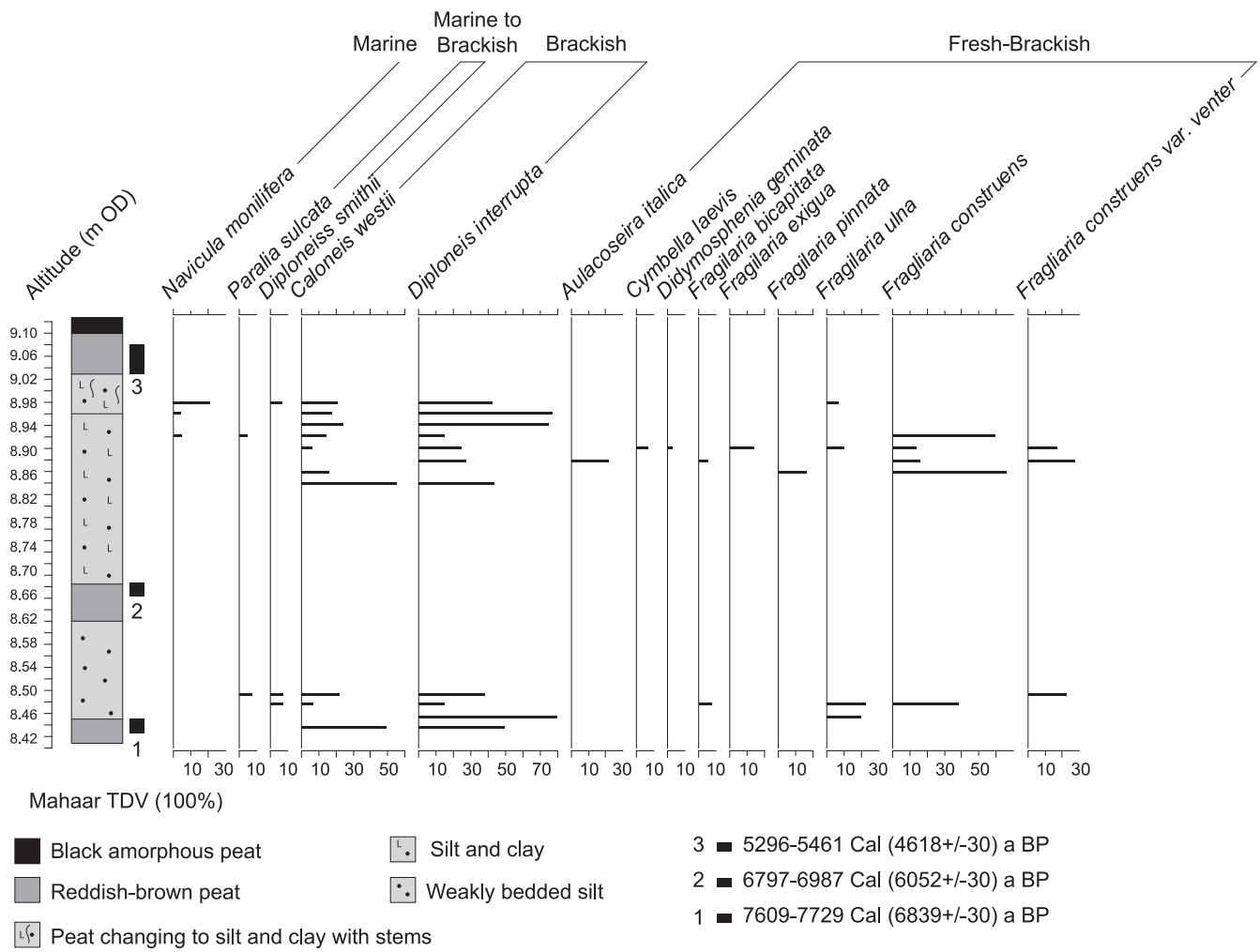


Figure 5. Diatom diagram from borehole 17b, Mahaar.

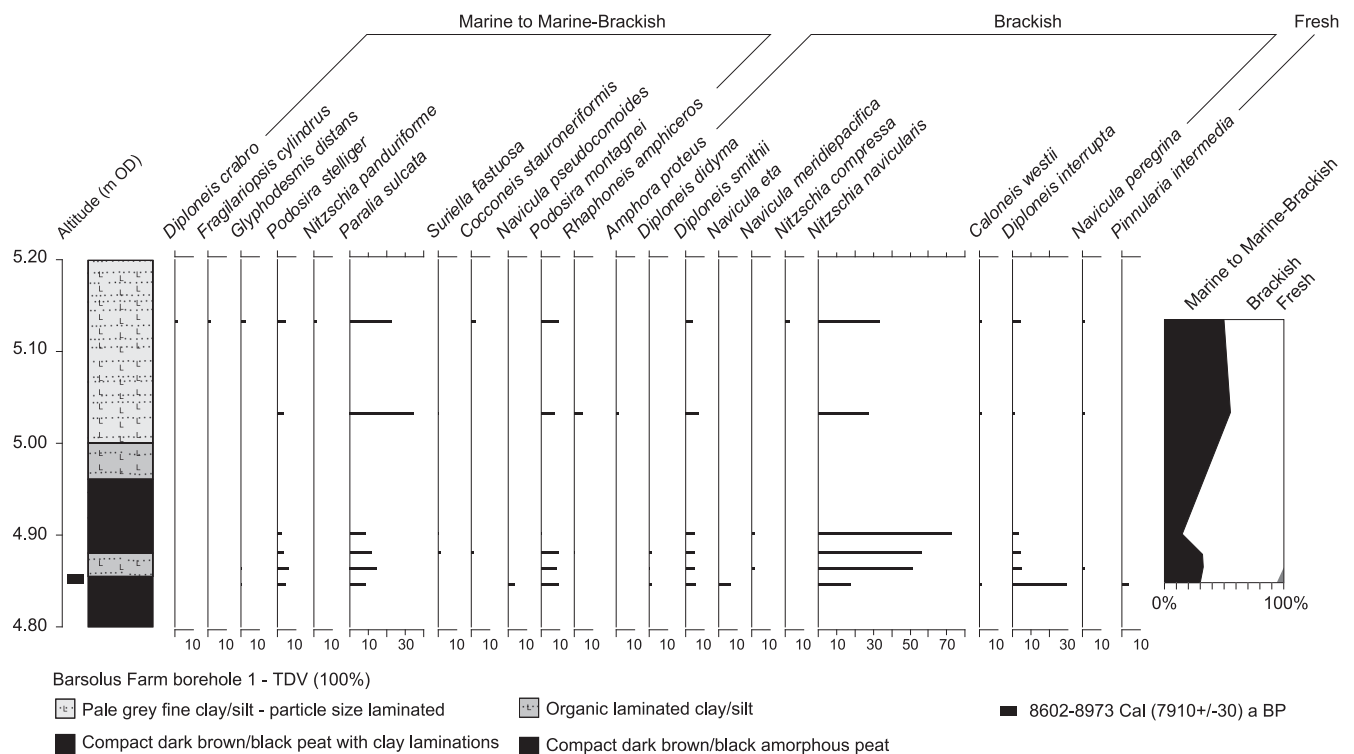


Figure 6. Diatom diagram from borehole 1, Barsolus.

