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JQS Journal of Quaternary Science QRA Quaternary Research Association

Holocene sea-level and environmental changes on the Isle of Mull, Scotland

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ABSTRACT: Sea-level and coastal changes are reconstructed on the Isle of Mull, western Scotland, from 10 988 to 10 507 cal BP to the present. This research has produced the first SLIP for the Isle of Mull. A multiproxy approach including pollen, spore, foraminifera and diatom analyses reveals palaeoenvironmental changes from two coastal sites. Marine phases are recorded from 10 988 to 10 507 cal BP in eastern Mull, when the relative sea level (RSL) was higher at 1.98 ± 0.15 mOD, and coinciding with the end of the Loch Lomond Stadial. The sea-level record for north-west Mull commences from 7570 to 7431 cal BP (285 cm [4.56 mOD]), showing higher RSL at 4.69 ± 0.14 mOD and approximately corresponding with the timing of the highstand recorded at nearby Arisaig. RSL is higher than present levels following marine transgression at 2273–1926 cal BP (153 cm [6.47 mOD], RSL: 3.78 ± 0.13 mOD) in north-west Mull and at 3460-2469 cal BP (317 cm [7.31 mOD, RSL: 2.39 ± 0.14 mOD]) in eastern Mull. Sea-level index points generally align well with RSL changes recorded regionally, though there is some indication that RSL was higher in north-west Mull. The data point at 10 988-10 507 cal BP can contribute to constraining the thickness of the British and Irish ice sheet as the thickest central dome of the ice sheet extended along this area of the British Isles. Coastal vegetation changes show little variation from grass-, sedge- and heather-dominated heathlands, with oak and birch shrublands throughout the Holocene. Following marine regression, there is indication of arboreal expansion in eastern areas, whilst a progressively more open environment is evident in north-west Mull. Corresponding changes in the herb pollen mosaic, NPPs and microcharcoal levels indicate a long-term anthropogenic presence on the island.

KEYWORDS: Holocene; human–environment; Inner Hebrides; sea-level change; vegetation change

Introduction

Western Scotland has the longest high-resolution record of relative sea-level (RSL) change in the British Isles produced from isolation basins and raised tidal marshes at Arisaig, Inverness-shire (Shennan et al., 1993; 1994; 1999; 2000a; 2005), due to its central proximity to the former British and Irish Ice Sheet (BIIS) (Shennan et al., 2005). Palaeoenvironmental records from western Scotland are therefore globally important for understanding the mechanisms of late Quaternary sea-level change as well as the dynamics of Devensian deglaciation and glacial isostatic adjustment (GIA). The Isle of Mull is the second largest island of the Inner Hebrides, but there are currently no dated RSL reconstructions from the island. Holocene sea-level studies show significant regional variation between central and western areas of Scotland (Shennan et al., 2018; Bradley et al., 2023). Increasing the resolution of sea-level records in the area is therefore important for developing a higher definition understanding of sea-level change and GIA.

A number of published pollen profiles exist for the Isle of Mull (Fig. 1), covering the Lateglacial to the present (Walker and Lowe, 1982; 1985; 1987; Lowe and Walker,1986a; 1986b; Walker, 1993a; 1993b). However, there is a significant opportunity to develop a greater understanding of the coastal vegetation changes on Mull by analysing the relationship between markers of vegetation change, including anthropogenic signals, and changing RSL. This research investigates Holocene coastal changes, including changes in sea-level, vegetation, hydrology and anthropogenic activities, from two sites on the island. It will adopt a multiproxy approach utilising foraminifera, diatom, ostracod, pollen, spore and geophysical analyses.

Background

The Isle of Mull forms part of the Inner Hebrides archipelago situated off the west coast of Scotland (Fig. 1). It is the second largest island, with a total land mass of 116 000 hectares. It is afforded protection from exposure to the Atlantic Ocean from the Isles of Tiree and Coll, and its proximity to the Scottish mainland coast. The present landscape of Mull is largely treeless, with the exception of pockets of plantations. Grass

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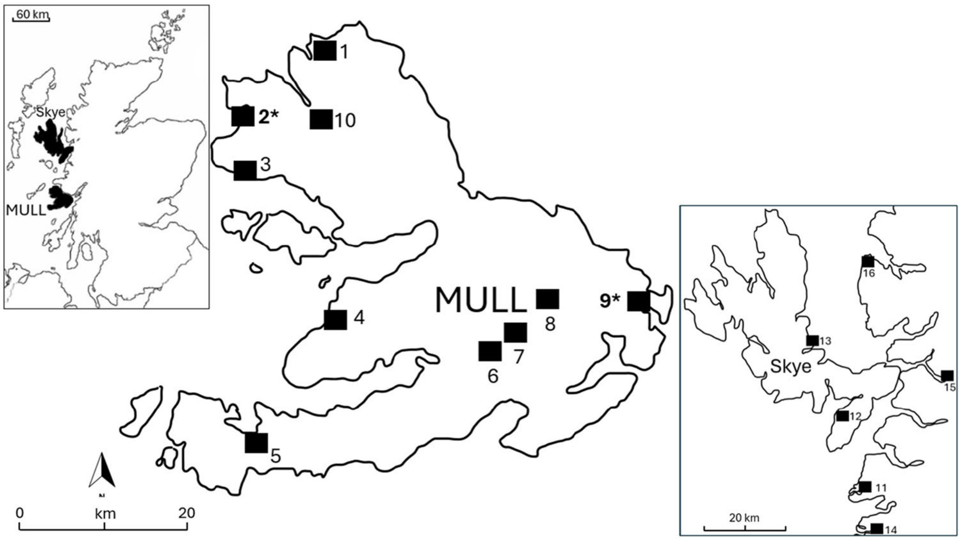

Figure 1. Location of the sites referred to in the text: 1 Mishnish, 2 Calgary Bay*, 3 Beinn Reudle, 4 Gribun, 5 Loch an t-Suidhe, 6 Fhuaran (Glen More), 7 Coire Clachach 8 Torness, 9 Grass Point* (*Indicates new site and data), 10 Criet Dubh, 11 Arisaig, 12 Inver Aulavaig, 13 Peinchorran, 14 Kentra, 15 Kintail and 16 Applecross.

and heathland communities, interspersed with bog and mire associations, provide the dominant vegetation across the island (Walker and Lowe, 1985).

Holocene sea-level and coastal changes in Western Scotland

Despite the absence of sea-level index points for Mull, elevations and Quaternary geomorphological features of coastal areas have been described, including the presence of pre-glacial shorelines (Wright, 1911; McCann, 1968). Some of the closest sea-level records to Mull are from the Isle of Skye (Fig. 1) (Selby et al., 2000; 2007; Selby and Smith, 2016; Best et al., 2021) alongside records from north-west Scotland, including Kentra, Arisaig, Kintail and Applecross (Shennan et al., 1995; 2000b). Early work on Skye mapped raised shorelines, indicating former periods of higher RSL (Richards, 1969; Huffman et al., 2025). RSL changes following the last glacial maximum (LGM) in western Scotland, including Skye, follow a similar pattern with differing magnitudes of change, which reflect increasing distance from the British–Irish ice sheet (BIIS) ice loading centre. Isolation basins at Arisaig record an initial fall of ca. 30 m between ca. 16 and 12 ka (Shennan et al., 1994; 2000a). Following a minimum at ca. 11 000 BP, RSL rises into the Holocene, reaching a mid-Holocene highstand, ca. 5 m above present at Arisaig between ca. 7000 and 6000 BP, and then falling to present (Shennan et al., 2018; Huffman et al., 2025). In southern Skye, a marine limit at ca. 23 mOD occurs after the Lateglacial Maximum, followed by an RSL fall to ca. 20 mOD at ca. 15 100 BP (Best et al., 2021). Isolation basin data, supported by terrestrial and marine limiting dates, record an RSL fall to 11.59 mOD by 14 200 BP (Best et al., 2021). In the Outer Hebrides, recent GIA modelling suggests that RSL from ca. 15 000 to ca. 8000 BP was below or at modern levels, rising up to ca. 3 m above present during the mid-Holocene (Bradley et al., 2023).

On the Isle of Skye, Selby et al. (2000) and Selby and Smith (2007; 2016) described estuarine conditions already present at Inver Aulavaig at 9030–7960 BP and continuing until after 6387–6024 BP. A second marine phase occurred between 3638–3382 and 3459–3253 BP. In the nearby back-barrier site of Peinchorran, estuarine conditions are replaced by a freshwater environment between 7610–7335 and 4868–4551 BP. This fluctuation is recorded at Loch nan Eala, Arisaig, where a brief episode of freshwater conditions replaced an estuarine environment at 7579–7435 BP (Shennan et al., 1994).

On Harris in the Outer Hebrides, a rise in RSL from at least the mid-Holocene to present is recorded from coastal wetland areas at 5450–4861 BP at 0.5-1.6 mOD and 3375–1948 BP at 0.3-2.3 mOD, respectively. A possible extreme flooding event is also recorded at 8348–7982 BP at 0.1 mOD (Jordan et al., 2010). In the Solway Firth, south-west Scotland, the rate of RSL rise was rapid prior to ca. 8600 to ca. 7800 cal BP before slowing, with a ca. 3 m rise over the following 3000 years (Smith et al., 2020). By ca. 4400 cal BP, RSL was falling towards present levels.

