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Holocene palaeoenvironmental reconstruction of sea level, coastal and vegetation changes along the southern Solway Firth, United Kingdom

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ABSTRACT: Holocene relative sea level (RSL) changes were reconstructed from four sites along the less-studied southern Solway Firth. A multiproxy approach, including lithostratigraphical and biostratigraphical analyses, combined with radiocarbon dating, produced ten sea level index points (SLIPs). These SLIPs constrained Holocene RSL changes in the region between ~8300 cal BP and ~6018 cal BP and captured the Main Postglacial Transgression. These ten new points are combined with the ten pre-existing SLIPS from the southern Solway Firth to greatly refine the trend of Holocene RSL changes across this region. The Main Postglacial Transgression was shown to occur between ~8320 and 7500 cal BP, reaching a highstand of 3.26 ± 0.56 mOD. The new data were combined with 73 existing SLIPS from two sites around the northern Solway Firth and compared to RSL predictions from glacial isostatic modelling. Comparison between the corrected SLIPs and RSL predictions using British and Irish ice sheet reconstructions showed that the timing of the Main Postglacial Transgression is best captured with a hybrid model for the presence of thick and thin ice sheets. Pollen analysis at Cowgate Farm and Herd Hill provided a record of vegetation and coastal changes, acting as a chronostratigraphic marker when compared to published pollen records of the region. The records show a general transition from saltmarsh to reed swamp, then peat bog as RSL declined through the mid to late Holocene, with some indications of human clearance in the Bronze Age.
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KEYWORDS: foraminifera; Holocene; pollen; sea level changes; SLIPs; Solway Firth

Introduction

The Solway Firth (Fig. 1), due to its close proximity to the former British and Irish Ice Sheet (BIIS) (Shennan et al., 2005), is an important location for understanding the mechanisms of late Quaternary sea-level change and glacial isostatic adjustment (GIA). There is a complicated relative sea-level (RSL) record for the region due to the local effects of the Lake District ice mass, causing differential crustal movements between the northern and southern Solway Firth (Lloyd et al., 1999). Following the retreat of the BIIS and subsequent uplift, there should be a signal for RSL fall. However, this signal is complicated by a near-equal rise in RSL due to the retreat of the other large continental ice sheets and the ocean loading signal from the increase in meltwater.

Despite being one of the largest macrotidal estuarine systems in the United Kingdom, RSL changes in the region are not well understood due to the lack of sea-level index points (SLIPs) for the southern shore of the Solway Firth. There are 75 SLIPs presently available along the northern coastline of the Solway Firth and only 13 SLIPs available for the southern shore of the Solway Firth (Walker, 1966; Tooley, 1974; 1978; Huddart et al., 1977; Lloyd et al., 1999). A lack of data from a particular region may contribute to the existing mismatch between geological field data and RSL predictions produced from GIA models (e.g. Kuchar et al., 2012; Shennan et al., 2018; Bradley

et al., 2023) (Edwards et al., 2017). In addition, the effect of changes in palaeo-tidal range in the Solway Firth throughout the Holocene was not previously taken into consideration when calculating most of the existing 88 SLIPs. If tidal range at the study sites was greater in the past, the reference water level assigned to the SLIPs would also be greater, resulting in a lower RSL than previously calculated (Horton et al., 2013). The development of numerical palaeotidal models, for example, Hill et al. (2011); for the Caribbean Sea, Gulf of Mexico and western Atlantic and Hall et al. (2013); for Delaware Bay, USA, has resulted in the prediction of temporal tidal-range changes throughout the Holocene in the respective studies. For the United Kingdom, palaeotidal changes have been modelled for the Humber Estuary (Shennan et al., 2003) and the western North Sea region. These have, and will enable, the refinement of the reference water level and the indicative range ascribed to the SLIPs produced, resulting in more precise data. The other significant vertical uncertainties that should be quantified is the effect of post-depositional lowering of sediments. SLIPs obtained from intercalated samples are most likely to have been subjected to post-depositional compaction, and this should be quantified to provide the most accurate sea-level reconstruction (Edwards, 2006; Massey et al., 2006; Horton & Shennan, 2009; Brain et al., 2011; 2012; 2015; Barlow et al., 2013; Horton et al., 2013).

In order to develop a greater understanding of the mechanisms of RSL change in the Solway Firth, this research reconstructs RSL and coastal changes at four coastal sites from the southern shore through palaeoenvironmental analyses. The

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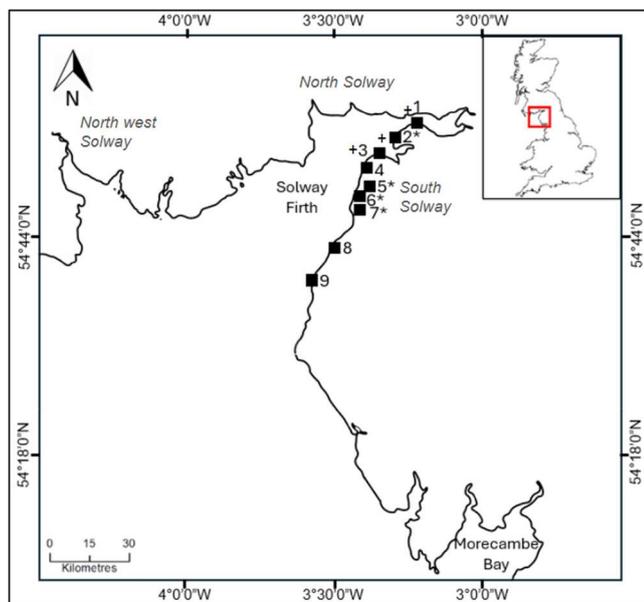Email: srderrett1@sheffield.ac.uk

Figure 1. Location map showing the study sites (*), reference point locations (+) and other locations mentioned in the text: 1+ Bowness Point Marsh, 2*+ Herd Hill and Cardurnock Marsh, 3+ Grune Point and Skinburness Marsh, 4 Silloth, 5* Pelutho, 6* Cowgate Farm, 7* Allonby, 8 Maryport, 9 Workington. [Color figure can be viewed at wileyonlinelibrary.com]

data will help to refine predictions for future GIA models and produce more accurate data points that consider the effects of changes in palaeo-tidal ranges and post-depositional compaction. SLIPs will be calculated based on a newly established local training set from foraminifera analysis of three contemporary saltmarshes. The timing and mechanisms of RSL change will be defined through pollen analysis and by comparing the SLIPs to GIA models.

Methodology

Study sites

Cumbria, which borders the Solway Firth, is located on the northwest coast of England and consists of farmed and coastal landscapes, including raised beaches, lowland raised mires and bogs, sand dunes, saltmarshes and intertidal flats (Fig. 1). Glaciofluvial outwash from the Devensian ice sheet overlies the bedrock, which is then covered by Holocene sediments (Walker, 1966; Lloyd et al., 1999; British Geological Survey, 2018). In some areas, peat has developed upon the glaciofluvial deposits (British Geological Survey, 2018), and extensive saltmarshes are present on the southern Solway Firth coast, with occasional relict sand bars observed in areas located behind the saltmarshes.

Three coastal sites at Allonby (54.783622, −3.408899), Cowgate Farm (54.813020, −3.407111), Pelutho (54.829901, −3.371133) and one inner estuary site at Herd Hill (54.928817, −3.28213) (Fig. 2) were investigated.

Fieldwork

A 1 m long, 2 cm diameter Eijelkamp gouge was used to test the stratigraphy of the sites using a grid system and recorded following the Tröels-Smith (1955) classification system (Fig. 3). A 50 cm long, 5 cm diameter Russian corer was used to extract a representative sample core, in order to obtain the most complete lithostratigraphical record of the environmental changes, and all boreholes, sample cores, contemporary

sample points and geomorphological features were levelled to Ordnance Datum (OD) using a differential global positioning system (δGPS) instrument.

To provide reference points for the SLIPs, samples were collected from transects located on three saltmarshes covering multiple sub-environments, from high marsh areas to tidal flats (Barlow et al., 2013; Horton and Edwards, 2006) (Figs. 1 and 4). For Skinburness Marsh, samples were taken at 30 metre intervals, while at Cardurnock and Bownes Point marshes, samples were taken at 5 metre intervals. The upper ~1 cm of surface sediments were collected at equal distances along the transect. A pH measurement (using CyberScan pH 310 handheld pH/mV/Temperature meter) for each sample was undertaken in the field. Sampled sediments were stored in sample jars and refrigerated (while still at the fieldwork site) and stored in the cold storage room (temperature < 5°C) at the University of York.