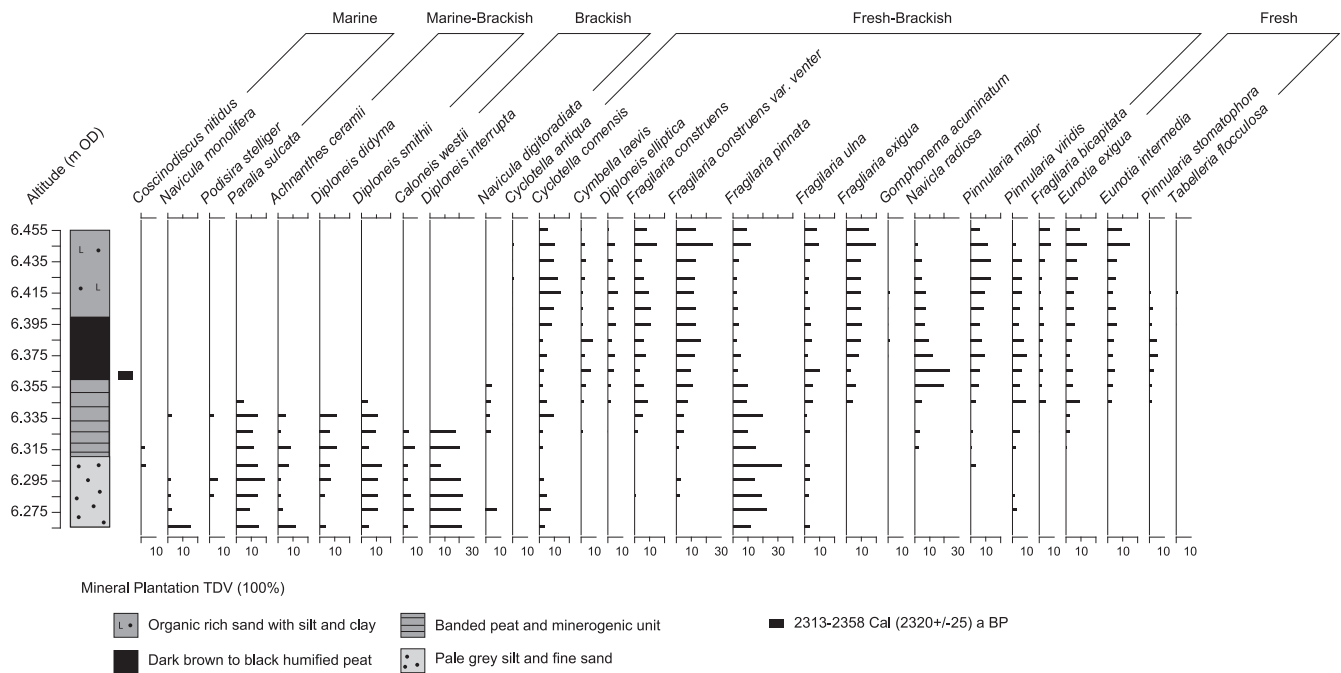


Figure 9. Diatom diagram from the exposure at Mineral Plantation.

F. ulna. From the base of the peat, a date of 794–925 cal (945 ± 30 ^{14}C) a BP was obtained.

At Kirminnoch (Figs 1, 4 and 8) the valley of a former proglacial meltwater channel is filled with a tapering wedge of silty clay and sand up-valley within peat. Basal fine sand overlain by humified peat occurs with horizons of silty clay, sometimes organic, above which peat occurs to the surface. At its furthest up-valley, the silty clay splits into two horizons. Borehole 2 is representative of the sediment stratigraphy (Table S4): stratigraphic boundaries are all gradual. At borehole 2, diatom analyses (Fig. 8) show freshwater species dominated by *Aulacoseria perlabra florinae* in the basal peat, but this becomes brackish–marine as indicated by *D. interrupta* sp., some 80% of the assemblage, a shallow water brackish benthic community as the peat becomes silty, and then to a marine–brackish fauna in the silty clay itself, with *D. didyma* and *D. stroemii* comprising 40% of the assemblage, and an increased marine influence is apparent from shallow/benthic species. The overlying peat becomes freshwater with a well-mixed freshwater assemblage. A radiocarbon date (KH1, Table 3) of 7820–7975 cal (7110 ± 30 ^{14}C) a BP was obtained from peat at the basal silty clay contact and a second date (KH2) of 6305–6410 cal (5640 ± 30 ^{14}C) a BP from peat at the upper silty clay contact.

At Mineral Plantation (Figs 1, 4 and 9), down-valley from Kirminnoch and at the mouth of the channel, organic sediment overlies the silty sand of a terrace which leads into the lowest sandy surface of the Piltanton Burn Lowland. Table S5 lists the detailed stratigraphy at the section examined. A radiocarbon date of 2313–2358 cal (2320 ± 25 ^{14}C) a BP (MP, Table 3) was obtained from the base of the peat at 0.885–0.89 m. Diatom analyses (Fig. 9) show a transition from marine and brackish conditions to that of a freshwater system, possibly a ponded area. A well-developed marine to brackish diatom assemblage typifies the basal sediments with *Paralia sulcata* and *D. interrupta* dominating. The presence of the tychopegalic *P. sulcata* suggests a well-established connection to open water for this marine species to occur in such abundance, as well as having continued freshwater input via the burn, evidenced from the abundance of the freshwater–brackish species *F. pinnata*. The marine–brackish diatom assemblage

continues throughout the banded peat/minerogenic sediment until the peat occurs, when planktonic *Cyclotella* sp. show the freshwater system becoming dominant, with the increased presence of the many benthic and tychopegalic *Fragilaria* species showing that this environment was either somewhat ephemeral as a freshwater body or a series of freshwater pools existed with numerous shallow environments.

In the Whitecrook Basin (Figs 1, 4 and 10) close to the Droughduil Burn, a borehole transect between commercial boreholes NXNE1031/1, NX1031/1a and NX1031/8 at the mouth of the embayment below the Droughduil motte is typified by the stratigraphy at borehole 8 (Table S6). Above basal minerogenic deposits, the uppermost 3 m contains a sequence of peat or organic-rich sand, overlain by well-sorted fine–medium sand which becomes structureless, in turn overlain by peat with overlying structureless sands and silts. The top 1 cm of basal organic material was dated at 8184–8332 cal (7430 ± 30 ^{14}C) a BP (WB1, Table 3) and contained a diatom assemblage, largely brackish–marine in origin, with *Caloneis westii*, *C. sublittoralis*, *Diploneis didyma*, *D. smithii*, *Navicula marina*, *N. digitoradiata* and *Paralia sulcata*, but also *Fragilaria construens* var. *venter*, *F. pinnata* and *F. ulna*, indicating the proximity of the site to drainage from land. The basal 1 cm of peat overlying the structureless sands was dated at 4249–4499 cal (3930 ± 30 ^{14}C) a BP (WB2, Table 3) and the diatom assemblage (Fig. 10) is similarly mixed, although predominantly brackish/marine, with brackish/marine species *Caloneis westii*, *Cocconeis scutellum*, *C. sublittoralis*, *Diploneis interrupta*, *Diploneis smithii* and *Paralia sulcata*. Freshwater species included *Pinnularia viridis*, *P. major*, *Fragilaria pinnata* and *F. ulna*. The diatom assemblages at both dated horizons indicate transitional marine/estuarine environments.

At No. 2 Holdings (Figs 1 and 4), at the head of Whitecrook Basin, a sample of organic-rich silt overlain by a thin horizon of sand at the surface was dated at 3649–3858 cal (3497 ± 33 ^{14}C) a BP (P, Table 3). The date relates to the commencement of deposition of dune sand at the locality. No diatoms were recovered from the silt, and the limiting date obtained registers the absence of marine/estuarine sedimentation on the valley side above the Whitecrook Basin site.