Holocene vegetation changes on Mull

The most complete and high-resolution pollen sequence for Mull comes from Gribun (56.416, –6.136) (95 mOD) in western Mull (Walker, 1993a) (Fig. 1). It highlights three distinct stages of vegetational development: (i) an early Holocene succession with open herbaceous vegetation; (ii) a phase of limited mid Holocene woodland expansion and diversification (i.e., *Quercus*, *Ulmus*, *Pinus* and *Alnus*); and (iii) a shift to heathland and grassland due to soil deterioration. Seven additional sites on Mull, including Loch an t-Suidhe (56.312, –6.254) (30 mOD) on the Ross of Mull, Mishnish (56.631, –6.151) (120 mOD) to the west of Tobermory and Beinn Reudle (56.536, –6.272) (170 mOD), provide valuable data for the vegetation history of the Lateglacial and early Holocene (Walker, 1993b). The pollen sequences vary across the sites, being attributed to pollen taphonomic processes, levels of preservation and variations in the degree of exposure of each site to prevailing winds (Lowe and Walker, 1986a; 1986b). Patterns of vegetational development at Loch an t-Suidhe and Mishnish broadly align to pollen data from the inland and south-easterly Glen More area of the island and also at the westerly site of Gribun (Walker and Lowe, 1982; 1985; 1987; Lowe and Walker, 1986a; 1986b; Walker, 1993a; 1993b). The early Holocene (ca. 11 820–9740 cal BP) vegetation reflected the tundra landscape of Mull at the end of the Loch Lomond Stadial, characterised by *Artemisia*, *Rumex*, Poaceae, Cyperaceae and *Lycopodium selago* (Lowe and Walker, 1986a; 1986b). *Empetrum* heath, with Juniper scrub and open birch woodland, developed as a result of climatic amelioration (Lowe and Walker, 1986a; 1986b), although this was absent at higher elevations in Glen More and likely reflected the continued presence of glaciers (Walker and Lowe, 1985). *Corylus* appeared at ca. 9740 cal BP, followed by limited arboreal representations of *Quercus*, *Ulmus*, *Pinus* and *Alnus* in upland areas, which remained in place throughout the mid Holocene (Walker and Lowe, 1985). The *Alnus* rise occurred at ca. 7420 cal BP (Walker and Lowe, 1985; Lowe and Walker, 1986a; 1986b). Juniper is absent and there is limited *Betula* development (Lowe and Walker, 1986a; 1986b), probably due to exposure to strong onshore winds and extensive Atlantic sea fetch. Late Holocene pollen records show an expansion of grassland- and *Calluna*-dominated heaths (Birks, 1977; Walker and Lowe, 1985). The changes from ca. 4000 cal BP are mainly attributed to soil deterioration due to the shift to wetter conditions (Birks, 1977; Walker and Lowe, 1985).

Anthropogenic presence on Mull

Archaeological evidence of human occupation is evident on Mull since the early Holocene (Mithen and Wicks, 2018). At Criet Dubh, north-west Mull, early activity is dated at 10 300 BP, representing the earliest dated activity in the western Scotland region (Mithen et al., 2020) (Fig. 1). This site is centred around a structure that is thought to have been frequented by mobile populations throughout the early Holocene alongside other locations in the Western Isles. The climate cooling event of ca. 8200 BP (e.g., Rush et al., 2023) is thought to have caused regional population decline, lasting until ca. 7000 BP, when the presence of shell middens increases in the area (Mithen et al., 2020). Microcharcoal data suggest phases of burning during the Mesolithic corresponding with rapid climate shifts, and local woodland reduction at ca. 8250 cal BP (Edwards et al., 2007). A significant cold event followed (ca. 7790–7470 cal BP) that recorded woodland recovery, which may have been due to reduced human or faunal activity (Edwards et al., 2007).

Structural evidence of the human occupation of Mull increases throughout the mid-Holocene, with evidence of brochs (circular tower structures) and crannogs (artificial islands) identified at various locations around the Mull coastline (Holley and Rolston, 1995). A pollen sequence from Loch an t'Suidhe (NM 371215) (33 mOD) indicates human activity at ca. 5710 cal BP (Sugden, 1999). Pollen records show an *Ulmus* decline (ca. 5710 cal BP) (Lowe and Walker, 1986b), which corresponds with the British elm decline and may be attributed to deliberate human clearance (ca. 5760 cal BP). Late Holocene pollen records show an expansion of grassland- and *Calluna*-dominated heaths, due to the shift to wetter conditions and as a response to anthropogenic activity (Birks, 1977; Walker and Lowe, 1985). Vegetation changes showing a shift from woodland and scrub in the late Holocene period are likely to be influenced by the expansion of arable agriculture, followed by intensified sheep grazing and a human population rise to ca. 10 000 by the 18th century (Birks, 1977; Walker and Lowe, 1985).

Methodology

Study sites

Calgary Bay (NM 3755851261)

Calgary Bay is located on the north-west coast of the Isle of Mull (Fig. 2). The area consists of a barrier with crest heights of 13.567–12.937 mOD across the bay. The site is open to the Atlantic, with minimal protection from the prevailing westerlies provided by the Isles of Coll (to the north-west) and Tiree (to the west). Calgary Bay is a flat low-lying grassy area with some sand dunes and machair present.

Grass Point (NM 7307732337)

Grass Point is located on the Moss headland of the Isle of Mull, on the south-west shore of Loch Don (Fig. 3). Grass Point used to be the main entry point to Mull and was at the end of a drive

Figure 2. Location of the coring site at Calgary Bay (Google Earth. Calgary Bay [2024]). [Color figure can be viewed at wileyonlinelibrary.com]

Figure 3. Location of the coring site at Grass Point (Google Earth. Grass Point [2024]). [Color figure can be viewed at wileyonlinelibrary.com]

road for cattle. The site consists of an extensive area of vegetated peat surrounded by rocky outcrops.

Fieldwork

At each site, a detailed lithostratigraphic survey was undertaken using a 1-m Eijkelkamp gouge corer. Transects were set up and boreholes were recorded using the Troels–Smith (1955) scheme. All boreholes and geomorphological features were levelled on closed traverses to Ordnance Datum (OD), with no closing error exceeding ±0.05 m. Altitudes are quoted in mOD. A representative core was taken from each site using a Russian-type corer from overlapping boreholes to minimise contamination and to contain all stratigraphic units (Jowsey, 1966). The sampled cores were sealed in uPVC and foil and labelled in the field, and then cold-stored at 4°C for laboratory analysis.

Laboratory analysis

Pollen analysis

Pollen analysis was carried out at both study sites to establish Holocene vegetation changes in the coastal environment. One centimetre cube subsamples were prepared for pollen analysis using standard extraction methods for peat (potassium hydroxide [KOH] digestion), and acetolysis (KOH, hydrofluoric acid [HF] and hydrochloric acid [HCl]) for minerogenic sediment. Extraction and mounting processes followed Barber (1976) and Moore et al. (1999). A maximum pollen sum of 350 total land pollen (TLP) was set and counted at magnification x400 (Birks and Gordon, 1985). All data are expressed as a percentage of the TLP. Aquatic taxa and spores are excluded from the TLP sum. In addition, microcharcoal (after Brayshay and Edwards, 1996) was counted (Edwards et al., 2000). Microcharcoal counts are also excluded from the TLP sum. All non-TLP counts are expressed as a percentage of TLP (where $n = 350$). Rare types (≤2%) are indicated by a cross (+). Exotic *Lycopodium clavatum* tablets (Stockmarr, 1971) were added to the pollen samples to determine pollen concentration and preservation levels (after Benninghoff, 1962). NPPs were also identified and counted during routine pollen analysis (following van Geel, 1978; Pals et al., 1980; van Geel et al., 1982/1983; 1995; 2003; van Hoeve and Hendrikse, 1998) and are expressed as a percentage of TLP plus total NPPs. Combined data were plotted using TiliaGraph 2.1.1 (Grimm, 2018). CONISS (Grimm, 1987) was used to statistically define local pollen assemblage zones (LPAZs) using stratigraphically constrained cluster analysis (with a dendrogram scale).

Loss on ignition and particle size analysis

Loss on ignition (LOI) analysis was undertaken at both study sites to identify any changes in the organic content of the sediments that could be associated with changes in vegetation, sedimentation and hydrological change. Standard methods (e.g., Heiri et al., 2001) were used to determine total organic carbon (TOC) content. Particle size analysis (PSA) was conducted to assess minerogenic:organic deposition. A Malvern Mastersizer Hydro 2000 laser granulometer was used (in accordance with standard manufacturers' operating procedures) after the removal of organics using hot H_2O_2. Standard sand (0.152–0.422 mm) was used to calibrate the granulometer. Measurements for each sample were triplicated and averaged. PSA data were divided into clay, silt and sand fractions (Wentworth, 1922; Friedman and Sanders, 1978).

Foraminifera and Ostracod analysis (Calgary Bay)

Foraminifera analysis was undertaken to identify changes in the palaeomarsh elevation at Calgary Bay following standard methods (e.g., Gehrels, 1994; Horton and Edwards, 2006; Kemp et al., 2018). The samples were weighed wet and oven-dried to a constant weight at 40°C. The samples were then weighed dry and then dispersed in de-ionised water. They were then wet-sieved over a 63-μm sieve, and the >63 μm fraction was retained and dried at 40°C. The samples were then weighed, dry-sieved at 125 μm and split to an appropriate fraction that would render >300 specimens. They were then picked, sorted and mounted onto an aluminium/card microscope slide for counting the benthic foraminifera in the >125 μm fraction (>300 specimens were counted where possible) and checking of taxonomic identifications. The samples were checked for signs of processing artefacts, such as the selective loss (or damage) of delicate agglutinated specimens, but no such artefacts were observed. Samples for ostracod analysis were prepared at the same time.

Diatoms (Grass Point)

Diatom analysis was undertaken at Grass Point to identify changes in local hydrology, including RSL. A total of 10 samples were taken every ca. 10 cm with increased sample resolution across stratigraphic boundaries. The samples were prepared using standard preparation techniques, including treatment with sodium hexametaphosphate, followed by hydrogen peroxide (30% solution) and/or weak ammonia (1% solution), depending on the organic and/or calcium carbonate content, respectively. Samples were sieved using a 10-μm mesh to remove fine minerogenic sediment (Battarbee, 1984). Diatom frequency is represented as percentages of the total diatom valves (up to 200 specimens were counted where possible). Diatom species were identified with reference to van der Werff and Huls (1958–1974), Hendy (1964) and Krammer and Lange-Bertalot (1986–1991). Ecological classifications for the observed taxa were achieved with reference to Vos and deWolf (1988; 1993), Dam et al. (1994), Denys (1991–1992; 1994) and Round et al. (2007).

Radiocarbon dating, age–depth models and sea-level index points

Bulk sediment samples from both study sites were extracted for radiocarbon dating based on key biostratigraphical and lithostratigraphical changes and submitted for AMS dating to the DirectAMS Laboratory (USA). Bulk sediment samples were selected for radiocarbon dating throughout to maintain consistency where macro- and microfossils were absent. Radiocarbon dates were calibrated using OxCal 4.4 (Bronk Ramsey, 2009) with the INTCAL 20 radiocarbon data set for terrestrial samples (Reimer et al., 2020) and the MARINE 20 calibration curve for marine samples (Heaton *et al*., 2020). Radiocarbon determinations for both sites are listed in Table 1. Age–depth models (Fig. 4) were constructed using Rbacon (Blaauw and Christen, 2011) in R version 4.4.x (R Core Team), using the IntCal20 calibration curve.