The funnel shape and macrotidal characteristic of the Solway Firth result in significant tidal level variations; multiple elevations were recorded of the high tide limit at Skinburness Marsh, Cardurnock Marsh, and Bowness Marsh to a reference tidal frame. Each high tide level measurement was levelled relative to OD using a Trimble (Model R8 GNSS/R6/5800) differential global positioning system (δGPS). The measurements of the local high tides at each contemporary site were compared to the same high tide level on the same day measured at the tide gauge station in Workington, which had been verified and corrected for atmospheric pressure, available approximately a month after the data were recorded (NTSLF, 2018). The tidal measurements allow the surface samples collected to be related to a standardised tide level, and also highlight the spatial variation in tidal range along the Solway Firth (Table 1).

Laboratory analyses

A multi-proxy approach was adopted to reconstruct Holocene sea level changes and environmental changes of the study sites. A combination of loss on ignition (LOI) (Heiri et al., 2001), particle size (PSA) (using a Malvern Mastersizer Hydro 2000 laser granulometer) and foraminiferal analyses was undertaken on sample cores from all sites. Pollen analysis was undertaken at Cowgate Farm and Herd Hill to provide information on the vegetation and environmental changes for the region. Loss on ignition particle size and foraminiferal analyses were undertaken on all 72 contemporary surface samples collected from Skinburness Marsh, Cardurnock Marsh and Bowness Marsh (Fig. 1) to define the contemporary foraminiferal distribution in the region, and for the development of a transfer function.

Samples were taken at 1 and 2 cm intervals across the cores for foraminiferal analysis, and at every 2 and 4 cm intervals for pollen analysis. For LOI and PSA analyses, samples were taken at stratigraphical changes in each of the cores. Foraminiferal sample preparation followed standard techniques (e.g. Scott and Medioli, 1980; Gehrels et al., 2001 and Horton and Edwards, 2006), and Moore et al. (1991) were also referenced for the preparation of pollen samples. A minimum count of 200 individuals, possibly for foraminifera, and 300 pollen grains and spores were recorded for each sample. Microfossil nomenclature followed Murray (1971, 2000) for foraminifera and Moore et al. (1991) and Faegri & Iversen (1989) for pollen. The zonation of the foraminiferal and pollen assemblages was then calculated using Constrained Incremental Sum of Squares (CONISS) cluster analysis using TILIA 2.0.41 and TILIA*Graph (Grimm, 1991; 2004). Radiocarbon dating was used to develop a chronology for the reconstruction of Holocene sea level and environmental changes at the

Figure 2. The sample core locations at: 1 Herd Hill (54.928817, −3.28213), 2 Allonby (54.783622, −3.408899), 3 Cowgate Farm (54.813020, −3.407111), 4 Pelutho (54.829901, −3.371133) (Google Earth, 2025a; 2025b; 2025c; 2025d). [Color figure can be viewed at wileyonlinelibrary.com]

study sites based on biostratigraphical and lithostratigraphical changes. All samples submitted for radiocarbon dating were in the form of bulk sediment. Radiocarbon ages obtained were calibrated to cal BP using OxCal v.4.3 (Ramsey, 2009) and the IntCal13 atmospheric curve (Reimer et al., 2013).

Transfer function

The transfer function used in this study was developed using C2 Version 1.7.7 (Juggins, 2007). A local training set was developed from the contemporary samples collected in this study (The Solway training set). The different tidal ranges measured at the three contemporary saltmarshes were converted into the sea water level index (SWLI), thus eliminating the variation in tidal range between the different locations. The SWLI equation used in this study followed Zong & Horton (1999):

$$SWLI_{ab} = [((A_{ab} - MTL_b)/(MHWST_b - MTL_b) \times 100) + 200]$$

Where $SWLI_{ab}$ is the SWLI of sample a at site b; A is the altitude (m OD) of sample a at site b; MTL_b is the mean tide level of site b (m OD); $MHWST_b$ is the mean high water spring tide value at site b (m OD). The addition of the constant (200) is to ensure that all SWLI calculated are positive.

All three contemporary marshes in this study show a vertical zonation based on their foraminiferal assemblages and tidal datum levels recorded: a vegetated high marsh environment dominated mainly by the agglutinated species *Entzia macrescens*; and a lower marsh and tidal flats environment (which falls above MHWNT at all contemporary sites) dominated mainly by the calcareous foraminiferal species *Ammonia beccarii*.

The Solway training set was used to develop the local transfer function for this study, consisting of 72 foraminiferal samples from the three contemporary marshes. The foraminiferal data for the 72 contemporary samples of the Solway training set were 119 plotted against SWLI, which ranged from 275 to 302 (Fig. 5).

Sea level index points

Holocene RSL changes at each site were reconstructed (see Shennan, 1986, 1989; Shennan et al., 2006; Van de Plassche, 2013) through the calculation of individual SLIPs. The indicative meaning for each index point was determined based on the relationship of the foraminifera's occurrence to the present-day depositional environment and reference water level (e.g. MHWST) as calculated at each contemporary saltmarsh site (Table 1). The effect of changes in palaeo-tidal range in the Solway Firth throughout the Holocene was not considered, but it is suggested that the range was smaller than today (Neill et al., 2010). SLIPs are calculated following the equation in Horton et al. (2013):
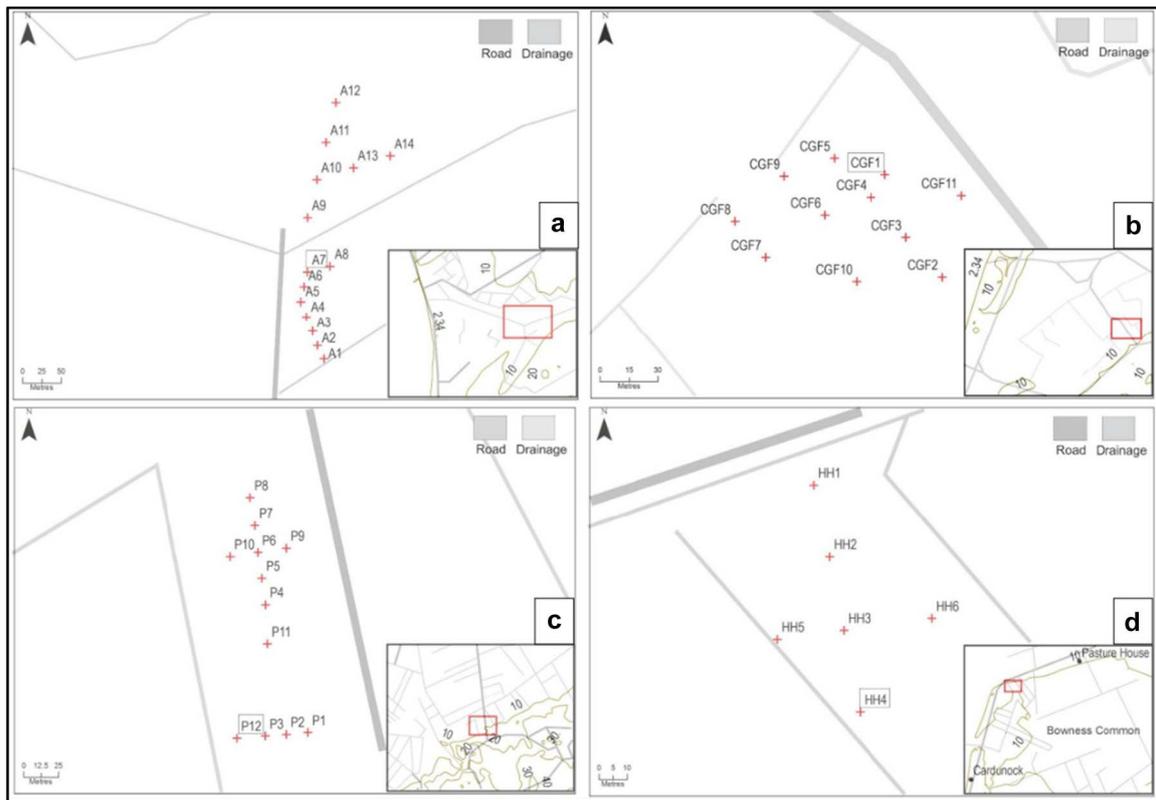
Figure 3. Location of the transects at: (a) Allonby (sample core A7) (54.783622, −3.408899), (b) Cowgate Farm (sample core CGF1) (54.813020, −3.407111), (c) Pelutho (sample core P12) (54.829901, −3.371133), (d) Herd Hill (sample core HH4) (54.928817, −3.28213). [Color figure can be viewed at wileyonlinelibrary.com]

Figure 4. Modern sample transect locations at: 1 Skinburness Marsh, 2 Cardurnock Marsh, 3 Bowness Marsh. [Color figure can be viewed at wileyonlinelibrary.com]