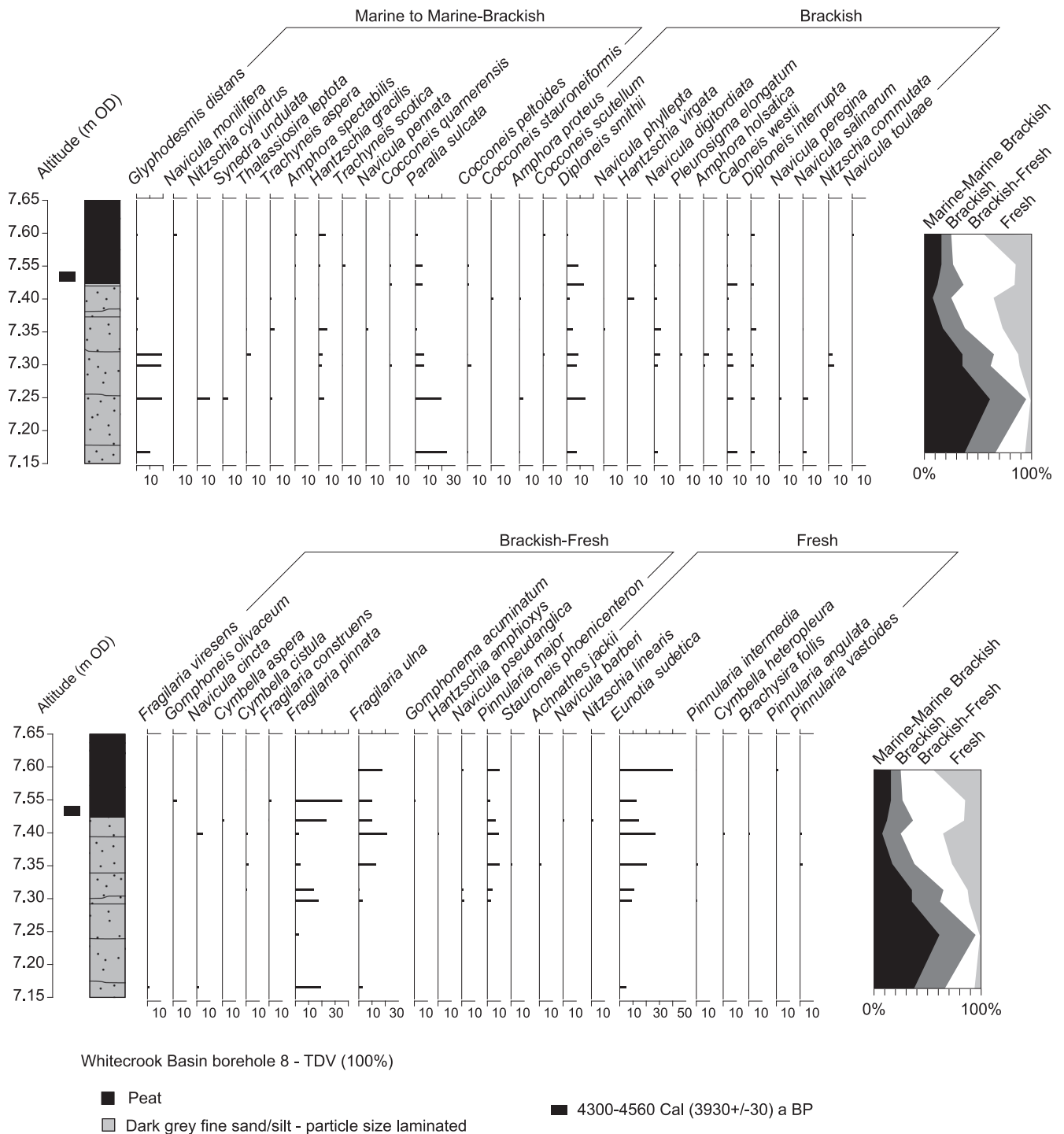


Figure 10. Diatom diagram from the regressive overlap at borehole 8, Whitecrook Basin.

RSL graphs based on the data described above and according to the methodology upon which the present study was based with the equivalent values from Hijma *et al.* (2015) and listed in Table 3 are shown in Fig. 11. At the sites examined, the regressive contact dated is probably close to the former mudflat surface, while the transgressive contact is probably close to the former saltmarsh (merse) surface.

RSL at Luce Bay was rising by the Early–Middle Holocene. In the Piltanton Burn lowland, RSL rose from 4.12 to 5.89 m OD (0.72–2.49 m MHWS) at 8603–8975 cal (7910 \pm 30 14 C) a BP at Barsolus, 7.55 to 9.30 m OD (4.24–5.97 m MHWS) at 7609–7729 cal (6839 \pm 30 14 C) a BP at Mahaar and 8.38 to 10.25 m OD (5.61–6.85 m MHWS) at 7820–7975 cal (7160 \pm 30 14 C) a BP at Kirminnoch; in the east, at Whitecrook

Basin, RSL rose above 3.83–5.54 m OD (1.55–2.09 m MHWS) at 8184–8332 cal (7430 \pm 30 14 C) a BP.

The highest recorded Holocene RSL in the area is recorded at Kirminnoch, where RSL had reached 9.23–11.16 m OD (5.89–7.76 m MHWS) by 6305–6410 cal (5640 \pm 30 14 C) a BP. At Barsolus, the rise reached between 6.52–8.40 m OD (3.12–5.00 m MHWS) (the early date) and 7.73–9.53 m OD (4.33–6.13 m MHWS) (the last date). At Mahaar, where the dates are only broadly supported by diatom evidence, RSL was rising at 7610–7731 cal (6839 \pm 30 14 C) a BP at 7.55–9.30 m OD (4.98–5.90 m MHWS) but a possible regressive contact, not dated, may occur before the rise was resumed by the limiting date of 6798–6990 cal (6052 \pm 30 14 C) a BP at 7.91–9.64 m OD (4.51–6.19 m MHWS), before falling again by 5298–5642 cal

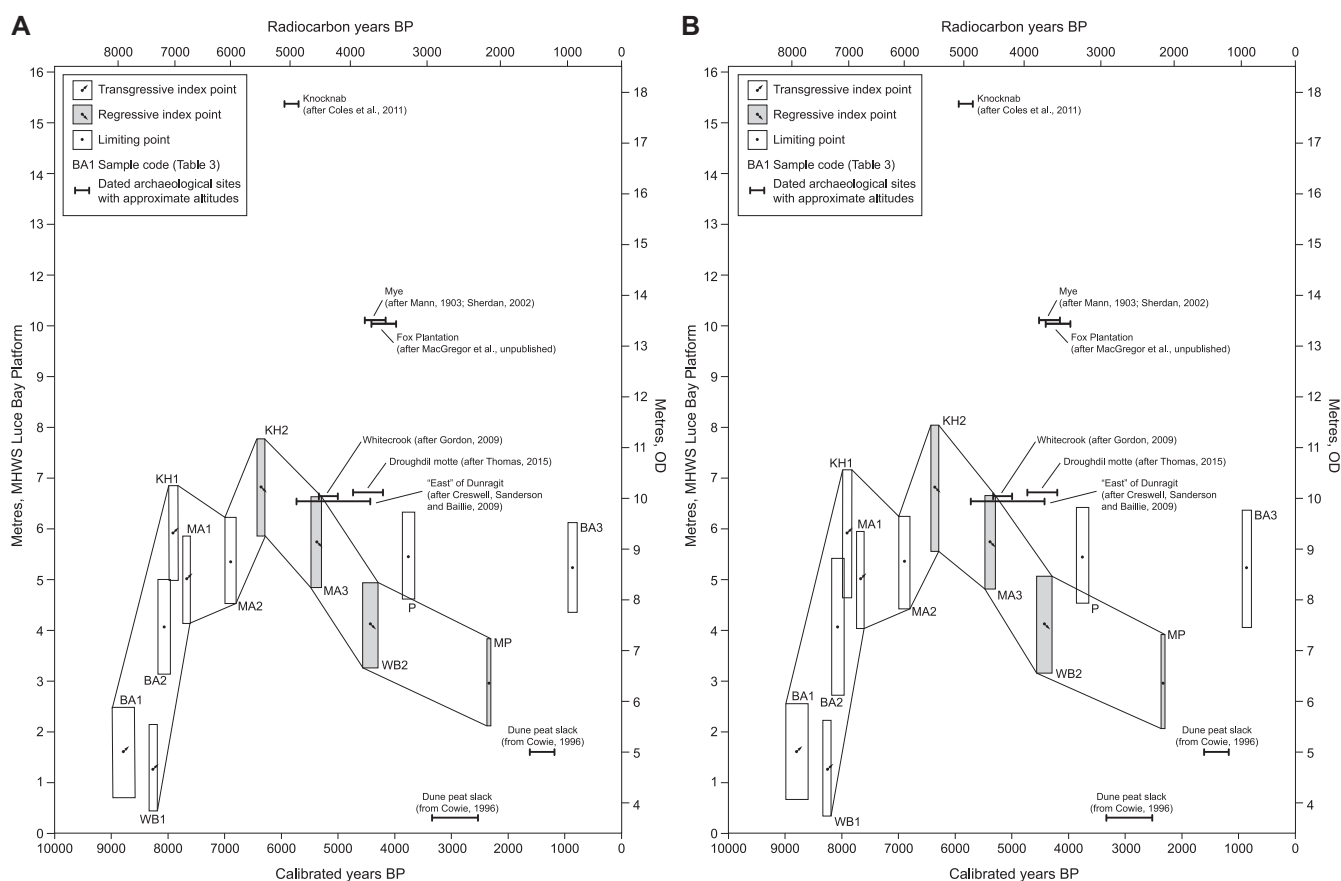


Figure 11. Relative sea level graphs for the head of Luce Bay with archaeological dates added. (A) Graph using altitudes based upon the methodology used in this paper; (B) graph using altitudes based upon the recommendations of Hijma *et al.* (2015).