Sea-level index points (SLIPs) were calculated following an established protocol (Hijma et al., 2015) to ascertain the former position of sea level (e.g., Engelhart and Horton, 2012). A SLIP consists of the age, altitude, tendency and indicative meaning of a sediment sample so that the increase or decrease in marine influence is determined (Barlow et al., 2013). The vertical errors include surveying error (±0.01), compaction during coring (±0.01 m), coring angle (±1% sediment overburden), sample thickness (±half sample thickness) and sediment compaction (Shennan, 1986). Tidal corrections are applied following Shennan et al. (2003). Four SLIPs were calculated defining the position of former sea-level in space and time referenced against a known water level (MHWS - 4.5 mOD). The relative sea level (RSL) is calculated using the following equation: RSL = A-RWL, where the relative sea level is calculated by subtracting the reference water level (RWL [-4.5 mOD]) from the altitude of the sample (A).

Table 1. ^{14}C determinations and SLIPs for Grass Point and Calgary Bay, Isle of Mull.

Site	Lab code	Depth (cm)	Altitude mOD	C^{13}:C^{12} (%)	Conventional ^{14}C age BP 1σ (* = AMS date)	Calibrated ^{14}C age range BP 2σ	Horizon/ material	IM of SLIP	Ten	RSL (m) ± error
Grass Point	D-AMS 029595	317	7.31	-27.0	3192 ± 32	3460–3360	Sandy silt	MHWS + HAT/2	-	2.39 ± 0.14
Grass Point	D-AMS 029596	363	6.85	-40.1	7094 ± 45	8012–7800	Silty–sandy clay			
Grass Point	D-AMS 029597	389	6.59	-22.2	9416 ± 47	10 988–10 507	Base	MHWS	+	1.98 ± 0.15
Calgary Bay	D-AMS 029590	64	7.36	-34.8	1792 ± 29	1745–1600	Sand + *Phragmites*			
Calgary Bay	D-AMS 036247	153	6.47		2577 ± 29	2273–1926	Sand + shells	MLWS	-	3.78 ± 0.13
Calgary Bay	D-AMS 029591	215	5.85	-24.1	3437 ± 36	3317–2960	Sand + shells			
Calgary Bay	D-AMS 029592	234	5.66	-39.6	3223 ± 35	3550–3367	Sand			
Calgary Bay	D-AMS 029593	239	5.61	-19.9	6579 ± 42	7568–7424	Sand			
Calgary Bay	D-AMS 029594	248	5.52	-17.1	6635 ± 40	7576–7431	Silty sand			
Calgary Bay	D-AMS 035835	285	4.56		6619 ± 31	7570–7431	Silty sand	MLWS	+	4.69 ± 0.14

HAT = highest astronomical tide; IM = indicative meaning; MHWS = mean high water spring tide; MLWS = mean low water spring tide. Ten = tendency.

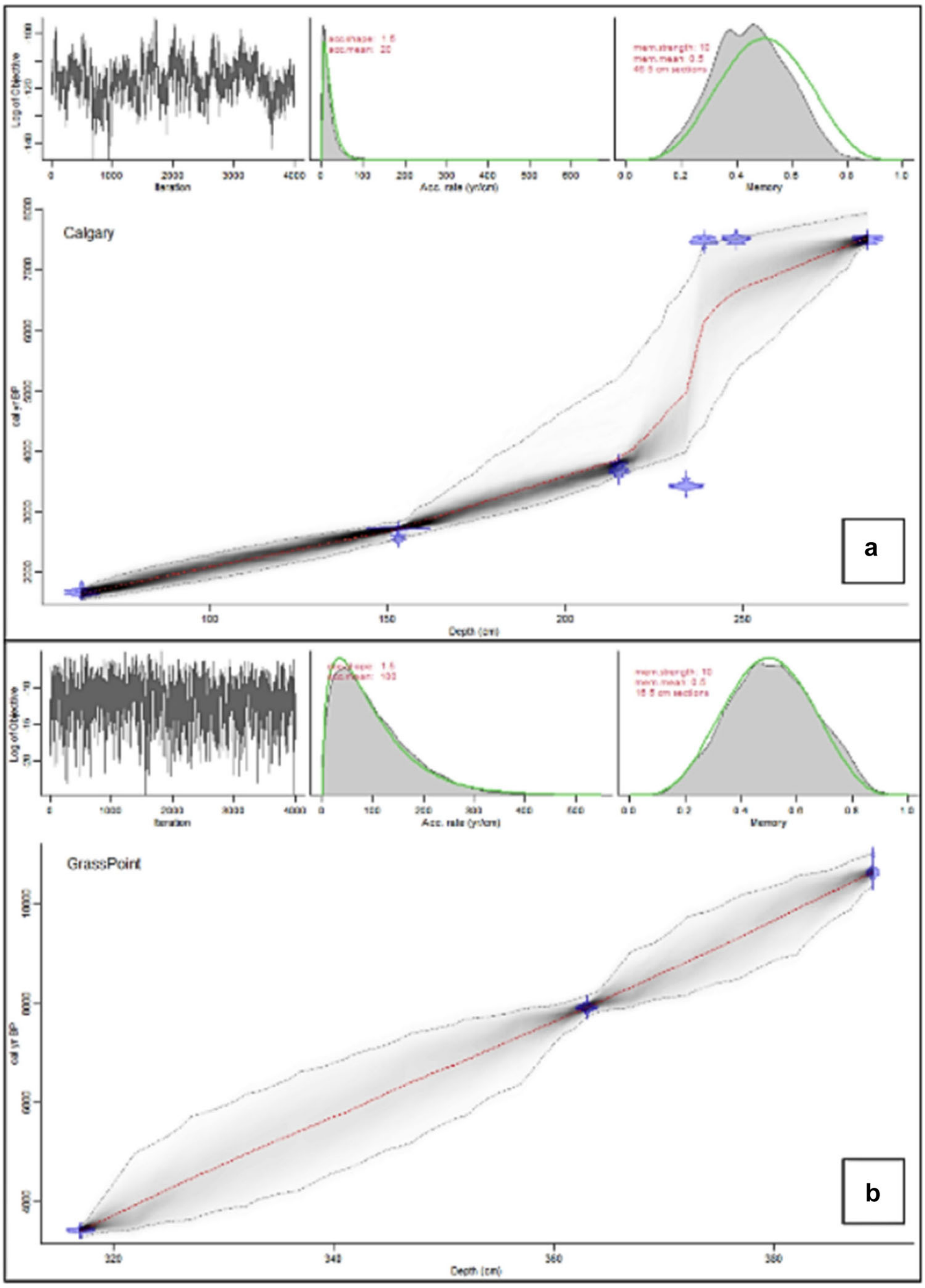

Figure 4. Age–depth models for Calgary Bay (a) and Grass Point (b), Isle of Mull. [Color figure can be viewed at wileyonlinelibrary.com]

Results

Lithostratigraphy

Lithostratigraphic descriptions of the sample cores are detailed in Table 2 and shown in Figs. 2 and 3.

Vegetation–Pollen analysis

The pollen percentage frequency plot for Calgary Bay is presented in Fig. 5. LPAZ descriptions and pollen characteristics are presented in Table 3. The data have been divided into four LPAZs (CB1-4). The data void (314–291 cm) (4.86–5.09 mOD) has not been zoned as a pollen assemblage category but is defined to emphasise the absence of pollen data.

The percentage pollen frequency plot for Grass Point is presented in Fig. 6. LPAZ descriptions and pollen characteristics are presented in Table 4. The data have been divided into three LPAZs (GP1-3).

Sea-level and hydrological change - Foraminifera, ostracod and diatom analysis

The foraminifera frequency plot for Calgary is presented in Fig. 7. The data have been divided into three zones (CBF1–CBF3), described in Table 5. The results of the ostracod analysis are presented in Table 6. The percentage diatom frequency plot for Grass Point is presented in Fig. 8. The data have been divided into three zones (GPD1–GDP3), described in Table 7.

Calgary Bay interpretations

Pollen analysis

LPAZ CB1 (371–314 cm) (4.29–4.86 mOD): Open grassland and heath

CB1 is dominated by varying quantities of sedge, grass and heather, and is likely to be of Late Pleistocene to Early

Table 2. Lithostratigraphic descriptions of the sample cores for Grass Point and Calgary Bay, Isle of Mull.

Site	Altitude (mOD)	Depth (cm)	Troels-Smith (1955)	Sedimentary description
Calgary Bay	8.00–7.57	0–43	*Th4*	Brown fibrous peat
	7.57–7.29	43–71	*Gs2 Dh2*	Grey sand with occ. *Phragmites*
	7.29–6.86	71–114	*Th3 Ga1*	Brown fibrous peat becoming sandy
	6.86–5.72	114–228	*Ga2 Dh2 part.test. (moll.)*	Sand with organics and shell fragments
	5.72–5.59	228–241	*Ga4*	Light grey sand
	5.59–3.08	241–492	*Gs4*	Dark grey silty sand
	3.08	492	Base	
Grass Point	10.48–7.55	0–293	*DG2 Th2*	Brown fibrous woody peat
	7.55–7.52	293–296	*Dl4*	Wood pieces/fragments
	7.52–7.43	296–305	*DG2 Th2*	Brown fibrous woody peat
	7.43–7.40	305–308	*Dl4*	Wood fragments
	7.40–7.32	308–316	*DG2 Th2*	Dark brown homogeneous peat
	7.32–7.22	316–326	*Ag3 Ga1*	Brown sandy silt
	7.22–7.15	326–333	*Ag2 Ga2*	Dark greyish brown silty sand
	7.15–6.82	333–366	*As2 Ag1 Ga1*	Grey silty sandy clay
	6.82–6.81	366–367	*Dl2 Gg(maj)2*	Wood fragments and small stones
	6.81–6.23	367–425	*AS2 Ag1 Ga2*	Dark grey silty sandy clay
	6.23	425	Base	