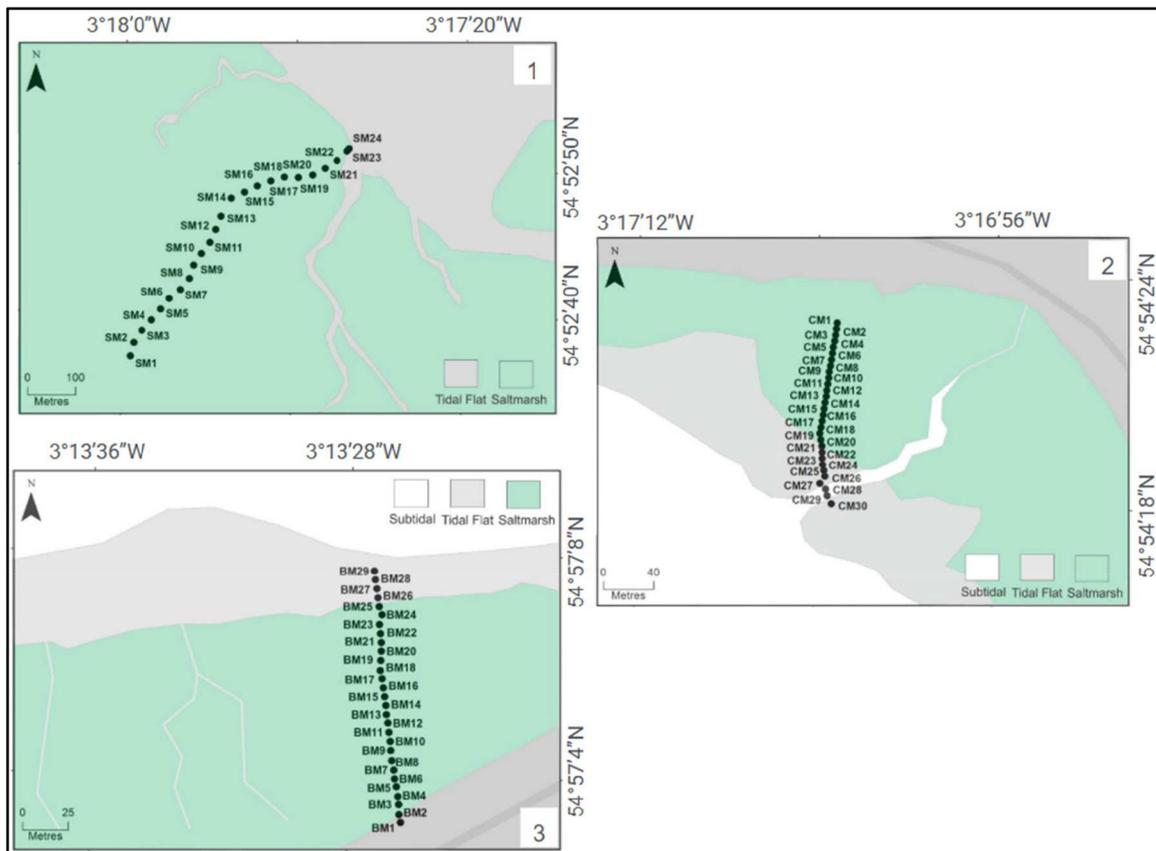**Table 1.** Tidal datum (mOD) at Workington, Maryport and Silloth tide gauges (Admiralty Tide Table, 2016; National Tidal and Sea Level Facility NTSLF, 2018) and the calculated tidal datum for Skinburness Marsh, Cardurnock Marsh and Bowness Marsh.

Site	HAT (mOD)	MHWST (mOD)	MHWNT (mOD)	MTL (mOD)
Workington Tide Gauge	5.1	4.1	2.2	0.4
Maryport Tide Gauge	5.3	4.3	2.3	0.4
Silloth Tide Gauge	5.9	4.8	2.7	0.5
Skinburness Marsh	6.3	4.9	2.4	−0.1
Cardurnock Marsh	7.3	5.6	2.3	−0.8
Bowness Marsh	6.7	5.3	2.7	0.1

Note: Highest Astronomical tide (HAT); Mean high water spring tide (MHWST); Mean high water neap tide (MHWNT) and Mean Tide level (MTL).
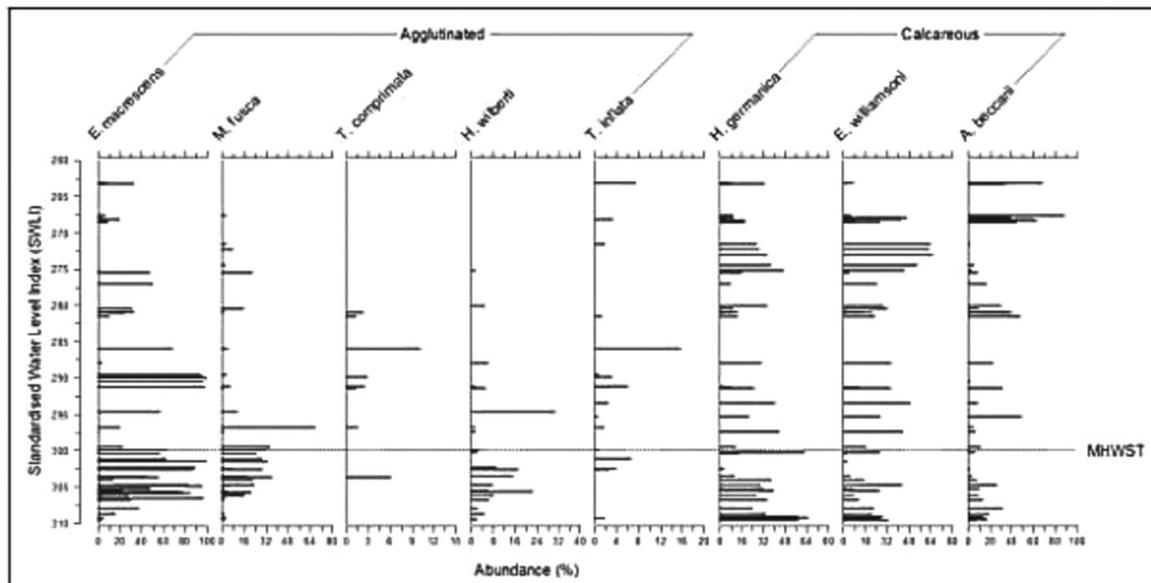
Figure 5. Contemporary foraminiferal samples from Skinburness Marsh, Cardurnock Marsh and Bowness Marsh ordered by elevation (expressed as standardised water level index).

Table 2. Sources of vertical error for the SLIPs in this research.

Source of error	Example	Magnitude
Altitude	High precision surveying (e.g. total station)	±0.05 m
Core collection	Angle of borehole	±1% overburden
	Sampling error	±0.01 m
	Compaction due to coring (for Russian hand corer)	±0.01 m
Sample	Thickness of the sample	Half of the sample thickness

$$RSL(m) = H(mOD) - RWL(mOD)$$

Where H is the altitude of the sample (subtracted from the surface altitude of the core, based on the depth of the sample down the core), and RWL is the altitude of the reference water level of the sample (mid-point of the indicative range).

Three sources of vertical error in the core were identified (Table 2): altitude (high precision surveying; ±0.05 m), core collection (angle of borehole; ±1% of overburden, sampling error; ±0.01 m, compaction due to coring; ±0.01 m) and sample thickness.

SLIPs were corrected for post-depositional lowering using a geotechnical model developed by Brain et al. (2011, 2012), thus providing estimates of compaction-induced post-depositional lowering (PDL) downcore. The geotechnical decompaction approach employed here used the relationships between LOI and sediment compression properties reported by Brain et al. (2012).

Results and interpretations

The summary of lithostratigraphical and foraminiferal frequencies is presented in Figs. 6–10. All samples including those with low individual counts (below 40 individuals; marked with red lines) were included in these diagrams. Red blocks next to the stratigraphy diagram indicate the zone where foraminifera were absent in the core. Radiocarbon dates and position in the core are also shown. A total of 10 radiocarbon dates were obtained from the four sites (Table 3). These were used to produce a series of SLIPs to constrain RSL in this region (Table 4).