(4618 ± 30 ^{14}C) a BP at 8.27–10.93 m OD (4.87–6.02 m MHWS). To the east, at Whitecrook Basin, the rise had ended by 4300–4560 cal (3930 ± 30 ^{14}C) a BP when RSL fell from 6.66 to 8.36 m OD (3.26–4.96 m MHWS), but unlike the sites at Kirminnoch, Barsolus and Mahaar, the borehole at Whitecrook Basin does not lie on a continuously tapering wedge of sediment, and the local limit of the fine silt and sand is unclear. It is possible that the stratigraphy at No. 2 Holdings, up-slope from Whitecrook Basin, marks the limit of the sediments dated at Whitecrook Basin and the value of 8.80–9.72 m OD (4.60–6.32 m MHWS), dated at 3649–3858 cal (3497 ± 33 ^{14}C) a BP at No. 2 Holdings marks a limiting value for the altitude of RSL at Whitecrook Basin.

The evidence from Luce Bay indicates that the rise of RSL between the transgressive contacts at Barsolus and Whitecrook Basin and those at Kirminnoch and Mahaar amounted to over 5 m between ca. 8600 and ca. 7800 BP cal a BP at a mean rate of 13.8 mm a^{-1} or 14.2 mm a^{-1} if Mahaar (where the diatom record is sparse) is excluded. While the rapidity of the rise at this time may have been due in part to the rapid rises recorded by Lawrence *et al.* (2016) between ca. 8800 and 8200 cal a BP in the Cree valley to the east, this cannot be confirmed in the absence of stratigraphic evidence at Luce Bay for such rises. The RSL rise at Luce Bay was greatly reduced to ca. 1 m between ca. 7800 and ca. 6300 cal a BP, at a mean rate of 0.66 mm a^{-1} . Subsequently, RSL fell by 2–3 m before 4400 cal a BP. Hence RSL had changed by only ca. 2–3 m for over 3000 years. RSL later fell to ultimately reach present levels, although the fall may have been interrupted around 2500 cal a BP.

Comparison with adjacent areas

RSL changes at Luce Bay can be compared with those from estuarine sites around the northern Irish Sea (Fig. 1; Table 4).

At the nearby sites of the Cree valley, Girvan, Woodgrange, Newbie Cottages and possibly the Nith valley, two or more episodes of rise then fall in RSL are identified, and it is maintained that a fluctuating rise in the Middle Holocene is very likely, even ignoring the possible fluctuation indicated by the stratigraphy but not dated at Mahaar (see above).

A period of relatively little change in RSL during the Middle Holocene was argued for the Arisaig area by Shennan *et al.* (2005, p. 104), who explained it as having been caused by changes in global sea level reflecting a gradual, rather than abrupt, cessation of the melting of the Antarctic and Laurentide ice sheets. An alternative interpretation may be derived if Middle Holocene RSL change varied around Scottish coasts, producing displaced shorelines, as has been argued for many years, and the evidence for such shorelines has been widely articulated (e.g. Smith *et al.*, 2012, 2019). In Fig. 12, isobases derived from Gaussian trend-surface modelling, based on over 450 shoreline altitude measurements, each measurement surveyed to an accuracy of $< \pm 0.05 \text{ m}$ for four Middle Holocene displaced shorelines, named the Storegga, Main Postglacial, Blairdrummond and Wigtown shorelines (Smith *et al.*, 2012, 2019) are shown. Individually produced, these models are similar in outline and in the location of their centres, thus showing little change in the spatial pattern of uplift since the shorelines were reached (for an example of two of the models produced individually, see Smith *et al.*, 2012: fig. 6). However, mindful of the fact that the Main Postglacial, Blairdrummond and Wigtown shorelines are diachronous, these models were combined by Smith *et al.* (2012) with the virtually instantaneously reached (and therefore not diachronous) Storegga shoreline (based upon survey of the demonstrable limit of the Holocene Storegga Slide tsunami) around a common centre and axis, showing little change. In Fig. 13, the

Table 4. Sites around the northern Irish Sea showing Holocene shoreline altitudes and regressive overlap values compared to modelled shoreline altitude values (based on the methodology of Smith *et al.*, 2012)

Site	Shoreline age (cal a BP), height (m MHWS)	Regressive overlap age (cal a BP), height (m MHWS)	Shoreline name (as inferred by Smith <i>et al.</i> , 2012)	Modelled shoreline altitude (m MHWS)	Reference
Cree valley	9400–9900, –4.8	9528–9026, –4.95	(Buried shoreline)		Smith <i>et al.</i> (2003a, 2012). See also Lawrence <i>et al.</i> (2016).
	7000–7500, +3.9 – +6.5	6790–7925 + 2.85 – +4.83	Main Postglacial	+5.53	
	ca. 5800, +4 – +6.3	4243–5998, +5.14 – +5.43	Blairdrummond	+5.73	
Nith valley	ca. 3100, +1.7 – +2.0	Not determined	Wigtown	+3.56	Smith <i>et al.</i> (2003b, 2012).
	ca. 8020, +1.59	8170–7870, +1.59	Localized feature		
Girvan	ca. 6720, +3.8 – +5.8	6554–6929, +2.85	Main Postglacial	+3.86	Smith <i>et al.</i> (2007, 2012).
	ca. 6800, +6.07	6793–7274, +6.07	Main Postglacial	+7.30	
Woodgrange, Lecale,	ca. 4200, +6.83	3979–4233, +6.83	Blairdrummond	+7.08	Dresser <i>et al.</i> (1973); Singh and Smith (1973); Smith <i>et al.</i> (2012).
Co. Down	6749–7970, –0.87	6749–7970, +0.87	Main Postglacial	+0.57	
Eastern Solway Firth	3150–5750, +2.23	3150–5750, +2.23	Blairdrummond	+1.66	Lloyd <i>et al.</i> (1999); Smith <i>et al.</i> (2012).
	6887–7688, +1.76 – +3.44	6887–7688, +1.76 – +3.44	Main Postglacial	+2.17	
Newbie Cottages	7336–7209, ca. +2.34	7336–7209, ca. +2.34	Main Postglacial	+2.74	Dawson <i>et al.</i> (1999); Smith <i>et al.</i> (2012)
	5329–5640, ca. +3.93	5329–5640, ca. +3.93	Blairdrummond	+3.50	
Isle of Man (Lhen Trench)	ca. 6600–4500, +2.25	4300–4808, +2.04	Blairdrummond	+2.73	Roberts <i>et al.</i> (2006), Smith <i>et al.</i> (2012)
	6305–6410, +5.89 – +7.76	6305–6410, +5.89 – +7.76 (Kirmimoch)	?Blairdrummond	+5.51	

shoreline-based isobase models for the Main Postglacial, Blairdrummond and Wigtown shorelines shown in Fig. 12 are superimposed, showing that in the Luce Bay area the Main Postglacial and Blairdrummond shorelines converge. RSL at Luce Bay would have apparently changed relatively little for a period during the Middle Holocene by this interpretation.

Coastal change and prehistoric archaeology at Luce Bay

Holocene coastal processes

Holocene coastal change at the head of Luce Bay was driven by the availability of sediment from the decay of the last ice sheet (McMillan *et al.*, 2011) and by the wind climate acting with changes in RSL to redistribute that sediment. As RSL at the head of Luce Bay rose in the Early–Middle Holocene, gravel barriers developed. Sediment for the barriers was derived from coastal areas both east and west of the Bay. At present, flood tide currents at the head of Luce Bay are clockwise and on the ebb tide anticlockwise. If the same situation applied during the Middle–Late Holocene, on the flood tide glacial outwash sediments at the western side of the bay would have been carried eastwards, while on the ebb tide fluvial and glacio-fluvial sediments were carried westwards from the Water of Luce delta. Along the coastline east of Dunragit, these opposing currents together enabled barriers to form. At the same time, the wide, shallow Luce Bay, with its large tidal range, provided sediment for winds to blow onshore and create dune fields across the barriers at Torrs Warren and across barriers and glacial sediments east of Dunragit. Today, winds at West Freugh Weather Station (for location, see Fig. 1) are predominantly from the south or north-west. If these wind directions pertained during the Holocene, the southerly wind would have brought sand onshore from Luce Bay to build up the dune systems, while the north-westerly winds would have been responsible for the development of blowthroughs in exposed parts of the systems. However, the availability of sediment and the wind climate alone could not have produced the coastal landscape of today. Changes in RSL were crucial to coastal change in the area.