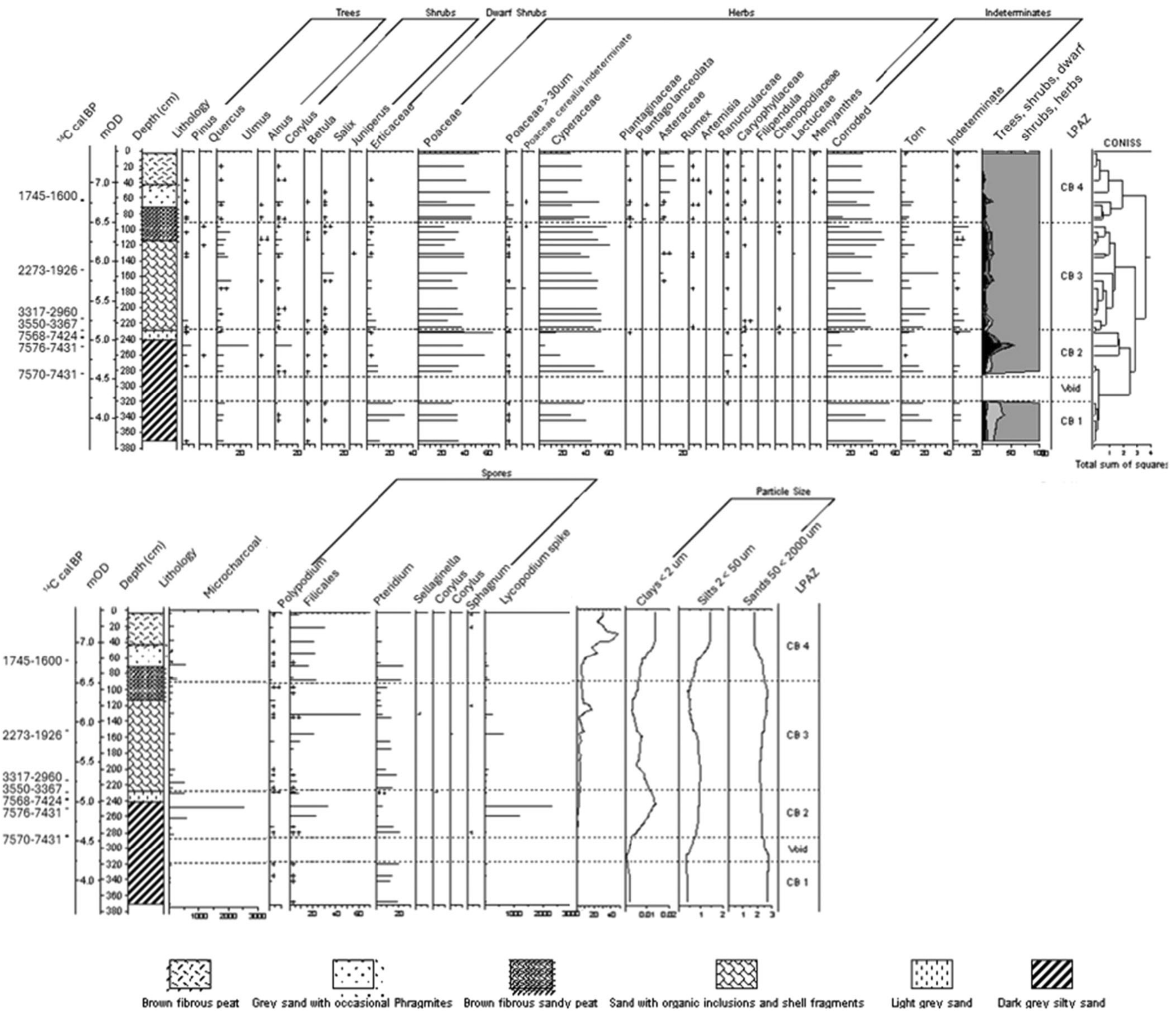

Figure 5. Pollen, spore and NPP frequency diagram showing %LOI (loss on ignition) and Particle size analysis (PSA) analyses for Calgary Bay, Isle of Mull.

Table 3. Local pollen assemblage zone (LPAZ) descriptions and pollen characteristics for Calgary Bay, Isle of Mull.

Pollen Zone	Altitude (mOD)	Depth (cm)	LPAZ description: Pollen characteristics	Quaternary period	Archaeological period
CB4	8.00–7.09	0-91	*Poaceae-Cyperaceae-Herbaceous taxa* Fluctuating Poaceae (26%–62%) and Cyperaceae (24%–51%. Decline of arboreal and shrubs. Fluctuating presence of Poaceae >35 μm (7%–3%) and decline of Poaceae cereal type (0.5%). Expansion of herb taxa. Appearance and increases in Plantaginaceae (0.5%–7%), *P. lanceolata* (0.5%–3%), Asteraceae (0.5%–13%), *R. acetosa* type (1%–4%). Fluctuating and dominant presence of *Filicales* (1%–30%). Decline in *Pteridium* (24%–3%). Fluctuating microcharcoal counts (52%–545%).	Late Holocene	Roman-Early Historic boundary
CB3	7.09–5.72	91–228	*Cyperaceae-Poaceae-*Quercus-C. avellana *type* Fluctuating dominance of Cyperaceae (46%–61%) and Poaceae (23%–42%). Rise of *Quercus* (0.5%–11%) and *C. avellana* type (0.5%–6%). Decline of Ericaceae (8%–0.5%) and *Pinus* (4%–1%). Low arboreal and shrub mosaic. Influx in Poaceae >35 μm (0.5%–9%). Appearance of Poaceae cereal type (1.5%–2%). Increase in herb taxa presence. Fluctuating influx of *Filicales* (0.5%–62%). Lesser and fluctuating quantities for *Pteridium* (5%–19%). Fluctuating and reduced microcharcoal counts (23%–496%).	Mid-Late Holocene	Bronze Age
CB2	5.72–5.09	228–291	*Poaceae-Cyperaceae-*Quercus-*Ericaceae* Fluctuating dominance of Poaceae (29%–64%) and Cyperaceae (55%–5%). Influx of *Quercus* (1.5%–26%). Fluctuating influx of *C. avellana* type and isolated peak (1%–14%). Decrease in Ericaceae (9%–1%). Increase of *Pinus* (1%–7%). Low arboreal and shrub mosaic. Appearance of herbs. Fluctuating influx of Ranunculaceae (0.5%–7.5%) and Caryophyllaceae (0.5%–2%). Increase of *Filicales* (2-23%). Decline of *Pteridium* (22%–2%). Fluctuating increase in microcharcoal (18%–2540%).	Early-Mid Holocene	Mesolithic-Neolithic transition
VOID	5.09–4.86	291–314	Zone void of microfossils.	Early-Mid Holocene boundary	Mesolithic
CB1	4.86–4.29	314–371	*Cyperaceae-Poaceae-Ericaceae-*Quercus Dominance of Cyperaceae (45%) and Poaceae (35%). Fluctuations and rise in Ericaceae (11%–33%). *Quercus* (5%). Fluctuating *Pteridium* (13%–21%). Microcharcoal rises (28%–68%). Low arboreal and shrub presence. Absence of herb mosaic.	Early Holocene	Mesolithic

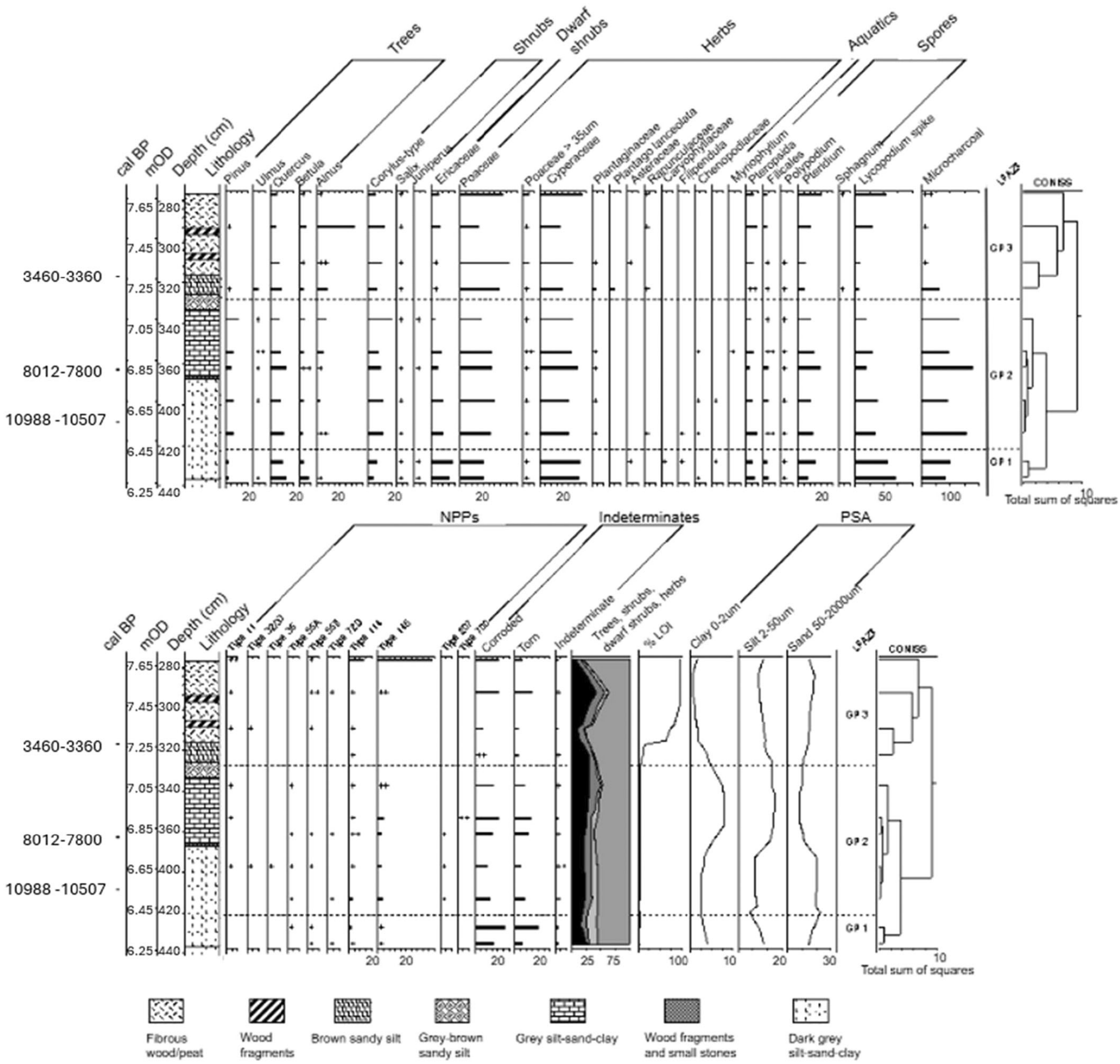

Figure 6. Percentage pollen, spore and NPP frequency diagram showing %LOI (loss on ignition) and particle size analysis (PSA) analyses for Grass Point, Isle of Mull.