Allonby

Lithostratigraphy

The Allonby site is located on the southern shore of the Solway Firth (Fig. 1), bordered by a gently sloping hill to the south and the Black Dub stream to the north, which flows into Allonby Bay at Dubmill. Low-lying farmland surrounds the site to the east and west, separated by a drainage channel between the two investigated fields. Three borehole transects were drilled across the site to establish a detailed stratigraphy (Fig. 6(a)), with surface altitudes ranging from 6.97 to 7.69 mOD. The
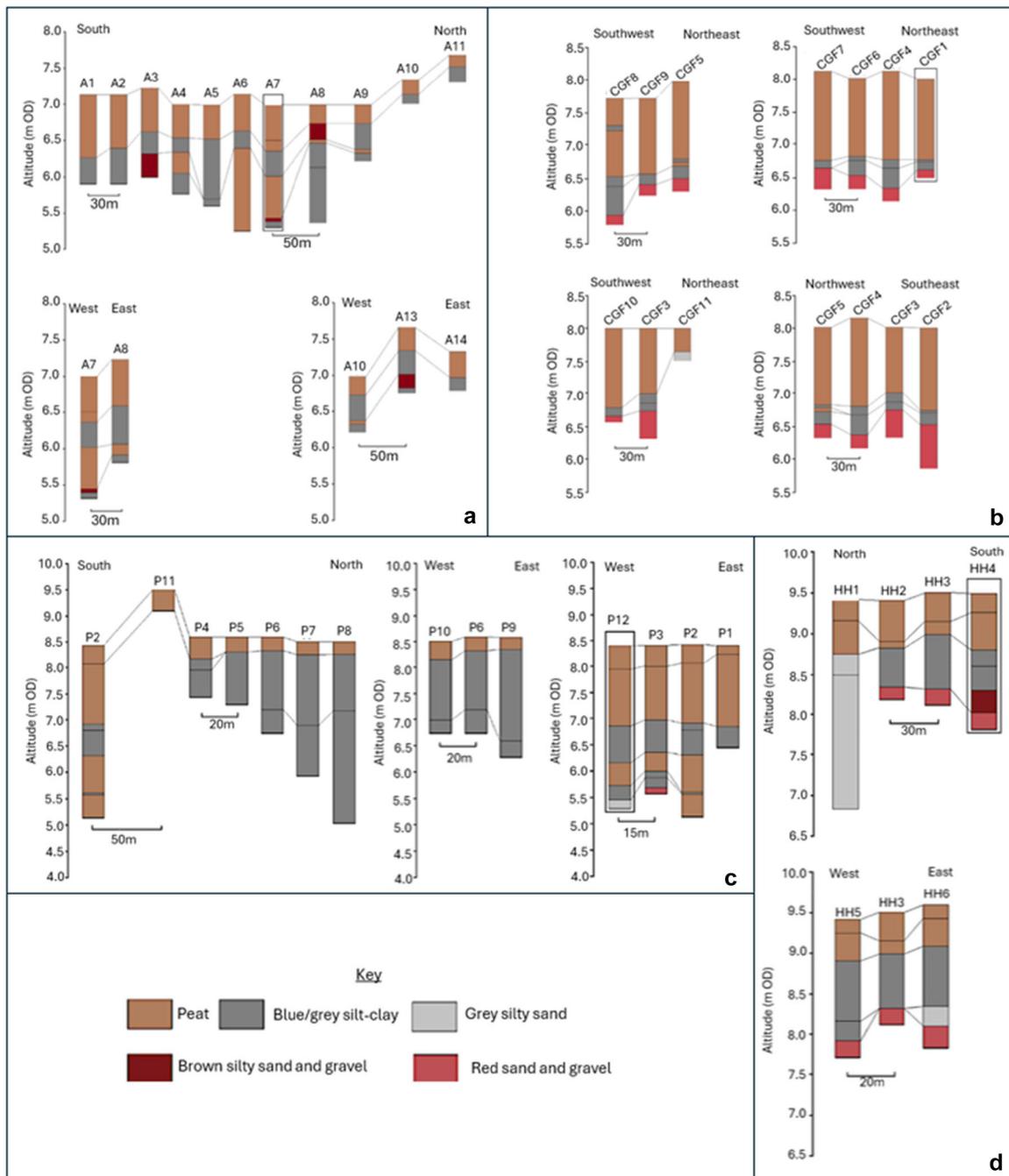
Figure 6. Simplified lithology diagram for (a) Allonby (b) Cowgate Farm (c) Pelutho (d) Herd Hill. [Color figure can be viewed at wileyonlinelibrary.com]

lithostratigraphy includes a basal clastic unit of organic blue/grey silt-clay with sand and gravel, followed by a peat unit with *Phragmites*. Above this, a second clastic unit of organic blue/grey silt-clay is capped by another peat layer with *Phragmites*.

Foraminifera analysis

The samples analysed from Allonby revealed five main agglutinated saltmarsh species comprising *Entzia macrescens, Miliamminia fusca, Tiphotrocha comprimata, Haplophragmoides wilberti* and *Trochammina inflata* (Fig. 7). No calcareous species were found in core A7, although test linings were observed in the core. The agglutinated saltmarsh foraminiferal species were observed between the depths of 0.36 m (6.64 m OD) to 1.38 m (5.62 m OD) (Figs. 6 and 7). No foraminifera were observed in the basal sandy organic blue/

grey silt-clay with gravel unit (1.70 to 1.62 m; 5.30 m OD to 5.38 m OD), the organic brown silt-clay unit (1.62 to 1.57 m; 5.38 m OD to 5.43 m OD), deeper sections of the silty peat with *Phragmites* unit (1.57 to 1.37 m; 5.43 m OD to 5.63 m OD) and in the surface peat unit from 0.35 m (6.65 m OD) towards the top of the core.

A transgressive contact, indicating rising sea levels, was dated to 8160–7946 cal BP, coinciding with the first appearance of foraminifera. This suggests the onset of a saltmarsh environment, marking the initial marine transgression. The silty peat with *Phragmites* layer was overlain by a blue/grey silt-clay unit, dated to 8158–7954 cal BP. Continued sea level rise is reflected in the expansion of the intertidal mudflat environment, evidenced by the deposition of the blue/grey silt-clay unit and a shift in biostratigraphy.

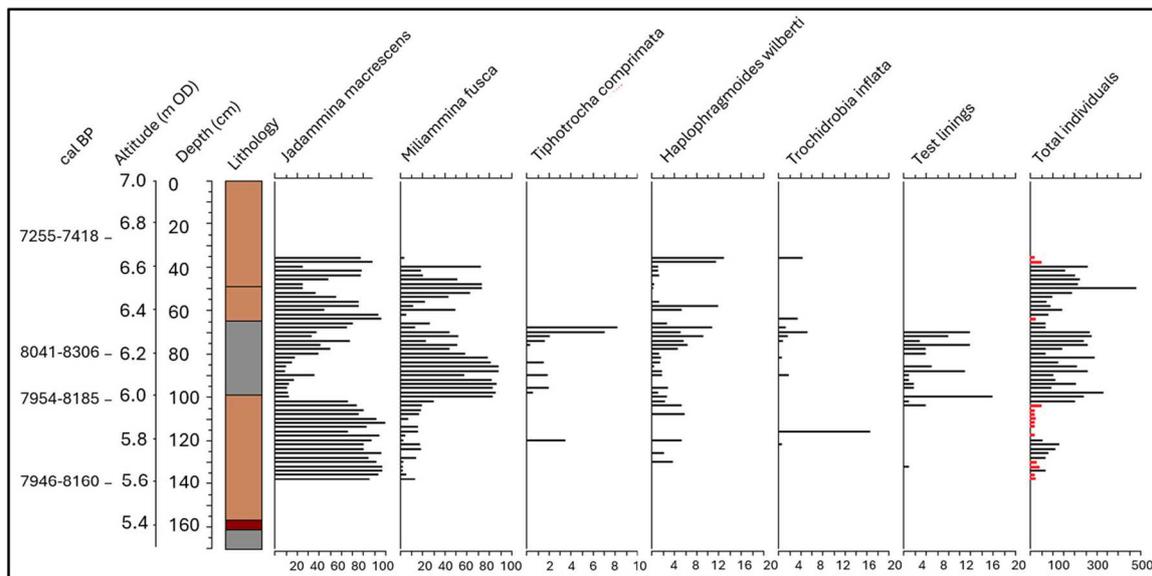Marine regression occurred at 0.35 m depth (6.65 mOD), as the saltmarsh transitioned to a freshwater environment,

Figure 7. Percentage foraminifera abundance diagram from Allonby core A7. [Color figure can be viewed at wileyonlinelibrary.com]

marked by the absence of foraminifera from 0.35 m (6.65 mOD) to the top of the core. This regressive contact is dated to 7418–7255 cal BP. No further changes in biostratigraphy or lithostratigraphy were observed in the top 0.35 m of the core.

The biostratigraphy of sample ALL-139 (Fig. 7) showed a dominance of the agglutinated saltmarsh species *E. macrescens* (85%), which is mostly associated with a high saltmarsh environment, as evidenced by the contemporary foraminifera collected from Skinburness Marsh and Bowness Marsh. The biostratigraphy of sample ALL-100 showed an increased presence of *M. fusca* (83%), immediately prior to the 146 transition into the overlying organic blue/grey silt-clay unit and is also interpreted as a high saltmarsh environment.

Sea-level index points

Three sea-level index points were produced for the Allonby site (Table 4). Samples ALL-35, ALL-100 and ALL-139 produced sea-level index points of 1.06 ± 1.46 m, 0.42 ± 1.46 m and 0.02 ± 1.46 m, respectively.