Dunes and archaeology

South-west of the Piltanton Burn estuary, the Torrs Warren dune field stretches 8 km from Sandhead in the south-west to Ringdoo Point in the north-east (see Fig. 1 above). The Torrs Warren dunes rise in altitude landward towards their inland margin where they reach over 28 m OD: a LIDAR map of part of the Torrs Warren dune field illustrates the main features of these dunes (Fig. 14), in which the main dune field is marked to seaward by distinctive linear features. Single and Hansom (1994) identified beneath the dunes a series of gravel ridges which can be followed intermittently towards the north-east, where they reach 12.5 m OD (9.1 m MHWS) in commercial boreholes NX15SW4025/29 and NX15SW4025/32. While it is not possible to demonstrate that these ridges are continuous, their presence over the area between Clayshant and Mid Torrs (Fig. 1) supports their probable continuity as far as the present estuary of the Piltanton Burn. The archaeology of these dunes provides some indication of their age. While the locations provided in early studies are imprecise, and many finds are portable, it is evident that the older archaeological sites are found towards the landward margin of the Torrs Warren dune field. The earliest radiocarbon- or pottery-dated archaeological site in them, on a ‘reasonably stable soil surface’ in the high

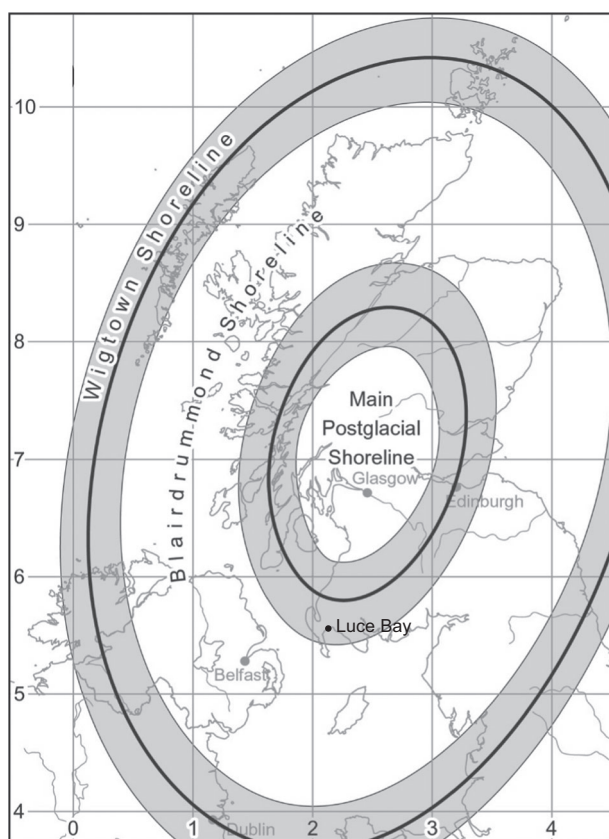


Figure 13. Gaussian Quadratic Trend Surface models shown in Fig. 12 superimposed, showing areas of shoreline convergence, based on Smith *et al.* (2012, 2019). Shaded bands about the shoreline overlaps are derived from the range of 95% of residual values of the surfaces computed.

dunes at Knocknab, NX1302.5490, dates to 5940–5700 cal (5005 ± 35) a BP, and thus very early Neolithic (Cowie, 1996; Coles *et al.*, 2011) and Mesolithic microliths have been reported (Coles, 1964; Coles *et al.*, 2011). These sites lie at unknown depths on earlier deposited sand, as do those containing early Neolithic Carinated Bowl assemblages on Flint Howe (Cowie, 1996). Sand blow across the area is recorded well to the west of High Torrs, in the site at Mye Plantation (Mann, 1903, 1905a, 1905b). Continued dune development is evident in the formation of linear dunes near the coast, where peat in a dune slack at NX132.541 at ca. 6 m OD provided radiocarbon dates of 1181–1614 cal (1480 ± 110 ^{14}C) a BP at 0.993–1.10 m depth and

2517–3329 ^{14}C (2780 ± 130) a BP at its base at 2.215–2.3 m depth (Newell in Cowie, 1996).

North of the Piltanton Burn estuary, blown sand is widespread. Excavations along the route of the A75 east of Dunragit (Fig. 1, above) have disclosed blown sand at ca. 10–12-m OD beneath marine sediments and optically stimulated luminescence (OSL) dated at 5100 ± 650 BP (Creswell *et al.*, 2019). At Whitecreek, birch charcoal at 0.17 m depth below a surface at ca. 10 m OD from a palisaded enclosure in blown sand was radiocarbon dated to 5340–5000 cal (4455 ± 40) a BP (Gordon, 2009). At Droughduil Mote, the base of which is ca. 10 m OD, and which probably rests on blown sand, an OSL date from the base yielded 4520 ± 250 BP (Thomas, 2015).

The archaeological evidence at Luce Bay indicates that sand blow and dune development began at least as early as the Neolithic, probably in the Mesolithic, and thus before ca. 6000 BP. The linear dunes at Torrs Warren were forming by ca. 3000 BP, perhaps representing a change in the pattern of sediment accumulation. The altitudes of available dates for archaeological sites in the Torrs Warren dune field are plotted in Fig. 11. They record the occupation of the area as RSL fell.

Coastal change

Evidence from sites studied for RSL in this paper show that the rise in RSL in the Early Holocene at Luce Bay reached its maximum at ca. 6300 cal a BP. The similarity in height of the gravel barriers south-west of Genoch Mains with the limit of silty clay at Mahaar, Barsolus and Kirminnoch (Fig. 1) implies that the lagoon along the Piltanton Burn (K, Fig. 1) formed at that time. The lagoon became increasingly isolated from the Bay as the barriers in the west reached higher outwash terraces at Genoch Mains and the only outlet became the present estuary of the Piltanton Burn at Piltanton Bridge.

Figure 15 shows the inferred maximum Holocene RSL in the area, and is derived from the altitude of the base of surface peat which had accumulated without apparent lacunae over demonstrably estuarine sediment at Kirminnoch, the surface of the sediment being at 9.23–11.16 m OD (5.89–7.76 m MHWS) at 6305–6410 cal a BP. At this time, the lagoon along the lower reaches of the Piltanton Burn (see Fig. 3) extended southward to the west of Torrs Warren. Here, the extensive peat moss is underlain by a surface of silty clay at 7.90–9.90 m OD according to boreholes from the British Geological Survey database, the altitudes of those boreholes determined in the present work by Lidar. Newell (in Cowie, 1996) recorded a surface of clay at 8 m OD beneath 2.5 m of peat in the same area. At Mye, towards the south-west of this area (Fig. 15),

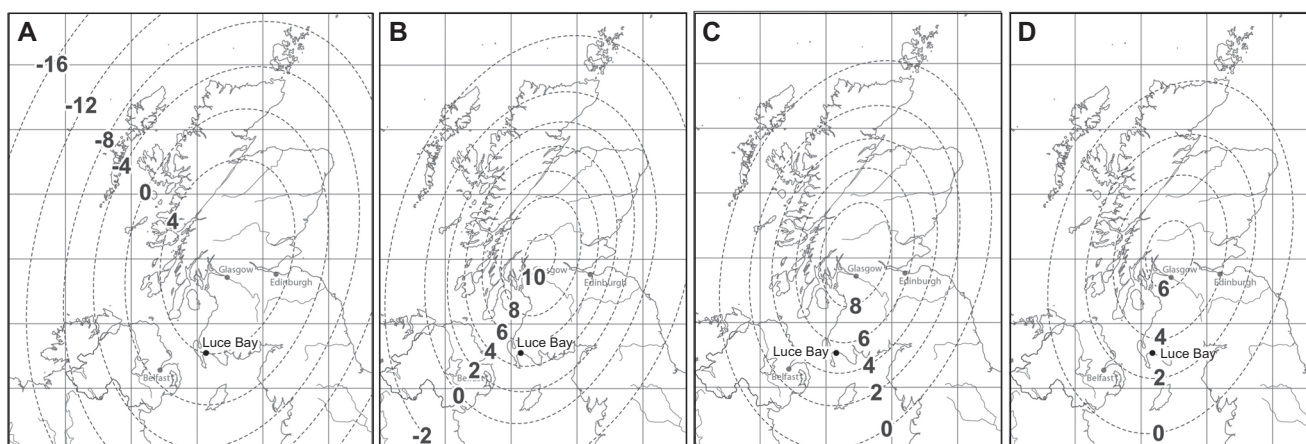


Figure 12. Gaussian Quadratic Trend Surface models for the Storegga (A), Main Postglacial (B), Blairdrummond (C) and Wigtown (D) shorelines in northern Britain and Ireland based on a common axis and centre, based on Smith *et al.* (2012, 2019).