Holocene age (Fig. 5; Table 3). Arboreal and shrub species are limited in the zone, with the exception of some oak. This is presumably due to the exposure of the site to the Atlantic weather system, which correlates with similar vegetation development recorded elsewhere on Mull (Walker and Lowe, 1985). The rare-type presence of large-diameter grass pollen is notable through the zone and may be reflective of wild grasses and/or undomesticated cereals (Edwards et al., 2005; Tweddle et al., 2005; Waller and Grant, 2012). Spore counts indicate that the dominant ground cover comprised ferns (den Ouden, 2000). Type 112 C ascospores are present and are markers for coprophilous and/or decaying organic matter (van Geel et al., 2003). Type 114 (scalariform perforation plates) indicates the deposition of woody detritus representative of birch (Pals et al., 1980). Type 146 is also present and is a marker for eutrophic sedimentary conditions (pH7–8.5) (van Geel et al., 1982–1983).

Void (314–291 cm) (4.86–5.09 mOD)

The cause of this data void cannot be defined but may be associated with a high input of terrigenous material leading to microfossil dilution.

LPAZ CB2 (291–228 cm) (5.09–5.72 mOD): Rough open grassland and oak scrub

The zone boundary between CB1 and CB2 is radiocarbon-dated at prior to 7568-7424 cal BP (Fig. 5). The vegetation in CB2 is dominated by increased grassland and sedge cover as heather decreases. Pine and oak woodland increases at 248 cm (5.52 mOD) prior to the lithostratigraphic change at 241 cm (5.59 mOD). The expansion of hazel at 248 cm (5.52 mOD), and at 7576–743 cal BP, demonstrates a lag in comparison with the hazel rise ca. 8800 BP at other sites across Mull (Walker and Lowe, 1982; 1987; Lowe and Walker, 1986a, 1986b; Walker, 1993a).

Table 4. Local pollen assemblage zone (LPAZ) description and pollen characteristics for Grass Point, Isle of Mull.

Pollen Zone	Altitude (mOD)	Depth (cm)	LPAZ description: Pollen characteristics	Quaternary period	Archaeological period
GP 3	7.72–7.18	276–330	*Poaceae-Cyperaceae*—*C.* avellana *type/Alnus* Dominance of Poaceae (17%–43%) and Cyperaceae (17%–38%) with similar fluctuations. Influx of Poaceae >35 μm (1%–5%), Plantaginaceae (3%) and *P. lanceolata* (5%). Reduction in microcharcoal (60%–1%) corresponding with temporary decreases in *C. avellana* type (19%–7%), *Alnus* (9%–2%), *Betula* (4%–0.5%) and Ericaceae (3%–0.5%). *Pteridium* rises (5%–20%) as microcharcoal declines. *Alnus* maximum (33%) coincides with the rise of Ericaceae (1%–8%) and reduction in microcharcoal. Low shrub and herb mosaic.	Mid-Late Holocene boundary	Bronze Age
GP2	7.18–6.46	330–402	*Cyperaceae-Poaceae*—*C.* avellana *type-Quercus* Dominance of Cyperaceae (24%–32%) and Poaceae (18%–30%), showing similar fluctuation patterns. Fluctuations and rise in *C. avellana* type (9%–19.5%). Initial rise of *Quercus*, followed by decline (13%–7%). Rise of *Alnus* (2%–7%). *Betula* shows slight recovery and small rise (2%–5%). Decline of Ericaceae (10%–3%). Fluctuating and small increase *in Pinus* (4%–11%). Fluctuating *Pteridium* (10%–19%). High and fluctuating microcharcoal counts (91%–178%) corresponding with the reduction of Ericaceae (10%–3%), fluctuations of *Pteridium* and gradual increase of *C. avellana* type and *Alnus*. Low shrub and herb mosaic.	Early Holocene-Mid Holocene	Mesolithic/Neolithic boundary
GP1	6.46–6.32	402–416	*Cyperaceae-Poaceae-Ericaceae*—Quercus-Betula Dominance of Cyperaceae (34%) and Poaceae (20.5%). Small influx of Ericaceae (15%–18%). Decrease in *Quercus* (13%–10%) and *Betula* (8%–3%). Increase in *C. avellana* type (4–8%). *Pinus* low presence (2%). Influx of *Pteridium* (8%–16%). Microcharcoal rises (83%–98%). Low shrub and herb mosaic.	Lateglacial-Early Holocene	Mesolithic

Herbaceous vegetation is limited, although the influx of buttercup at 261 cm (5.39 mOD) may be a marker for a shift to wetter ground conditions (Behre, 1986). The isolated peak in NPP Type 35 (14%), which corresponds with the maximum buttercup count, is also a palaeoenvironmental indicator for relatively wet and meso-oligotrophic conditions (van Hoeve and Hendrikse, 1998). Decreases in arboreal species between 248 and 232 cm (5.52–5.68 mOD) correspond with the lithostratigraphic changes at 241 cm (5.59 mOD) and 228 cm (5.72 m OD), dated at 7568–7424 cal and 3550–3367 cal BP.

Anthropogenic activity

At 261 cm (5.39 mOD), the large rise in microcharcoal may indicate proximate anthropogenic activity (Edwards et al., 2007). The decline in fern spores at this depth further suggests Mesolithic human activity linked to increased clearance via burning (Edwards et al., 2007). Corresponding peaks at 248 cm (5.52 mOD) in coprophilous NPP Types 55 A (19%) and 112 C (5%) suggest the presence of herbivores (van Geel, 1978; van Geel et al., 1982/1983; 2003), whilst Type 55 B (7%) has been identified as a marker for mesotrophic conditions (van Geel, 1978; van Geel et al., 1982/1983).

LPAZ CB3 (228–91 cm) (5.72–7.09 mOD): Rough open grassland with oak and hazel scrub

The zone boundary between CB2 and CB3 is radiocarbon-dated at 3550–3367 cal BP. The overlying radiocarbon date of 3317–2960 cal BP at 215 cm (5.85 mOD) represents an age reversal that may be related to erosion, coastal dynamics (including storm erosion) or root penetration. There is an expansion of oak woodland at 166 cm (6.34 mOD) in an area still dominated by grasses and sedges. There is an expansion of hazel and alder at 130 cm (6.70 mOD) following the decline of willow at 155 cm (6.45 mOD), which may be a response to drier conditions. The temporary disappearance of bracken at this depth, along with the influx of fern spores, coincides with an increase in microcharcoal counts. The subsequent fern maximum at 130 cm (6.70 mOD) corresponds with the rise in arboreal and shrub pollen, the reappearance of coprophilous NPP Types 55 A and 72 C, and a further peak in microcharcoal counts. It is feasible that the influx of ferns is associated with the understorey ground cover of oak and hazel shrubland canopy (Vera, 2000).

LPAZ CB4 (91–0 cm) (7.09–8.00 mOD): Rough open pasture

Grass and sedge continue to dominate CB4. The final major peak in microcharcoal counts at 68 cm (7.32 mOD) corresponds with the disappearance of arboreal, shrub and dwarf shrub taxa. The onset of peat development and the shift to wetter ground conditions at 43 cm (7.57 mOD) are not associated with any notable change in vegetation apart from an influx of daisy and bogbean at 52 cm. Both species are indicative of wet ground (Behre, 1986). The notable peaks in NPP Type 114 at 52 cm (18%) and 36 cm (7.64 mOD) (32%) suggest the presence of reasonable quantities of woody detritus (Pals et al., 1980), which may have provided the organic matter sufficient for the initiation of peat development. Wet ground conditions are represented by the presence of NPP Type 35 (van Hoeve and Hendrikse, 1998).

A mid-zone late Holocene date of 1745–1600 cal BP is provided at 64 cm (7.36 mOD) for CB4.

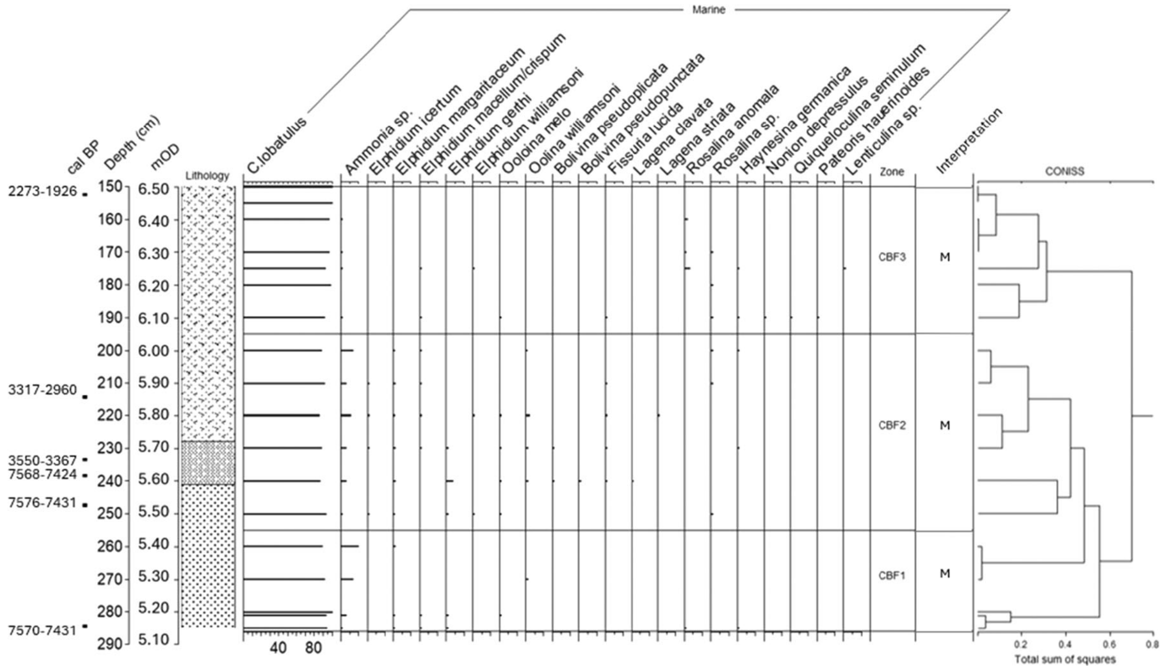

Figure 7. Percentage foraminifera frequency diagram for Calgary Bay, Isle of Mull. Interpretation: M = marine.