Cowgate farm

Lithostratigraphy and pollen analysis

The site at Cowgate Farm is on the southern shore of the Solway Firth. The site is located 400 m from Cowgate and is situated near a gently-sloping hill to the south, with flat and low-lying farmland to the north, east and west of the site (Fig. 1). Drainage channels are located in the north and west of the site, and to the east of the site, a small road connecting the farming areas and town is present. A detailed stratigraphy of the site was established through four transects of boreholes, with the surface elevation of the boreholes and the sample cores ranging from 7.6 to 8.1 mOD.

The general stratigraphy recorded at Cowgate Farm was basal sand and silt overlain by peat with *Phragmites* (Fig. 2(b)). The base of CGF1 was dated 8334–8450 cal BP and has low arboreal pollen percentages, suggesting restricted local woodland development due to poor soil cover. These low frequencies correspond to the deposition of the minerogenic clastic unit in the core, suggesting that the arboreal pollen (birch, alder and pine) was likely transported from nearby

areas (Selby, 1997). Pollen from grasses and sedges was abundant, suggesting it was an open grassland with only small areas of woodland in the surrounding catchment area.

The clastic units in core CGF1 were overlain by a peat with *Phragmites* unit, indicating that a freshwater peat environment had developed at the site. The transition at 1.25 m (6.75 mOD) coincides with an increase in arboreal pollen species, mainly *Alnus* and *Quercus*, albeit in low frequencies (Fig. 8). These findings suggest that as marine influence receded, soil cover at the site improved, facilitating the development of woodland in the catchment area (Tipping, 1995). The low frequencies of *Pinus* pollen at Cowgate Farm suggest limited local pine populations, consistent with patterns observed across north-east England during the Holocene (Birks, 1989). There is also a low occurrence of spores: *Polypodiaceae*, *Polypodium*, *Pteridium*, which may represent that ferns formed the understorey components of the woodlands that developed at the site and the surrounding areas.

Foraminifera analysis

A total of five agglutinated saltmarsh foraminiferal species were identified in core CGF1 and no calcareous foraminiferal species were found (Fig. 8(a)). The agglutinated foraminifera species of *E. macrescens*, *M. fusca*, *T. comprimata*, *H. wilberti* and *T. inflata*.

A saltmarsh environment developed at the site starting at a depth of 1.11 m (mOD) evidenced by the first presence of foraminifera in the core (Fig. 8(a)) and saltmarsh species like *Plantago maritima*, which grows in sandy soils in coastal areas, as well as *Aster*-type and *Artemisia* (Fig. 8(b)). This marine transgression was dated at 8412–8200 cal BP and may indicate the first recording of the Main Postglacial Transgression at the site, although the date seems to be older than those recorded at other sites investigated in this study. The transition from the peat with *Phragmites* unit representing a saltmarsh environment (evidenced by the presence of microfossil), to the overlying surface peat unit of freshwater origin at a depth of 0.29 m (7.71 mOD), corresponds to the absence of foraminifera in the core. Woodland continued to expand with increased arboreal pollen percentages (e.g., *Betula* and *Alnus*), indicating mixed woodland coverage in
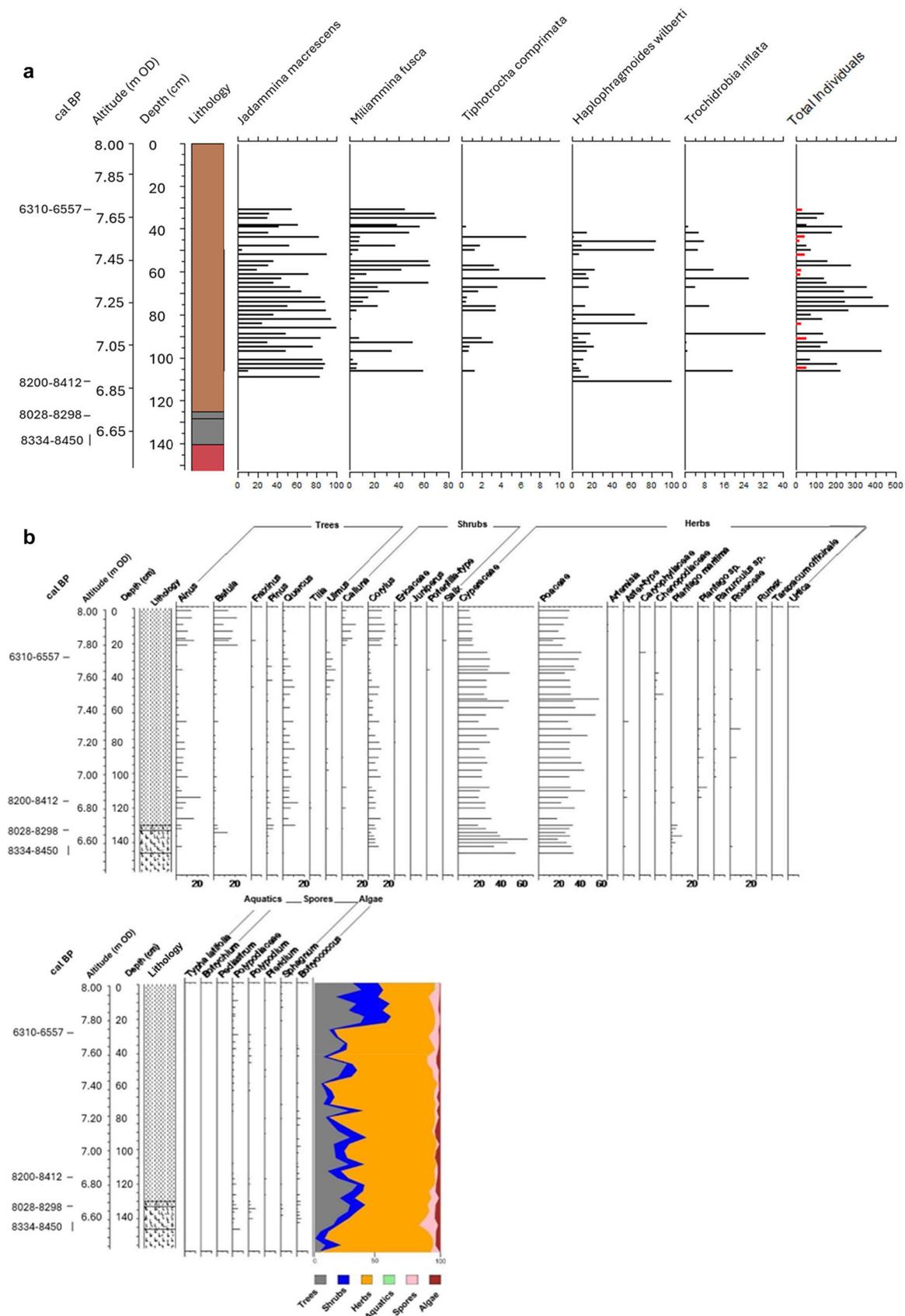
Figure 8. (a) Percentage foraminifera abundance diagram from Cowgate Farm core CGF1 (b) Percentage pollen abundance diagram from Cowgate Farm core CGF1. Pollen frequencies are expressed as a percentage of total land pollen. [Color figure can be viewed at wileyonlinelibrary.com]

the catchment area. This regressive contact in the core, indicating a negative sea level tendency, was dated at 6557–6310 cal BP. No further changes in the biostratigraphy and lithostratigraphy were observed in the core from 0.29 m (7.71 mOD) to the top.

Sea-level index points

The sea-level index points for sample CGF-29 at 7.71 m OD and sample CGF-111 at 6.89 m OD produced sea-level index points of 2.12 ± 1.46 m and 1.30 ± 1.46 m, respectively (Table 4).

Figure 9. Percentage foraminifera abundance diagram from Pelutho core P12. [Color figure can be viewed at wileyonlinelibrary.com]

Pelutho

Lithostratigraphy

The study site at Pelutho is located on the southern shore of the Solway Firth (Fig. 1). The site is bordered by a gentle hill towards the south, low-lying farmland in the north, east and west, a drainage channel to the west, and a road to the east. Three transects were cored at Pelutho, with the surface elevation of the boreholes ranging between 8.4 and 9.5 mOD. The stratigraphy consists of a basal clastic blue/grey clay unit that has developed on top of the underlying bedrock, and is overlain by a peat unit (Fig. 2(c)). The basal sandy blue/grey silt-clay with gravel unit is overlain by a more organic blue/grey silt-clay unit, where the first presence of foraminifera was observed in the core.

Foraminifera analysis

Five main agglutinated saltmarsh species, comprised of *E. macrescens*, *M. fusca*, *T. comprimata*, *H. wilberti* and *T. inflata*, were observed in the samples analysed (Fig. 9). The assemblage was dominated mainly by *E. macrescens* and *M. fusca*.