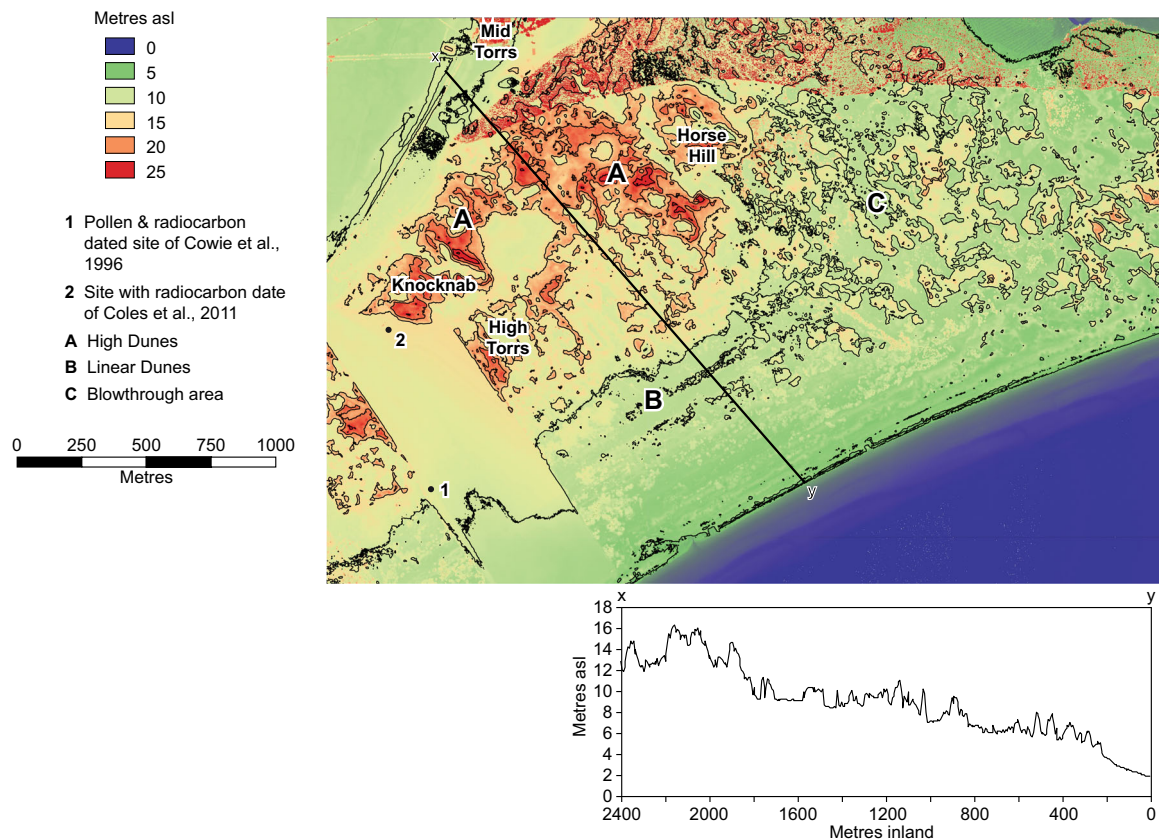


Figure 14. LIDAR map of part of the Torrs Warren dunes, illustrating the main morphological features of the dune field. Transect from Mid Torrs to the coast shows the High Dunes inland and the linear dunes near the coast. A: High Dunes; B: Linear Dunes; C: Dunes with blowthroughs. [Color figure can be viewed at wileyonlinelibrary.com]

Mann (1903, 1905a, 1905b) described the excavation of sunken anthropogenic structures in a surface of sand and shallow peat of around 15 m OD, probably a few metres above the edge of the main peat area. A report of the excavation, which was some 2–2.5 m in depth, disclosed peat at the surface, with sand (possibly blown sand) and blue clay beneath. Inserted into the clay were concentric rings of inverted faceted stakes of *Alnus*, *Betula* and *Corylus*, one *Alnus* sample subsequently dated to 4185–4505 cal (3193 ± 39 ¹⁴C) a BP (Sheridan, 2002). The purpose of the structures is unknown but to function at all, sea level controlling the groundwater level had to be below 13–14 m OD.

Along the seaward edge of the area of peat around Mye, boreholes in the British Geological Survey database support the observation of Mann (1903, 1905a, 1905b) that blown sand partially overlies the silty clay along its valley side margins, indicating that ultimately the sea withdrew. At Kirminnoch, Mahaar and Whitecrook Basin RSL fell by ca. 2–3 m from before ca. 7000 to ca. 4400 cal a BP. However, while the fall in RSL resulted in the lagoon along the Piltanton Burn and its extension to the south around Mye shrinking in extent, elsewhere the shoreline position changed little. The slender peninsula upon which the Droughduil Motte now stands may well have been briefly inundated by exceptionally high tide levels, but remained essentially a fixed feature on the coast. Bradley *et al.* (2016) have argued that such fixed points on the coast, protected by gravel bars, served as trading places, ‘maritime havens’, for sea-going communities in the Neolithic period. Luce Bay is one of their examples, one of the most productive areas for archaeological finds in Scotland (Cowie, 1996). Bradley *et al.* (2016) provided modelled maps for mean sea level at Luce Bay at 4000, 3000 and 2000 bc.

The map for 4000 bc is very different from the map for 6305–6410 cal a BP in the present paper. In particular, Bradley *et al.* (2016) do not show an extension of the Piltanton Burn lagoon in the West Freugh and Mye area. The differences with Fig. 15 in the present paper probably reflect that whereas Bradley *et al.*'s maps were derived from modelling, Fig. 15 is based on detailed field survey and stratigraphic work. Much of the discrepancy probably arises because Bradley *et al.* do not appear to take account of the presence of estuarine sediments beneath the extensive peat cover or beneath dune sand in the area.

More spatially detailed reconstruction of RSL data is critical in understanding the precise relationship between specific monuments and coastal change in Luce Bay. The base of the Droughduil motte is at 10 m OD (6.6 m MHWS). It was positioned south of and apart from the major later Neolithic monumental complex at Dunragit at the west end of the Whitecrook Basin. It is dated by OSL to the later Neolithic (4470 ± 270 cal a BP; Thomas, 2015, Figure 1). Our reconstruction of the maximum position of RSL in the Holocene shows that during the late Neolithic the motte was joined to the mainland by a narrow (in places <100 m wide) neck of land to the north (Fig. 15) which may have lain perhaps no more than 2 m above the level of the highest tides, and thus ‘magically’ appearing as a separate island (Tipping *et al.*, 2015). The spatial pattern of later prehistoric settlements surrounding the Piltanton Burn lowland (Fig. 3) might also be related to the maintenance of high groundwater tables long after 6000 BP. Later prehistoric archaeological sites, including the only excavated site at Fox Plantation, dated to 3990–4410 cal a BP (MacGregor *et al.*, unpublished) are not only above the valley floor but are confined to high ground to the north and west of Piltanton Burn, ringing the lowland (Fig. 3). Only one