Table 5. Foraminifera zone descriptions for Calgary Bay, Isle of Mull.

Foram Zone	Altitude (mOD)	Depth (cm)	Description
CBF3	6.50–6.05	150–195	*Final marine phase*—C. lobatulus *C.lobatus* dominant (1–343 count) (95%–99%). Very low foraminifera species richness. Counts drop to 4 and 1 at 155 cm (6.45 mOD) and 150 cm (6.50 mOD), respectively, before disappearing to the core top.
CBF2	6.05–5.45	195–255	*Marine*—C. lobatulus and Ammonia sp. *C.lobatus* dominant (281–344 count) (88%–94%) with *Ammonia sp.* (3%–7%). Species richness increases at 240 cm (5.68 mOD). Highest foraminifera species richness in this interval.
CBF1	5.45–5.15	255–285	*Marine*—C. lobatulus and Ammonia sp. *C.lobatus* dominant (122–345 count) (90%–97%). Foraminifera levels are very low at 280 cm (5–20 mOD) (6 count). *Ammonia sp.* make up 10% of the count at 260 cm (5.40 mOD) and 1%–7% throughout.

Table 6. Marine mollusc, ostracod and foraminifera presence (+) and ecological interpretations for Calgary Bay.

Depth (cm)	Altitude (mOD)	Marine molluscs	Marine foraminifera	Marine ostracods	Interpretation	
118	6.82	-	-	-	Regression; site now above tidal access	
138	6.62	-	-	-		
144	6.56	-	-	-		
158	6.42	+	+	+	Strandline assemblage washed out of shallow marine seagrass/algal community	
166	6.34	+	+	+		
178	6.22	+	+	+		
198	6.02	+	+	+		
218	5.82	+	+	+		
238	5.62	+	+	+		
258	5.42	+	+	+		
261	5.39	+	+	+		
262	5.38	+	+	+		
269	5.31	-	+	-		
274	5.26	-	+	-		
278	5.22	-	+	-		◄ *Initial tidal access*
285	5.15	-	-	-	Site above tidal access	
298	5.02	-	-	-		
318	4.82	-	-	-		
338	4.62	-	-	-		
358	4.42	-	-	-		

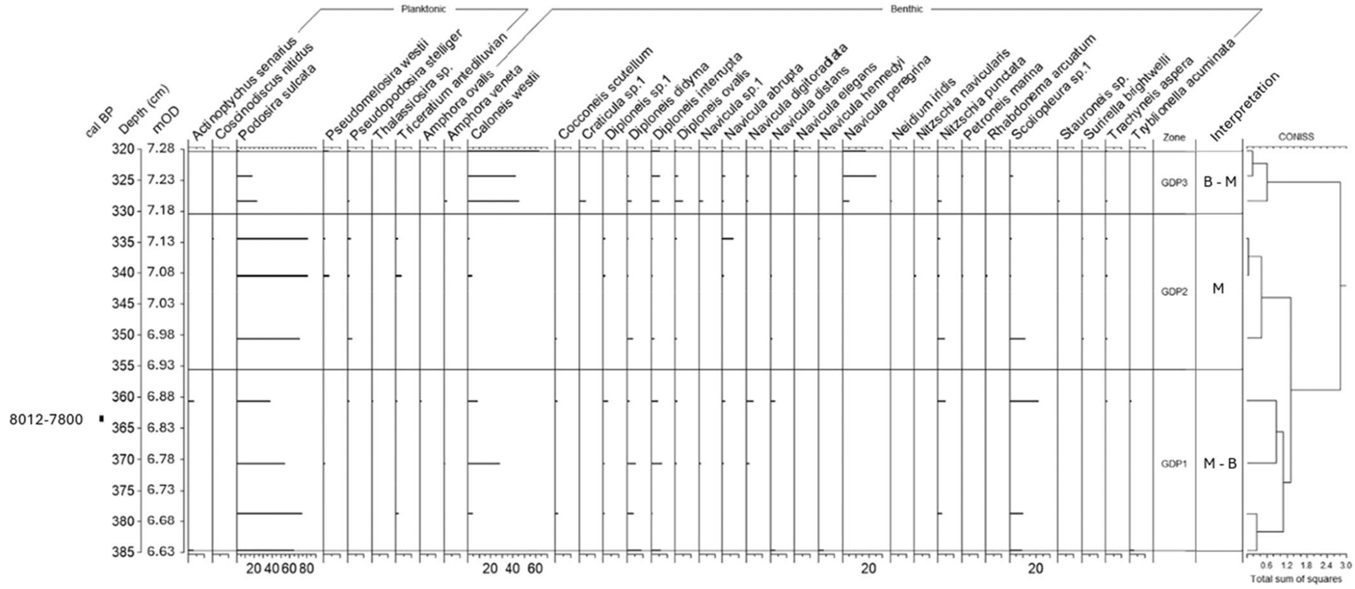

Figure 8. Percentage diatom frequency for Grass Point, Isle of Mull. Frequencies of diatoms are represented as percentages of total diatom valves. Interpretation: B = brackish; M = marine.

Table 7. Diatom Zone descriptions for Grass Point, Isle of Mull.

Diatom Zone	Altitude (mOD)	Depth (cm)	Zone description
GPD3	7.28–7.14	320–334	*Brackish–marine conditions* Characterised by benthic brackish taxa, with *Caloneis westii* dominant and high levels of *Navicula peregrina*.
GPD2	7.14–6.88	334–360	*Marine conditions* Characterised by planktonic taxa, with *Podosira sulcata* dominant alongside *Paralia westii*, *Paralia stelligera* and *Triceratium antediluvium*.
GPD1	6.88–6.64	360–384	*Marine to brackish conditions* Characterised by planktonic taxa, with *P. sulcata* dominant. There are low levels of benthic taxa, including *Diploneis*, *Nitzschia* and *Navicula*. There is an influx of *C. westii* at 370 cm (-2.22 mOD) and high benthic species richness at 360 cm (-2.12 mOD).

Anthropogenic activity

Above the radiocarbon date of 1745–1600 cal BP at 64 cm (7.36 mOD), the presence of large-diameter grass pollen alongside the expansion of herb taxa, including plantains, sorrel and goosefoot, indicates proximate agricultural activities (Behre, 1986; Edwards and Whittington, 2003). Whilst there is a decrease in microcharcoal counts in the upper half of this zone (65–3 cm [7.35-7.97 mOD]), the burning signal remains constant and appears to be associated with the suppression of bracken (Pakeman et al., 2000). The presence of NPP coprophilous Type 55 A ascospores (10%) (van Hoeve and Hendrikse, 1998; van Geel et al., 2003) at 19 cm (7.81 mOD) suggests an animal presence that may also be associated with the reduction and suppression of bracken and fern ground cover (Pakeman et al., 2000; McGlone et al., 2005). The local landscape appears treeless and pastoral (Birks and Williams, 1983; Walker and Lowe, 1985; Brown et al., 2007).

Foraminifera, mollusc and ostracod analyses

CBF1 (285–255 cm) (5.15–5.45 mOD): Marine

Foraminifera are present at Calgary Bay from 285 cm (5.15 mOD) (7570–7431 cal BP), whilst initial tidal access is identified in the ostracod sequence at 278–279 cm (5.22–5.21 mOD) (Fig. 5; Table 6). The foraminifera assemblage, which indicates marine conditions throughout, is unusual, as it contains very high relative abundances (typically between 90% and 100%) of *Cibicides lobatulus*. The species is commonly found living in high-energy environments, often attached to lithic fragments, macroalgae and shelly material (Freiwald, 1995). Its complete dominance of the entire assemblage, together with the presence of abraded and broken tests, suggests that the fauna may be located adjacent to (but not within) a high-energy coastal environment, although deposition itself has taken place in a lower energy environment (Verma and Singh, 2019). The sedimentary units support this interpretation, with the clay–silt–sand deposits atypical of the habitat in which *C. lobatulus* lives, but consistent with its local transport and deposition into an adjacent low-energy environment. Common secondary species include *Ammonia* sp. and a diverse group of elphidiids, including *Elphidium incertum, E. margaritaceum, E. macellum/crispum, E. gerthi* and *E. williamsoni.*

Ostracod analysis likewise indicates a marine assemblage to 158–159 cm (6.42–6.41 mOD), which probably represents a strandline on the foreshore, the material having been washed out of shallow water in the bay in an active environment. This is supported by the fact that only the most thickly calcified ostracods occur (and these are worn) (Symphonia and Nathan, 2021). These are *Hemicythere villosa, Heterocythereis albomaculata, Pontocythere elongata* and *Leptocythere pellucida* and would have been living on or in the marine sediment or in algal littoral/sublittoral communities.

CBF2 (255–195 cm) (5.45–6.05 mOD): Marine

Whilst *C. lobatulus* continues to dominate the assemblage, species richness increases at 240 cm (5.68 mOD). A total of 22 species, plus an indeterminate category, have been identified with the greatest species richness at 230 cm (5.70 mOD) (ca. 3550–3370 cal BP) (11 species). In general, the increase in species richness precedes maximum foraminiferal abundance, the latter being dominated by *C. lobatulus*. The general sub-dominance of *Ammonia* sp. and diverse, very well-preserved elphidiid taxa within the interval of high species richness are noteworthy. The common secondary species include taxa characteristic of the intertidal to shallow subtidal coastal environment of NW Europe. They make up an assemblage with similarities to some of the modern (less organic carbon-rich) assemblages from Shetland (Lo Giudice Cappelli et al., 2019). Unlike the specimens of *C. lobatulus* observed at around 150 cm (6.50 mOD) and 285 cm (5.15 mOD), which show broken tests, the diverse assemblages here are very well preserved and do not suggest significant transport and abrasion prior to (re) deposition. This suggests that the interval of highest species richness at around 230 cm (5.70 mOD) is associated with a local high stand in sea level. However, there is the possibility of an unconformity or break in the stratigraphy at around 230 cm (5.70 mOD), where the lithology changes from sand to sand with organics and shell fragments.