The presence of the agglutinated foraminifera in the organic blue/grey silt-clay unit indicates that the deposition of the organic blue/grey silt-clay recorded a transgressive contact at the site, and is consistent with an intertidal mudflat environment. The transgressive contact was dated at 8174–8018 cal BP, and is possibly related to the Main Postglacial Transgression. The organic blue/grey silt-clay unit was overlain by a silty peat unit, recording a negative tendency in sea level at the site. No foraminifera were observed in the deepest 0.30 m of the silty peat unit, indicating that a freshwater environment had developed at the site. Foraminifera were again observed in the silty peat unit at a depth of 2.40 m (6.00 mOD), recording another transgressive contact. The increased RSL was dated at 7435–7275 cal BP, with the previous freshwater environment developing into a saltmarsh environment. The lower silty peat unit was overlain by organic blue/grey silt-clay, recording a positive sea level tendency in the core. RSL at the site would have continued to increase, resulting in another expansion of the intertidal mudflat environment into the site. The upper organic blue/grey silt-clay unit was overlain by the surface silty peat unit, which recorded a decrease in RSL at the site and possible development of a saltmarsh suggested by the change

in lithostratigraphy and the foraminiferal assemblages. At a depth of 1.51 m (6.89 mOD), the absence of foraminifera was observed, suggesting that relative sea level decreased, leading to a freshwater environment. The regressive contact was dated at 7254–7016 cal BP. No further changes in foraminifera were observed from 1.51 m (6.89 mOD) towards the top of the core.

Sea-level index points

Samples PEL-151, PEL-240 and PEL-289 produced sea-level index points of 1.35 ± 0.56 m, 0.50 ± 0.57 m and 0.58 ± 0.57 m, respectively.

Herd Hill

Lithostratigraphy and pollen analysis

The study site at Herd Hill is approximately 200 m from the present coastline on the southern shore of the Solway Firth (Fig. 1). The site is bordered by a gently sloping hill to the north and west of the site, and farmland to the east and south of the site. Bowness Common, a raised peat bog, is situated southeast of Herd Hill and has been studied previously (Walker, 1966; Huddart et al., 1977). Two transects of boreholes were cored across the site to establish a detailed stratigraphy, with the surface altitude of the boreholes ranging from 9.4 to 9.6 mOD. The general lithostratigraphy at Herd Hill is a red sand and gravel unit over the bedrock, overlain by a silty brown sand and gravel unit, which transitioned into a blue/grey silt-clay unit and the surface peat unit (Fig. 6).

Within the silty brown sand and gravel unit there was very little arboreal pollen species, with only two slight peaks of *Alnus* observed at 1.42 m (8.08 mOD) and 1.30 m (8.20 mOD), and a singular peak of *Betula* at 1.30 m (8.20 mOD) (Fig. 10(b)). This lack of mixed woodland at Herd Hill at the time was likely restricted due to inadequate soil cover, indicated by the silty brown sand and gravel units. *Alnus* was first observed at Herd Hill at 1.46 m (8.04 mOD) and dated to 5741–5900 cal BP. Other records of *Alnus* were found at Cowgate Farm (8334–8450 cal BP), Boustead Hill (7928–8304 cal BP) and Drumburgh Moss (8403–8947 cal BP) (Lloyd et al., 1999), suggesting alder likely established at Herd Hill around the same period as these sites. High frequencies of Poaceae and Cyperaceae were found within

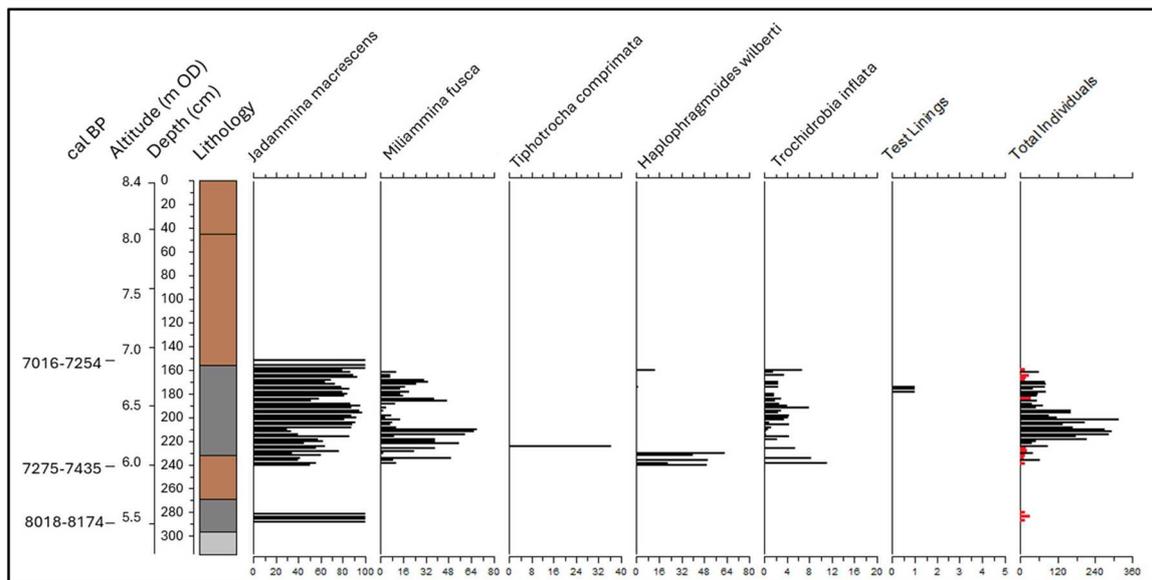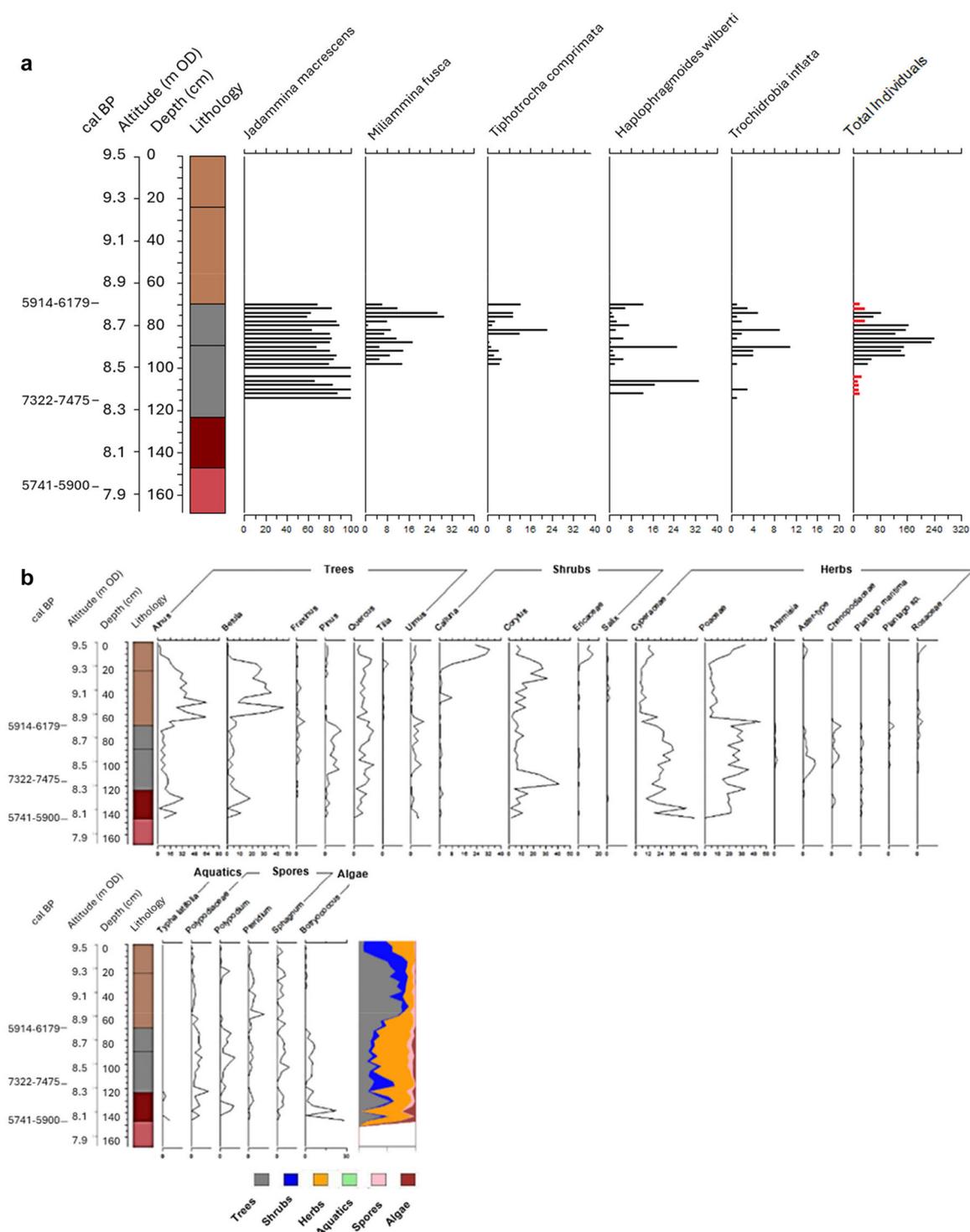**Figure 10.** (a) Percentage foraminifera abundance diagram from Herd Hill core HH4. (b) Percentage pollen abundance diagram from Herd Hill core HH4. Pollen frequencies are expressed as a percentage of total land pollen. [Color figure can be viewed at wileyonlinelibrary.com]

the 8.04–0.78 mOD zone, indicating an open environment dominated mainly by grass and sedges. It is probable that trees were growing in the pollen catchment area close to the site, whilst the grass and sedges were growing locally at the site.