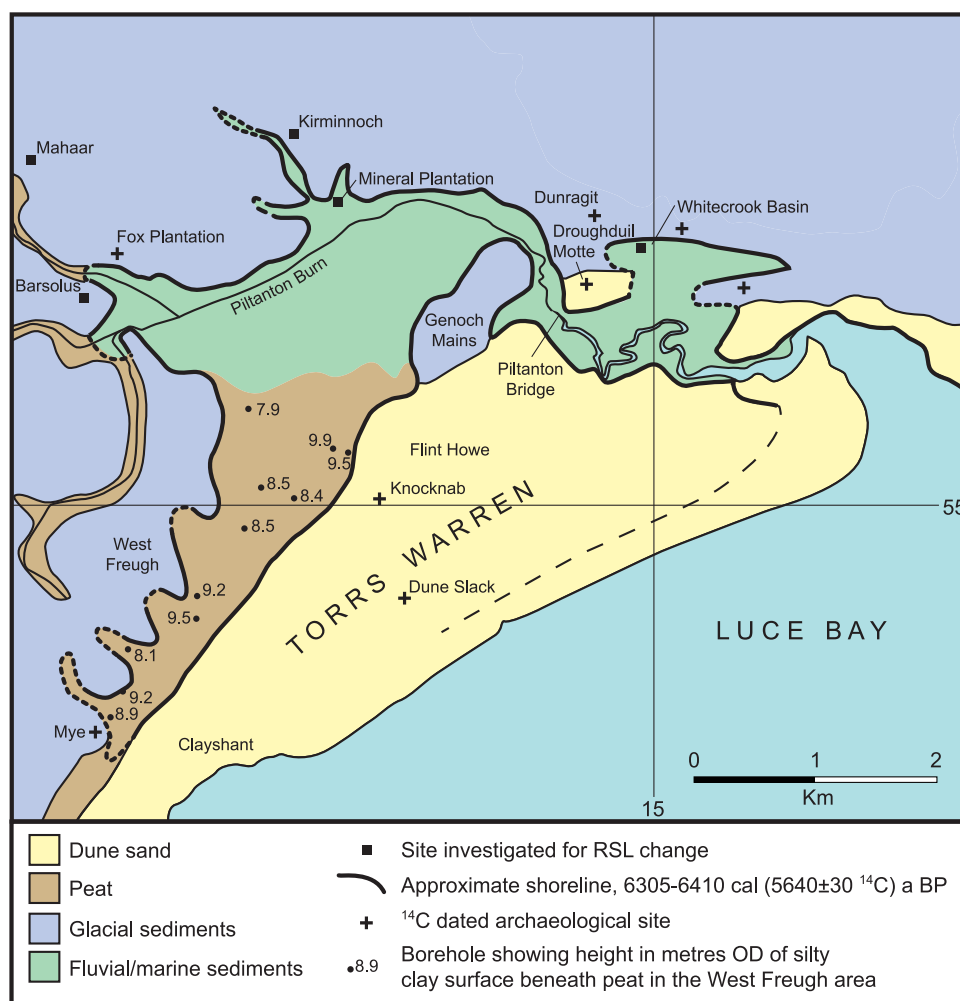


Figure 15. RSL at 6305–6410 cal (5640 ± 30 ^{14}C) a BP in the Luce Bay area, based on the base of ^{14}C -dated peat over estuarine sediments at Kirminnoch (see Table 3), showing dunes, surface peat, estuarine sediments and glacial sediments, with boreholes showing the elevation of estuarine sediments in the Mye–West Freugh area. [Color figure can be viewed at wileyonlinelibrary.com]

crop-marked archaeological site, a sub-rectangular, probably Iron Age but unexcavated enclosure, is found on the valley floor (Historic Environment Scotland. Canmore Database 79044).

In the east of the Piltanton Burn lowland, dating of organic material overlying the silty sand at Mineral Plantation at 2313–2358 cal (2320 ± 25 ^{14}C) a BP may mark a reduction in the rate of RSL fall. The lowland below ca. 6 m OD bears the hallmarks of relatively recent flooding, with abandoned meanders of the Piltanton Burn visible through much of the area. The river was straightened and embanked before the first Ordnance Survey map of the area (1843), and such changes would have steepened its course: before these changes, the river would have had a gentler gradient and thus been subject to flooding both from the estuary and from high river flow. Since installation in 1988, the Barsolus River Gauge recorded a maximum level of 8.97 m OD (Scottish Environment Protection Agency), higher than the surface of most of the lowland, and combined with the highest astronomical tide at the Luce Bay Platform of 4.1 m OD, it is likely that the lower part of the lowland would have been inundated occasionally, especially before the changes made to the channel of the Piltanton Burn.

Conclusions

Middle to Late Holocene coastal changes at Luce Bay were marked by the emplacement of barrier systems across which

dune fields developed as RSLs rose and fell. Morphologically, the area is marked by the Torrs Warren dunes and the remarkable sediment sink in the Piltanton Burn lowland to landward, explained by the abundance of sediment and the large tidal range in the Bay, exposing extensive sandflats. Stratigraphically, the RSL record is notable for the 3000-year period of relatively little change in the Middle Holocene, reflected here in the convergence of two Holocene shorelines. These coastal changes have had important impacts on later prehistoric occupation of the area. A relatively stable coastline during the Middle Holocene, with a prominent peninsula at Dunragit, influenced the development of a remarkable ceremonial complex and associated dwellings. In turn, coastal archaeology can inform and constrain contemporary environmental conditions induced by RSL change. Luce Bay is an area where coastal change and archaeology are closely linked and where knowledge of each contributes to the other in an understanding of the changing coastal environment.

Supporting information

Additional supporting information may be found in the online version of this article at the publisher's web-site.

Table S1. Stratigraphy at Borehole 17a, Mahaar. National Grid Reference NX 10003.57425.

Table S2. Stratigraphy at Borehole 1, Barsolus. National Grid Reference NX 1052.5685.

Table S3. Stratigraphy at Borehole 5, Barsolus. National Grid Reference NX 1052.5680.

Table S4. Stratigraphy at Borehole 2, Kirminnoch. National Grid Reference NX 1215.5802.

Table S5. Stratigraphy from the section at Mineral Plantation. National Grid Reference NX 1263.5753.

Table S6. Stratigraphy at Borehole 8, Whitecrook Basin. National Grid Reference NX 15 284.57102.

Acknowledgements. Historic Environment Scotland kindly supported work supporting the archaeological investigation at Dunragit. Dr. Robin Cullingford and Mr Peter Fretwell are thanked for their help with fieldwork in the Piltanton Burn lowland. Mr Alistair Buckoke is thanked for his advice on the archaeology of the area. Dr Alistair Rennie, Scottish Natural Heritage, is thanked for enabling the use of LIDAR imagery. Mr Declan Hurl is thanked for his advice on archaeology along the A75 route. Thanks are due to Ailsa Allen, School of Geography, University of Oxford, for cartographic work. The referees are thanked for their constructive comments which have enabled improvements to be made in this paper.

Data availability statement

The data that support the findings of this study are available in the Supporting Information of this article

Abbreviations. AMS, accelerator mass spectrometry; LGM, Last Glacial Maximum; MHWS, Mean High Water Spring Tides; OSL, optically stimulated luminescence; RSL, relative sea level; SLIP, sea level index point; SLLP, sea level limiting point.