Despite maximum foraminiferal abundances observed above 230 cm (5.70 mOD), the high species richness and shallow sub-tidal assemblages point to a maximum marine influence at this site at around 230 cm (5.70 mOD). Therefore, while the foraminiferal assemblages are unlikely to be able to fully constrain relative sea-level changes at this site because of the likelihood of transport/redeposition, the first and last marine influences are clear and the interval of maximum marine influence can also be constrained.

CBF3 (195–150 cm) (6.05–6.50 mOD): Final marine phase

The highest foraminiferal abundance is recorded at 180 cm (6.20 mOD) (nearly 6000 specimens per gram of dry sediment; >125 μm). A larger number of broken and etched tests of *C. lobatulus* occur at around 150 cm (6.50 mOD), coinciding with a lithostratigraphic change and an increase in % LOI, perhaps suggesting both a change in the environment and increasingly acidic soil conditions at ca. 2273–1926 cal BP. A shell bed is identified in the ostracod assemblage at 167–158 cm (6.33–6.42 mOD). The last marine influence at 150 cm (6.50 mOD) coincides with the occurrence of specimens of *C. lobatulus* with both 'etched' and 'enlarged' pores, suggesting post-depositional dissolution in organic-rich sediments, which may be associated with a regressive sea-level contact and increase in lacustrine/terrestrial organic matter accumulation at this site in the late Holocene.

A comparison of the foraminiferal-bearing horizons with the local pollen assemblage zones shows that they coincide with CB2 and CB3. The last occurrence of foraminifera at 150 cm (6.50 mOD) occurs within CB3. CONISS in the pollen diagram at 140–160 cm indicates that there may be a small vegetation change that coincides with the final marine phase (6.60–6.40 mOD) (Fig. 5).

Grass Point interpretations

Pollen analysis

LPAZ GP1 (416–402 cm) (6.32–6.46 mOD): Heath with oak and birch scrub

The zone is dominated by sedge and grass, with heather presence, indicating an open environment (Fig. 6; Table 4). The low pollen concentrations in the zone are characteristic of Lateglacial deposits (Havinga, 1967; Tipping, 1987; Edwards et al., 2000). The establishment of arboreal and shrub species including oak, birch and hazel may indicate local scrub tree cover (Birks and Peglar, 1979), likely established within an open coastal heath environment. Ameliorating climate conditions may have led to increased wildfire incidence, indicated from 416 to 408 cm (6.32–6.40 mOD) by the influx of fern spores by ca. 50% (Pakeman et al., 2000; McGlone et al., 2005) alongside a 15% increase in microcharcoal counts and a small rise in hazel.

Ellipsoidal spores Type 55B indicate mesotrophic conditions (van Geel, 1978; van Geel et al., 1982/1983). The presence of the NPP Types 72D (fragments of postabdomina of *Eurycercus* cf. l*amellatus*) and 146 (*Gloeotrichia*) is a marker for eutrophy, with the latter Type 146 being indicative of alkaline sedimentary conditions (i.e., pH 7–8.5) (van Geel et al., 1982/1983).

LPAZ GP2 (402–330 cm) (6.46–7.18 mOD): Open rough grassland with heather and oak scrub

From 10988 to 10 507 cal BP, sedges and grasses are the dominant vegetation, alongside low levels of arboreal species, indicating an open environment with shrubland. The low pollen concentration in this zone may be related to the poor preservation conditions of the minerogenic sediments. Eutrophic conditions (Havinga, 1967) are indicated by the increase in the presence of NPP Type 146 (van Geel et al., 1982/1983).

Anthropogenic activity

The presence of anthropogenic disturbance marker species, such as plantain and goosefoot between 394 and 354 cm (6.54–6.94 mOD), coincides with fluctuating and raised microcharcoal counts, bracken spores and the presence of the coprophilous NPP Type 55 A, potentially suggesting small-scale anthropogenic activity.

LPAZ GP3 (330–276 cm) (7.18–7.72 mOD): Open grassland with hazel and alder scrub

The vegetational mosaic is dominated by grasses and sedges. A shift to wetter conditions is illustrated by the development of peat at 316 cm (7.32 mOD), corresponding with decreases in arboreal, shrub and dwarf taxa. The subsequent expansion of alder at 292 cm (7.56 mOD) is probably a response by this taxon to open conditions triggering an abrupt, and in this case, an isolated phase of rapid expansion (Brown, 1988; Chambers and Elliott, 1989). The alder expansion corresponds with the expansion of birch and hazel, and the reappearance of heather, whilst grasses and sedges decline (43%–17% and 28%–17%, respectively). The radiocarbon date of 3460–3360 cal BP at 317 cm (7.31 mOD) marks the initiation of peat development on the boundary of the mid-late Holocene.

Anthropogenic activity

The notable increase in plantain and ribwort plantain corresponds with a 50% reduction in bracken spores and a decrease in microcharcoal counts. Plantain species can be markers for anthropogenic disturbance (Behre, 1986; Brown et al., 2007). The concurrent decline of bracken and microcharcoal suggests two potential causes. The first is increased grazing pressure (suggested by the presence of Type 55 A coprophilous ascospores in the underlying LPAZ GP2), suppressing rhizome growth and spore output (Lowday and Marrs, 1992), and the second is a decrease in anthropogenic burning, which appears to have reduced fire-stimulated bracken spread (Simpson et al., 2025) by 3460–3360 cal BP.

From 316 cm (7.32 mOD), the increase in large-diameter grass pollen coincides with a notable reduction in microcharcoal counts, the decline and subsequent disappearance of plantain and the continued absence of Type 55 A coprophilous ascospores. This would suggest a change in land use practices occurring during the mid-late Holocene, with a probable shift from small-scale animal husbandry or grazing to an established open environment and agrarian activity, such as the cultivation of wild grasses and/or undomesticated cereals (Edwards et al., 2005; Tweddle et al., 2005).

Diatom analysis

GPD1 (384–355 cm) (6.64–6.93 mOD): Marine–brackish conditions

Marine to brackish conditions are present between 384 and 355 cm (6.64–6.93 mOD), inferred through the relative abundance of the marine planktonic diatom *Podosira sulcata*, a common open water marine species (Vos and de Wolf, 1988; 1993) (Fig. 8; Table 7). The presence of the relative abundance of *Caloneis westii* towards the centre of the zone (370 cm [6.78 mOD]), combined with a higher benthic species richness at 360 cm (6.88 mOD), is noted. The epipelic diatom *Diploneis interrupta* are common and allude to shallow coastal conditions, potentially on a mudflat/saltmarsh-type depositional setting, but one that remains exposed to tidal inundation to account for the relative abundance of marine plankton (Vos and de Wolf, 1988; 1993).

GPD2 (355–330 cm) (6.93–7.18 mOD): Marine conditions

Benthic taxa reduce significantly in abundance between 355 and 330 cm (6.93–7.18 mOD), whilst *P. sulcata* increases. The diversity of open marine planktonic diatoms also increases, including low but consistent counts of *Pseudomelosira westii* and *Triceratium antediluvianum*. This suggests a shift to more open marine conditions, potentially alluding to deeper waters (Vos and de Wolf, 1988; 1993).

GPD3 (330–320 cm) (7.18–7.28 mOD): Brackish–marine conditions

A return to the dominance of marine–brackish benthic diatoms, at the expense of marine planktonic diatoms, typifies the upper zone. It is reflected in the dominance of *C. westii*, supported by *Navicula peregrina, Diploneis didyma* and *Diploneis interrupta*, suggesting a return to more coastal marginal and shallow marine conditions such as mudflat or saltmarsh (Vos and de Wolf, 1988; 1993). The reduction in the influence of marine plankton from GPD2 to GPD3 likely records the site becoming less influenced by open marine and/or tidal inundation with time. This is reinforced by the absence of brackish and marine diatoms above 320 cm (7.28 mOD), coinciding with the shift in sedimentation to peat deposition at 316 cm (7.32 mOD). This would support the suggestion of RSL fall at Grass Point with an absence of evidence for marine conditions apparent at the site for the remainder of the profile.

Discussion

Sea-level changes

The four SLIPs generated in this study represent the first for the Isle of Mull (Fig. 9). RSL change follows the end of the Loch Lomond Stadial (ca. 12 900–11 700 BP), during which time, there was a regrowth of mountain ice caps on Mull that terminated in coastal areas (Gray, 1975; Bickerdike et al., 2018). The marine transgression at Grass Point follows deglaciation, when glacial water would have flooded low-lying areas at a faster rate than isostatic uplift was occurring.

The diatom record from Grass Point in east Mull suggests a sea level above present from 10 988–10 507 to 3460–3360 cal BP. The older data point at Grass point (10 800 cal BP) is a vital new data point. Although there are over 1500 SLIPS in the British Isles database, the number of points older than 10 ka and sensitive to local ice sheet changes (Shennan et al., 2018) is significantly less. The RSL predictions are shown (Fig. 9a) for the range of ice thickness of the BIIS produced from Bradley et al. (2023), a characteristic of the ice sheet that remains relatively poorly constrained. There is a ca. 5-m range in the predicted RSL at around 11 ka BP due to variations in the ice sheet thickness, with a thicker BIIS (dotted line) producing a higher RSL and a thinner BIIS (dashed line) producing a lower RSL. The hybrid ice sheet reconstruction (solid line, Fig. 9a) is the best match to this older data point. In this ice sheet reconstruction, the thick central dome of the ice sheet that covers this NW region of Scotland was altered into a two-dome structure. The predicted rate of fall towards present day following the Holocene highstand is just captured by the younger data point (2920 cal BP; 2.39 mOD) at this site.

The foraminifera profile from Calgary Bay, in north-west Mull, provides information about the nature of the Holocene highstand across the Isle of Mull. The older SLIP at 7621–7248 cal BP records an RSL of 4.69 mOD, a similar timing as the highstand recorded at Arisaig (Shennan et al., 2018), and is correlated with the Main Postglacial Transgression in the area. These data also suggest that the timing of the rise to the Holocene highstand is earlier than suggested by this selection of RSL predictions, which is similar at other Scottish sites (Bradley et al., 2023), where there is an underprediction. This timing of this rise is controlled by changes to the deglaciation history of the North American ice sheet complex as highlighted by Bradley et al. (2023).