Foraminifera analysis

The samples analysed revealed five agglutinated saltmarsh species comprised of *E. macrescens*, *M. fusca*, *T. comprimata*, *H. wilberti* and *T. inflata* (Fig. 10(a)). Foraminifera were observed within the blue/grey silt-clay unit, indicating a marine environment. The deposition of the blue/grey

silt-clay unit, which recorded the transgressive contact in core HH4, was dated at 7475–7332 cal BP, and is most probably related to the Main Postglacial Transgression at the site. The increase of RSL would have resulted in an expansion of the intertidal mudflat environment at the site. The presence of saltmarsh pollen species (e.g. *Aster*-type and Chenopodiaceae pollen) in the blue/grey silt-clay unit supports this. The blue/grey silt-clay unit transitioned to the overlying peat unit, indicating that the previous intertidal mudflat environment may have developed into a more freshwater environment as RSL decreased from the site; this is supported by the lithostratigraphy and the absence of foraminifera from 0.69 m

Table 3. New radiocarbon dates from this research.

Lab code	Study site	Depth (cm)	mOD	Material	Fraction	^{14}C age $\pm 1\sigma$	Calibrated age BP
D-AMS 022222	Allonby	35	6.65–6.66	Peat	Bulk carbon	6377 ± 34	7418–7255
D-AMS 025777	Allonby	78	6.22–6.23	Organic clay	Bulk carbon	7359 ± 32	8306–8041
D-AMS 025776	Allonby	100	6.00–6.01	Peat	Bulk carbon	7209 ± 41	8158–7954
D-AMS 022223	Allonby	139	5.61–5.62	Peat	Bulk carbon	7203 ± 49	8160–7946
D-AMS 016391	Cowgate Farm	29	7.71–7.70	Peat	Bulk carbon	5655 ± 50	6557–6310
D-AMS 016392	Cowgate Farm	111	6.89–6.90	Peat	Bulk carbon	7521 ± 55	8412–8202
D-AMS 016393	Cowgate Farm	127	6.73–6.74	Organic clay	Bulk carbon	7345 ± 36	8298–8028
D-AMS 016394	Cowgate Farm	135/141	6.65–6.59	Wood	Bulk carbon	7583 ± 41	8450–8334
D-AMS 022226	Pelutho	151	6.89–6.90	Peat	Bulk carbon	6231 ± 35	7254–7016
D-AMS 025778	Pelutho	240	6.00–6.01	Peat	Bulk carbon	6456 ± 45	7435–7275
D-AMS 022227	Pelutho	289	5.51–5.52	Organic clay	Bulk carbon	7285 ± 36	8174–8018
D-AMS 022224	Herd Hill	69	8.81–8.80	Peat	Bulk carbon	5236 ± 46	6179–5914
D-AMS 022225	Herd Hill	115	8.35–8.34	Organic clay	Bulk carbon	6497 ± 36	7475–7322
D-AMS 025779	Herb Hill	146	8.04–8.03	Silty sand	Bulk carbon	5059 ± 26	5900–5741

Table 4. SLIPs produced in this study, corrected for changes in palaeo-tidal range.

Lab code	Study site	Lat/long	mOD	^{14}C age $\pm 1\sigma$	Calibrated age BP	RSL (m)	Ten
D-AMS 022222	Allonby	54.783, −3.408	6.65–6.66	6377 ± 34	7418–7255	1.06 ± 1.46	−
D-AMS 025776	Allonby	54.783, −3.408	6.00–6.01	7209 ± 41	8158–7954	0.42 ± 1.46	+
D-AMS 022223	Allonby	54.783, −3.408	5.61–5.62	7203 ± 49	8160–7946	0.02 ± 1.46	+
D-AMS 016391	Cowgate Farm	54.812, −3.405	7.71–7.70	5655 ± 50	6557–6310	2.12 ± 1.46	−
D-AMS 016392	Cowgate Farm	54.812, −3.405	6.89–6.90	7521 ± 55	8412–8202	1.30 ± 1.46	+
D-AMS 022226	Pelutho	54.829, −3.371	6.89–6.90	6231 ± 35	7254–7016	1.35 ± 0.56	−
D-AMS 025778	Pelutho	54.829, −3.371	6.00–6.01	6456 ± 45	7435–7275	0.50 ± 0.57	+
D-AMS 022227	Pelutho	54.829, −3.371	5.51–5.52	7285 ± 36	8174–8018	0.58 ± 0.57	+
D-AMS 022224	Herd Hill	54.928, −3.285	8.81–8.80	5236 ± 46	6179–5914	3.26 ± 0.56	−
D-AMS 022225	Herb Hill	54.928, −3.285	8.35–8.34	6497 ± 36	7475–7322	3.41 ± 0.56	+

Abbreviation: Ten, tendency.

(8.81 mOD) towards the top of the core. A shift towards grass pollen rather than sedges corresponds to the transition from the blue/grey silt-clay and indicates an environmental change from reed swamp to freshwater limnic sediment and turfa, as well as a possible evidence of changing groundwater table in the area (Zong and Tooley, 1999).

No further changes in foraminifera biostratigraphy were observed from 0.69 m (8.81 mOD) towards the top of the core; however, vegetation changes are recorded with the presence of more arboreal species from 0.54 m (8.96 mOD), marking a further development of woodland as RSL fell, facilitating soil formation. The change in lithostratigraphy to the surface peat occurred at 0.23 m (9.27 mOD). At 0.18 m (9.32 mOD) arboreal pollen species declined, possibly as a result of Bronze Age human activities, as an increase in heather (*Calluna*) and Ericaceae suggest a transition to nutrient-poor, peat-rich environments. At other regional sites, similar environmental progressions have occurred, pointing to long-term shifts in vegetation and landscape shaped by human influences. The regressive contact indicating a negative sea level tendency at Herd Hill was dated at 6179–5914 cal BP.

Sea-level index points

Two sea-level index points were produced for Herd Hill. Samples HH-69 and HH-115 produced sea-level index points of 3.26 ± 0.56 m and 3.41 ± 0.56 m, respectively.

Discussion

Multiproxy palaeoenvironmental analysis has reconstructed Holocene RSL and coastal environmental changes at four sites

from the southern shore of the Solway Firth over ~8300 years, producing ten new SLIPs.

Observed and predicted RSL across the Solway Firth

The 10 new SLIPs (Fig. 11(a)) were combined with the ten previously published data points for South Solway Firth (Fig. 11(b)). To understand the RSL signal across the Solway Firth Estuary, these data were compared with the RSL signal at the two other sites from the North of the inlet: North and North West Solway (Shennan et al., 2018). This new SLIP data record constraints RSL between 8.1 ka BP and 5.5 ka BP, where RSL was between ~−1.1 m, rising to ~4 m above present. The existing SLIP record for South Solway still constrains the oldest data for the rise above present day (but with a limiting point) at 8.3 ka BP, reaching a highstand at 5.5 ka BP of ~4 m, and falls towards present, sometime between 5 and 2.1 ka BP. Combining these two datasets improves the constraint on the timing of the rise of RSL above present, which was previously constrained by the two limiting points to between ~8320 and 7500 cal BP. The main change with the addition of these new SLIPs is a shift in the timing of the height of the highstand from 5.5 to ~7.1 ka BP. Although we note the larger error bars on the new SLIPS.