References

- Admiralty Hydrographic Department. 1996. *Admiralty Tide Table, Volume 1: European Waters Including the Mediterranean Sea*. Hydrographer of the Navy: Taunton.
- British Geological Survey (NERC) National Geoscience Data Centre. 2017. *Borehole Scans*. www.bgs.ac.uk/data/boreholescans/home.html
- Bradley R, Rogers A, Sturt F *et al.* 2016. Maritime havens in earlier prehistoric Britain. *Proceedings of the Prehistoric Society* **82**: 125–159.
- Clark CD, Ely JC, Greenwood SL *et al.* 2017. BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British-Irish Ice Sheet. *Boreas* **47**.
- Coles D, Sheridan A, Begg C. 2011. Excavation and recording of three sites at Knocknab on Torrs Warren, West Freugh. *Transactions of the Dumfriesshire and Galloway Natural History and Antiquarian Society* **85**: 17–52.
- Coles JM. 1964. New aspects of the Mesolithic settlement of South-West Scotland. *Transactions of the Dumfriesshire and Galloway Natural History and Antiquarian Society* **41**: 67–98.
- Cowie TG. 1996. Torrs Warren, Luce Sands, Galloway: a report on archaeological and palaeoecological investigations undertaken in 1997 and 1979. *Transactions of the Dumfriesshire and Galloway Natural History and Antiquarian Society* **71**: 11–106.
- Creswell AJ, Sanderson DCW, Baillie W 2019. *Luminescence dating of samples from sand layers at Dunragit, Dumfries and Galloway*. Scottish Universities Environmental Research Centre: East Kilbride.
- Dawson S, Dawson AG, Cressey M *et al.* 1999. Newbie Cottages, Inner Solway Firth: Holocene relative sea level changes. In *The Quaternary of Dumfries and Galloway: Field Guide*, Tipping RM (ed). Quaternary Research Association: London; 98–104.
- Denys L 1991/2. *A check-list of the diatoms in the Holocene deposits of the western Belgian coastal plain with a survey of their apparent ecological requirements. 1: Introduction, ecological codes and complete list*. Professional Paper 26. Ministère des Affaires Economiques. Services Géologique de Belgique.
- Dresser PQ, Smith AG, Pearson GW. 1973. Radiocarbon dating of the raised beach at Woodgrange, C. Down. *Proceedings of the Royal Irish Academy* **73**: 53–56.
- Gordon D. 2009. Excavation of an Iron Age Round House and associated Palisaded Enclosure at Whitecrook Quarry, Glenluce. *Transactions of the Dumfries and Galloway Natural History and Antiquarian Society* **86**: 77–118.
- 1964–1976>Hendey NI. 1964–1976. *An Introductory Account of the Smaller Algae of British Coastal Waters, Part V: Bacillariophyceae (Diatoms)*. Fishery Investigation Series IV. Otto Koeltz: Koenigstein.
- Hijma M, Engelhart SE, Törnqvist TE *et al.* 2015. A protocol for a geological sea-level database. In *Handbook of Sea-Level Research*, Shennan I, Long AJ, Horton BP (eds). Wiley: Chichester; 536–553.
- Historic Environment Scotland. Canmore Database. <https://www.historicenvironment.scot/archives-and-research/archives-and-collections/canmore-database/>.
- Husted F 1930–1991. *Die Kieselagen Deutschlands, Österreichs und der Schweiz unter Berücksichtigung der übrigen Länder Europas sowie der angrenzenden Meeresgebiete*. Koeltz Scientific Books: Hessen.
- Jowsey PC. 1966. An improved peat sampler. *New Phytologist* **65**: 245–248.
- Krammer K, Lange-Bertalot H 1986–1991. *Süswasser von Mitteleuropa: 1 Teil: Naviculaceae (1986); 2 Teil: bacillariaceae, Epithemiaeaceae, Surirellaceae (1988), 3 Teil: Centrales, Fragilariaceae, Eunotiaceae (1991), 4 Teil: Acanthaceae Kritische Ergänzungen zu Navicula (lineolateae) und Gomphonema Gesamtliteraturverzeichnis (1991)*. VEB Gustav Fischer Verlag: Stuttgart.
- Lawrence T, Long AJ, Gehrels WR *et al.* 2016. Relative sea-level data from southwest Scotland constrain meltwater-driven sea-level jumps prior to the 8.2 kyr BP event. *Quaternary Science Reviews* **151**: 292–308.
- Lloyd JM, Shennan I, Kirby JR *et al.* 1999. Holocene relative sea-level changes in the inner Solway Firth. *Quaternary International* **60**: 83–105. [https://doi.org/10.1016/S1040-6182\(99\)00009-9](https://doi.org/10.1016/S1040-6182(99)00009-9)
- Mann LM. 1903. Report on the excavation of prehistoric pile-structures in pits in Wigtonshire. *Proceedings of the Society of Antiquaries of Scotland* **97**: 370–345.
- Mann LM. 1905a. Prehistoric pile structures in Pits in South-West Scotland. *Antiquary* **1**: 287–293.
- Mann LM. 1905b. Prehistoric pile structures in Pits in South-West Scotland. *Antiquary* **1**: 333–340.
- McCabe AM, Clark PU, Clark J. 2005. AMS ¹⁴C dating of deglacial events in the Irish Sea Basin and other sectors of the British-Irish Ice Sheet. *Quaternary Science Reviews* (1673–1690).
- McCabe M, Dunlop P. 2006. *The Last Glacial Termination in Northern Ireland*. Geological Survey of Northern Ireland: Belfast.
- McCabe M, Knight J, McCarron S. 1998. Evidence for Heinrich event 1 in the British Isles. *Journal of Quaternary Science* **13**: 549–568.
- McMillan AA, Merritt JW, Auton CA *et al.* 2011. *The Quaternary Geology of the Solway*. British Geological Survey Research Report RR/11/04. British Geological Survey: Nottingham.
- Patrick R, Reimer CW. 1966. *The diatoms of the United States, exclusive of Alaska and Hawaii*. Sutter House: Litz, PA.
- Reimer PJ, Baillie MGL, Bard E *et al.* 2009. Quaternary Isotope Laboratory Radiocarbon Calibration Program. University of Washington. radiocarbon.pa.qub.ac.uk/calib/calib.html
- Roberts DH, Chiverrell RCV, Innes JB *et al.* 2006. Holocene sea levels, Last Glacial Maximum glaciomarine environments and geophysical models in the northern Irish Sea Basin, UK. *Marine Geology* **231**: 113–128.
- Shennan I, Hamilton S, Hillier C *et al.* 2005. A 16 000-year record of near-field relative sea-level changes, northwest Scotland, United Kingdom. *Quaternary International* **133–134**: 95–106.
- Sheridan A. 2002. The radiocarbon dating programmes of the National Museums of Scotland. *Antiquity* **76**: 794–796.
- Singh G, Smith AG. 1973. Post-glacial vegetational history and relative land- and sea-level changes in Lecale, Co. Down. *Proceedings of the Royal Irish Academy* **73**: 1–57.
- Single MB, Hansom JD 1994. *Torrs Warren–Luce–Sands SSSI: Documentation and Management Prescription*. Scottish Natural Heritage Report 13.
- Smith DE, Barlow NLM, Bradley SL *et al.* 2019. Quaternary sea level change in Scotland. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* **110**: 219–256.
- Smith DE, Cullingford RA, Firth CR. 2000. Patterns of isostatic land uplift during the Holocene: evidence from mainland Scotland. *The Holocene* **10**: 489–501.
- Smith DE, Cullingford RA, Mighall TM *et al.* 2007. Holocene relative sea level changes in a glacio-isostatic area: new data from south-west Scotland, United Kingdom. *Marine Geology* **242**: 5–26.

- Smith DE, Fretwell PT, Cullingford RA *et al.* 2006. Towards improved empirical models of Holocene land uplift for mainland Scotland, UK. *Philosophical Transactions of the Royal Society A* **364**: 949–972.
- Smith DE, Haggart BA, Cullingford RA *et al.* 2003b. Holocene relative sea-level change in the lower Nith valley and estuary. *Scottish Journal of Geology* **39**: 97–120.
- Smith DE, Hunt N, Firth CR *et al.* 2012. Patterns of Holocene relative sea level change in the North of Britain and Ireland. *Quaternary Science Reviews* **54**: 58–76.
- Smith DE, Wells JM, Mighall TM *et al.* 2003a. Holocene relative sea levels and coastal changes in the lower Cree valley and estuary, SW Scotland, UK. *Transactions of the Royal Society of Edinburgh Earth Sciences* **93**: 301–331.
- Stuiver M, Reimer PJ. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* **35**: 215–230.
- Thomas J. 2015. *A Neolithic Ceremonial Complex in Galloway*. Oxbow Books: Oxford.
- Tipping RM, Smith DE, Jordan JT. 2015. Relative sea-level change and experiencing the Droughdil Mound. In *A Neolithic Ceremonial Complex in Galloway*, Galloway Thomas J (ed). Oxbow Books: Oxford; 104–109.
- United Kingdom Hydrographic Office. 2010. *Total Tide: Luce Bay Offshore Platform*. tides@ukhi.gov.uk.
- Van der Werff A, Huls H 1957–1974, 1976. *Diatomeenflora van Nederland (Diatom flora of The Netherlands)*. Otto Koeltz: Koenigstein.
- Vos PC, De Wolf H. 1993. Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects. *Hydrobiologia* **269–270**: 285–296.
- Walker M, Head MJ, Lowe J *et al.* 2019. Subdividing the Holocene Series/Epoch: formalization of stages/ages and subseries/subepochs, and designation of GSSPs and auxiliary stratotypes. *Journal of Quaternary Science* **34**: 173–186.