The RSL remains above present (3.78 mOD) until 2806–2572 cal BP, which is ca.1 m higher than a similar age SLIP at Grass point and above the predicted RSL. This is interesting, as the RSL predictions infer a higher highstand at Grass point, as it was covered by thicker ice during the last glacial period and the Loch Lomond Stadial (Gray, 1975; Bickerdike et al., 2018), so the cause of a prolonged period of elevated sea level at this more distal coastal site is yet to be determined.

Vegetation and coastal environmental changes

Although the vegetation history reconstructed here broadly mirrors earlier Mull pollen sequences (see Walker, 1993a; Walker and Lowe, 1985), the value of these new records lies in their coastal context and integration with multiproxy evidence. By directly linking pollen, spores, microcharcoal and NPPs to

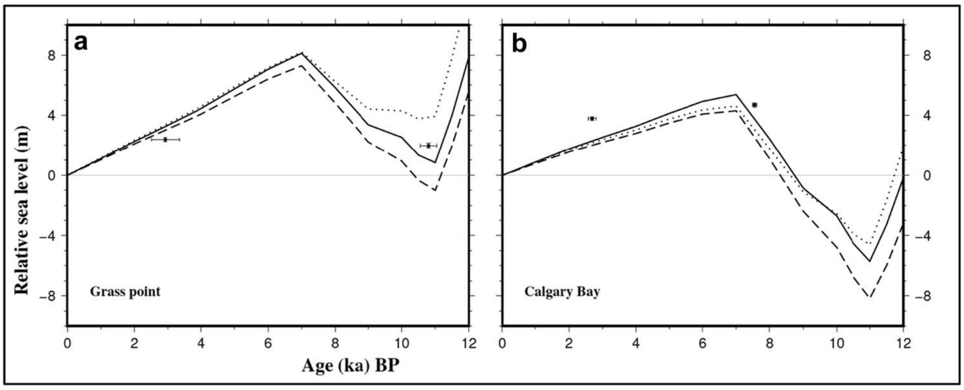

Figure 9. RSL plot for (a) Grass Point and (b) Calgary Bay comparing the observed SLIPs (Table 1) to a recent selection of RSL predictions from a Glacial Isostatic adjustment model. The predictions are for three different local ice sheet reconstructions changing the thickness of the ice sheet: mid-thick (dotted), hybrid (solid) and mid-thin (dashed).

dated sea-level index points, this study demonstrates how vegetation mosaics responded to marine transgression and regression, with arboreal expansion more evident in sheltered eastern settings and persistent openness in the exposed north-west. This coastal perspective adds a novel dimension to the established Mull vegetation history, highlighting the interplay between relative sea-level change, exposure and human activity at the shoreline. In this respect, the findings build on and extend work on Holocene coastal change (see Punwong et al., 2018; Selby et al., 2023), which emphasises the importance of situating vegetation records within dynamic marine and geomorphological frameworks. The Mull sequences therefore not only corroborate regional vegetation trajectories but also provide new insights into how coastal ecosystems were shaped by shifting RSL and anthropogenic disturbance, offering a more nuanced understanding of human–environment interactions in the Inner Hebrides.

Local vegetation changes evident at the two study sites are comparative to published pollen profiles for the Isle of Mull, other Hebridean islands and also the Scottish west coast. There are biostratigraphic and chronological similarities between the vegetation successions at Grass Point and Calgary Bay, that is, localised environments of open grassland dominated by fluctuating influxes of Cyperaceae and Poaceae, lesser quantities of heath taxa and relatively consistent low representations of arboreal and shrub species. However, there are no marked key vegetation changes. Both records commence with the long-term presence of open heath, dominated by grass, sedge, heather and oak/birch shrubland. Vegetation changes are noted that correlate to events such as the increase in hazel (ca. 9740 cal BP) (Walker and Lowe, 1982; 1985; 1987; Lowe and Walker, 1986a, 1986b; Walker, 1993a) and alder rise (ca. 7420 cal BP) (Lowe and Walker, 1986a, 1986b; Walker and Lowe, 1987) on the island. However, these appear to occur later, with hazel increasing at Calgary Bay at 7576–743 cal BP, and at Grass Point, where alder rises after 8012–7800 cal BP. The early-Holocene *Empetrum* maximum and subsequent expansion of *Juniperus* are both absent from the Grass Point and Calgary Bay profiles, as is the Neolithic elm decline. Both coastal pollen profiles reflect very local vegetational environments heavily affected by altitude, exposure and marine influence. There are contrasts in the environmental conditions of both study sites following marine regression: at Calgary Bay, there is an initial expansion of sedges, perhaps reflecting an increase in freshwater input, followed by increased grassland coverage alongside the ongoing retraction of arboreal species. The cessation of marine influence at Grass Point is accompanied by an increase in alder carr and arboreal expansion, suggesting drier environmental conditions. The different levels of arboreal coverage at the study sites may reflect differential exposure, Calgary Bay being more exposed and less suitable for woodland expansion compared to the more protected eastern position of Grass Point.

Radiocarbon dates at Calgary Bay

There is an abrupt expansion of sedges at Calgary Bay from 228 cm (5.72 mOD) at ca. 3500 BP. The environmental change coincides with a change in pollen zonation and a lithological transition from sand to sand with shell fragments and organic material at 228 cm (5.72 mOD). An age reversal in the radiocarbon dates is evident from this section of the borehole, with the sediments at 215 cm (5.85 mOD) dated at 3317–2960 cal BP and those from 234 cm (5.66 mOD) dated at 3550–3367 cal BP. The age reversal, together with the lithological and biostratigraphic changes, suggests reworking of older sediments into the newer stratigraphy as a result of marine processes. Alternatively, the reversal may be a result of younger root penetration into older sediments.

The age reversal is accompanied by a sharp change in the age of the sediments (Fig. 4), showing ca. 4000 years between the sediments deposited at 2.39 and 2.34 mOD. The age shift occurs within the same stratigraphic unit; therefore, no erosional contact is evident. The overlying radiocarbon dates indicate a relatively steady rate of sediment accumulation thereafter, so younger root activity is the unlikely cause of the abrupt change. The shift is therefore likely to indicate a hiatus in the sediment record as a result of channel migration or tidal changes that led to a significant reduction in sediment deposition at the study site.

Human–Environment interactions

The inclusion of NPP data and microcharcoal counts in the two pollen sequences has enabled the anthropogenic perspective of each low-lying site to be explored. Coprophilous NPP markers, particularly Type 55 A, suggest phases and fluctuating intensities of animal presence at both sites, which have the potential for association with human activity (van Hoeve and Hendrikse, 1998; van Geel et al., 2003). NPP-type presence and microcharcoal:pollen ratios suggest small-scale human impact at Grass Point at the time of climatic amelioration at the boundary between the Lateglacial/early Holocene with activity that continued throughout the Mesolithic and Neolithic periods. Peat development and the shift to wetter ground conditions began in the Bronze Age, during the mid-late Holocene boundary, when there also appears to be a temporary downturn in human activity. This coincides with marine regression at the site from 3460 to 3360 cal BP, which may have influenced a change in human land use in the area.

At the more exposed northerly location of Calgary Bay, clear markers for Mesolithic human activity are evident during the early Holocene. The beginning of marine influence from 7576 to 743 cal BP would cause wetter ground conditions to occur at the site alongside improved access to marine resources. The location does not appear to have been abandoned as conditions deteriorated. This is indicated by a peak in microcharcoal counts, which may reflect early coastal burning by humans. In addition, there is a notable presence of coprophilous NPP 55 A ascospores acting as markers for the likely presence of herbivores at the site (Innes and Blackford, 2023). The utility of anthropogenically induced fire is also indicated by the corresponding modest influx of ferns/bracken spores, which suggests an opportunistic response (perhaps in localised openings) of this minor vegetational component in the early Holocene (Walker and Lowe, 1985). A higher RSL is recorded at 7568–7424 cal BP at 239 cm (5.61 mOD) and at 3550–3367 cal BP at 234 cm (5.66 mOD). There appears to be no downturn in regional anthropogenic activities in relation to this marine event, as high microcharcoal counts are recorded. The presence of Poaceae >35 μm and cereal-type pollen suggests that small-scale agriculture continued after the mid-Holocene, prior to and continuing after the cessation of marine influence at 2273–1926 cal BP. It is possible that the open environment is maintained by burning immediately after this event as the climate improves. The subsequent decline in wild grass and cereal-type pollen indicates that there may have been a return to animal husbandry (indicated by the return of coprophilous NPPs Types 55 A and 72 C in the pollen profile and continual phases of burning) as climatic conditions became cooler and wetter during the Bronze Age (Edwards and Whittington, 2003; Brown, 2008; Armit et al., 2014). By the Late Holocene, the pollen sequence illustrates a relatively treeless environment, with anthropogenic marker taxa synonymous with the Roman agrarian economy, and subsequent transition to the boundary of the Roman:Early Historic (cum-Norse) period to a pastorally weighted system of agriculture (Dumayne and Barber, 1994; Manning et al., 1997; Edwards and Whittington, 2003).

Conclusions

This research reconstructs RSL, vegetation and anthropogenic influence at two coastal sites on the Isle of Mull, contributing to the body of evidence available for the Inner Hebrides during the Lateglacial and Holocene. It produces the first sea-level index points for the island and increases understanding of human–environment interactions in one of the earliest known inhabited areas of the western Scotland region. The sea-level record commences in eastern Mull at 10 988–10 507 cal BP (389 cm (6.59 mOD), with RSL at 1.98 ± 0.15 mOD. The sea-level record for north-west Mull commences from 7570 to 7431 cal BP (285 cm (4.56 mOD), with RSL at 4.69 ± 0.14 mOD. Evidence for a marine transgression is found at both study sites in the late Holocene as a result of GIA.

Vegetation changes on Mull are minimal throughout the Holocene, showing the sustained presence of an open environment of grass and sedge heathlands with oak and birch shrubs. Increases in hazel at ca. 9740 cal BP and alder after 8012–7800 cal BP correspond with regional palaeoenvironmental records. The environmental responses to marine regression differ between north-west Mull, with herb expansion recorded, and eastern Mull, where arboreal species expanded in response to the drier conditions. The combination of pollen, NPPs and microcharcoal analysis shows early and long-term evidence of an anthropogenic presence on the island. Early Holocene activities focused on deliberate burning to create more open areas suitable for grazing. The steady decrease in arboreal pollen in the late Holocene in north-west Mull indicates intensified grazing pressures.

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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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