When combined with the existing SLIP data from this site (Fig. 11), the timing for the rise of RSL above present in the early Holocene (Main Postglacial Transgression) occurred between ~8320 and 7500 cal BP, reaching a highstand of 3.26 ± 0.56 mOD, falling to 1 mOD by 2500 cal BP. This is a later rise compared to the two sites along the Northern coast of the estuary, where the Main Postglacial Transgression
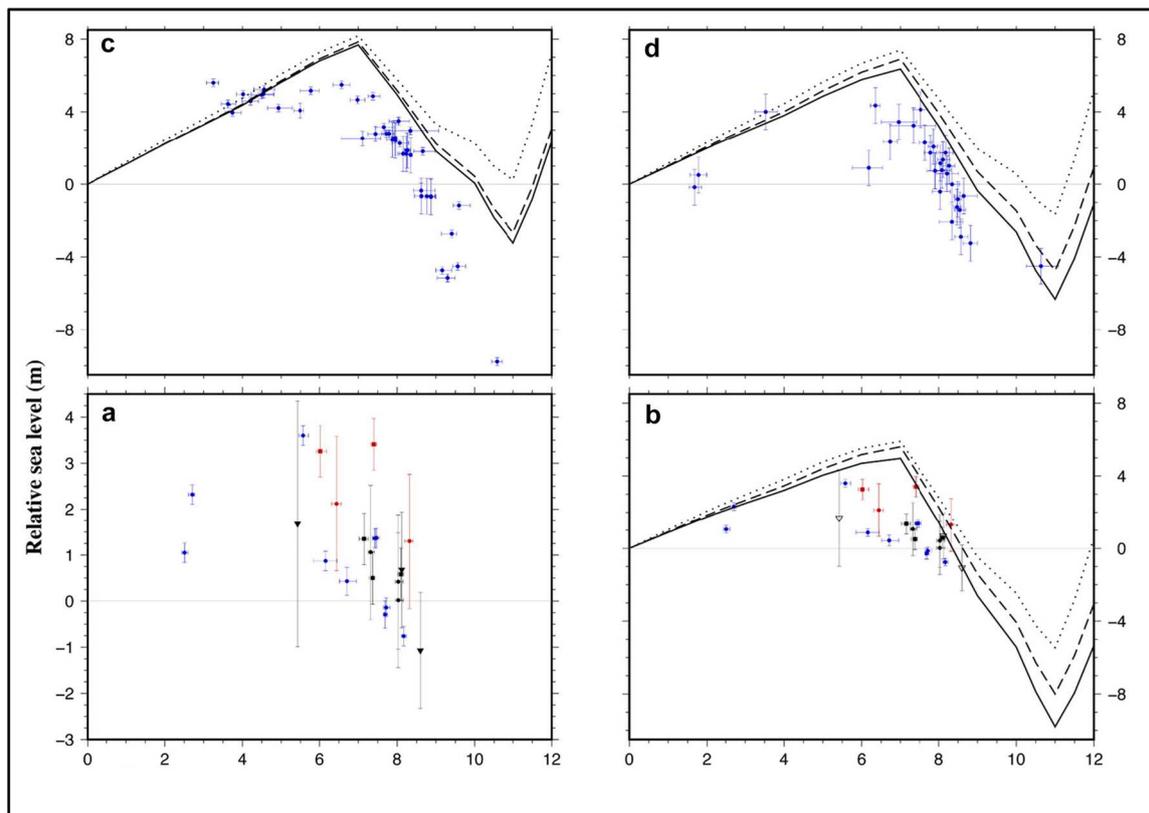
Figure 11.   Observed and predicted RSL at three sites around the Solway Firth. (a) New sea level index points produced from this study at Allonby (black circle), Cowgate farm (red circle), Pelutho (black square) and Herd Hill (red square) combined with existing data from Shennan et al., 2018 SLIP (blue circles), limiting points (inverted black triangle). Panels (b) South Solway (54.85 N; −3.33 W), (c) North Solway (54.99 N; −3.59 W) and (d) North West Solway (54.9 N; −4.4 W) show a comparison between observed and predicted RSL using ice sheet reconstructions from Bradley et al., 2023, for three different thicknesses of the British and Irish ice sheets (BIIS): Thick (dotted), thin (dashed) and hybrid of the two (solid). [Color figure can be viewed at wileyonlinelibrary.com]

occurred ~8500 cal BP. The maximum height of the highstand is higher at the NW and North sites (Fig. 7(c), (d)) at 5.49 and 4.35 mOD, respectively, which is to be expected given their closer proximity to the centre of ice loading.

RSL predictions were generated at the three sites around the Solway Firth using British and Irish ice sheet reconstructions from Bradley et al. (2023) and compared to the new and previously published observed data (Fig. 11). This new data was not used in the development of these ice sheet reconstructions. This selection of ice sheet-earth model combinations shows the possible spread in RSL predictions across this region, with no model capturing the SLIP data (both the height of the highstand and timing of the Holocene rise above present day) at all three sites.

At the south Solway site, the range of input BIIS changes the height of the highstand by ~1 m and the timing when RSL is above present day sea level (Holocene Main Postglacial Transgression) by ~500 yr. With a thicker local ice sheet, the highstand is overpredicted, and the Holocene Main Postglacial Transgression is too early at all three of the sites around the Solway Firth. The hybrid reconstruction, where the location of the ice divides was changed across NW Scotland (Bradley et al., 2023), captures the timing of the Main Postglacial Transgression the best. However, the timing of the fall towards the present and the nature of the highstand are too sharp (with a peak at ~7000 BP) compared to the more prolonged, smooth signal shown in the SLIPs.

Coastal changes

Pollen analysis from Cowgate Farm and Herd Hill, combined with LOI and PSA analyses, provided some chronostratigraphic

evidence for the RSL changes and helped support the indicative meanings of the SLIPs, whilst providing evidence of the broader environmental changes in the region. Both pollen records commence with open environments with taxa characteristic of reed swamp (sedge and grass) and saltmarsh (*Aster*-type, sea plantain and goosefoot) (Tooley, 1974; Zong & Tooley, 1996; Lloyd et al., 1999), with low woodland coverage of birch, alder, pine and hazel in the surrounding area. It is probable that trees were growing in the pollen catchment area close to the site, whilst the grass and sedges were growing locally at the site. The presence of ferns and peat moss is common in acidic wetlands, including bogs and swamps, and these may have developed at the site or in nearby areas as the relative sea level increased and marine influence expanded into the site. The low occurrence of spores of *Polypodiaceae, Polypodium* and *Pteridium* may represent ferns that formed the understorey components of the woodlands that developed at the sites and the surrounding areas.

A decrease in RSL is indicated at Cowgate Farm from ~6400 cal BP by increased woodland coverage, including an expansion in alder and birch, and the development of more organic soils. The change in ratios between sedges and grasses (more grasses and less sedges) may indicate a change from reed swamp to a more freshwater limnic sediment and turfa (Zong and Tooley, 1999), and possible evidence of a changing groundwater table in the area (Zong and Tooley, 1999). A decrease in RSL is indicated later at Herd Hill from ~6000 cal BP from similar palaeoenvironmental indicators. As RSL continued to decrease in the area, the pollen signal alludes to regional environmental changes that are potentially associated with human activities. For example, the absence of elm at ~5000 cal BP at both sites broadly agrees with the dates of elm decline recorded at 5130 cal BP in Ennerdale Water, 5100 cal

BP in Blea Tarn and 5540–4860 cal BP in Blelham Tarn in the Lake District, Cumbria (Pennington, 1964). The Neolithic elm decline has been assigned to both anthropogenic and natural causes (Batchelor et al., 2014). The decrease in arboreal pollen at Herd Hill may be attributed to increased clearance in the Bronze Age (e.g. Hodgkinson et al., 2000; Wimble et al., 2000). Decreased woodland coverage in the area is associated with the expansion of peat bog from the fen in the late Holocene (Gallego-Sala et al., 2016).

Conclusions

Holocene RSL changes for the northwest Cumbrian coastline were reconstructed. A multiproxy approach combining lithostratigraphic and biostratigraphic analysis was adopted to produce ten new SLIPs constraining the period between ~8300 cal BP to ~6000 cal BP. This has now doubled the amount of sea level data available for southern Solway, and has further refined the height of the Holocene highstand and the timing of when the sea level rose above the present day in the mid-Holocene.

Episodes of RSL higher than present were recorded, most likely related to the Main Postglacial Transgression. No subsequent increase in RSL was recorded from ~6000 cal BP onwards, and it is probable that the glacio-isostatic rebound of the land in the study area had outpaced any increase in global sea level that occurred in the late Holocene. Based on the newly produced and corrected SLIPs from the region, it appears that differential crustal movement between the northern Solway Firth and the southern Solway Firth resulted in the higher relative sea level values at the former. Comparison between the corrected SLIPs and RSL predictions using British and Irish ice sheet reconstructions was also made, showing that the timing of the Main Postglacial Transgression is best captured with a hybrid model for the presence of thick and thin ice sheets. Pollen analysis revealed environmental and vegetation changes, showing a transition from saltmarsh to freshwater, which corroborated the lithostratigraphical and biostratigraphical evidence, strengthening sea level reconstruction.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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