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Truncated drumlins and their implication for past sea level reconstructions

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Coastal erosion of glacigenic sediments, particularly in the form of retreating drumlin bluffs, is a key process in paraglacial landscape evolution during periods of relative sea-level (RSL) rise. As marine transgression reworks formerly subaerial glacial terrains, drumlins act as discrete sediment sources generating characteristic erosional and depositional drowned landforms. In this study, we identify extensive fields of submerged truncated sediment drumlins across several locations in the Irish Sea and along the western Scottish seaboard. The drumlins were formed during maximum and retreat phases of the last British-Irish Ice Sheet (BIIS). They now exhibit flat-topped morphologies often associated with gravel tails, tombolos and coalesced platforms, closely resembling previously described examples of eroding drumlin coasts from the west coast of Ireland and North America. The geomorphic assemblages are consistent with wave-driven erosion of drumlin bluffs during lower sea-level stands, and we interpret the truncated drumlins as terrestrial-limiting indicators of past RSL. Comparison with existing RSL reconstructions and glacio-isostatic adjustment (GIA) models reveals discrepancies between observed truncation depths and predicted sea-level minima, suggesting that current models may underestimate lowstand magnitudes in parts of Britain and Ireland. These findings highlight the potential of submarine geomorphological records to refine regional sea-level reconstructions and improve understanding of post-glacial coastal evolution.

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Lateglacial through to Holocene relative sea-level (RSL) rise flooded vast regions of the Northern Hemisphere continental shelves, drowning landscapes that had temporarily persisted as terrestrial environments during expansion and retreat of major mid-latitude ice sheets (e.g. Clark *et al*. 2022; Bradley *et al*. 2023). This progressive marine transgression, occurring in regions where eustatic sea level rise outpaced local glacio-isostatic rebound, held significant capacity for geomorphic modification of existing terrestrial landscapes and geomorphological features (e.g. Guilcher 1962; Westley *et al*. 2011; Lebrec *et al*. 2022). In the case of lowland glacial landscapes, the retreat of low coastal cliffs (bluffs) composed of glacigenic sediment constitutes a form of paraglacial reworking, releasing sediment to the nearshore environment, influencing coastal landforms and processes (Ballantyne 2002).

Drumlin coasts represent a subset of paraglacial coasts, with individual drumlins acting as discrete sources of sediment (Forbes & Syvitski 1995); they have been described in several locations across formerly exposed mid-latitude shelves, including the eastern coastlines of Nova Scotia (Canada), the shorelines of the Great Lakes, Massachusetts Bay in the USA, and numerous sites in western Ireland and the UK (Guilcher 1962; Carter *et al*. 1989; Pinet & McClennen 1997; Knight & Harrison 2019; Plets *et al*. 2019; Black *et al*. 2025) (Fig. 1A–C). During the Lateglacial and Holocene, wave erosion of drumlin hills driven by marine transgression fed cycles of paraglacial barrier growth, which was followed by planation as sediment supply failed to keep pace with rising sea level (Ballantyne 2002). Based on observations at Clew Bay (Ireland), Carter & Orford (1988) developed a conceptual model for drumlin erosion, whereby the removal of sediment from drumlins is associated with the development of prograding spits, leeside gravel tails, tombolos and gravel barriers (Fig. 2). In this model, initial coarse debris accumulates along the flanks of the drumlin, forming an armour. Erosion continues confined to the seaward face, while depositional gravel tails accumulate on the lee side. At a later stage, long transverse spits form, although failing sediment supply may result in proximal thinning of this feature from a reworking of the limited sediment volume. Drumlin flank erosion is aided by subaerial processes like slides and slumps, the intensity of which increases as flanks become more exposed to marine attack. Because drumlins normally occur in swarms, and the pattern of erosion and deposition produced by marine transgression is complicated by physiographic setting, inter-drumlin wave pattern and tidal currents, planation morphologies are varied. For example, in the context of rias, barriers may evolve at the mouths of individual inlets, creating an irregular embayed coastline (Carter *et al*. 1992). Instead, if the drumlin field is located within broader shallow basins, as in Clew or Donegal Bay, Ireland or Boston Harbour, Massachusetts, spits prograde at sites of longshore drift convergence, linking drumlin headlands and creating tombolos or gravel barriers (Rosen & Leach 1987; Carter *et al*. 1989; Himmelstoss *et al*. 2006). Variations in wave type and approach may cause preferential erosion and the non-systematic development of landforms. Furthermore, sediment may be transferred from one drum-

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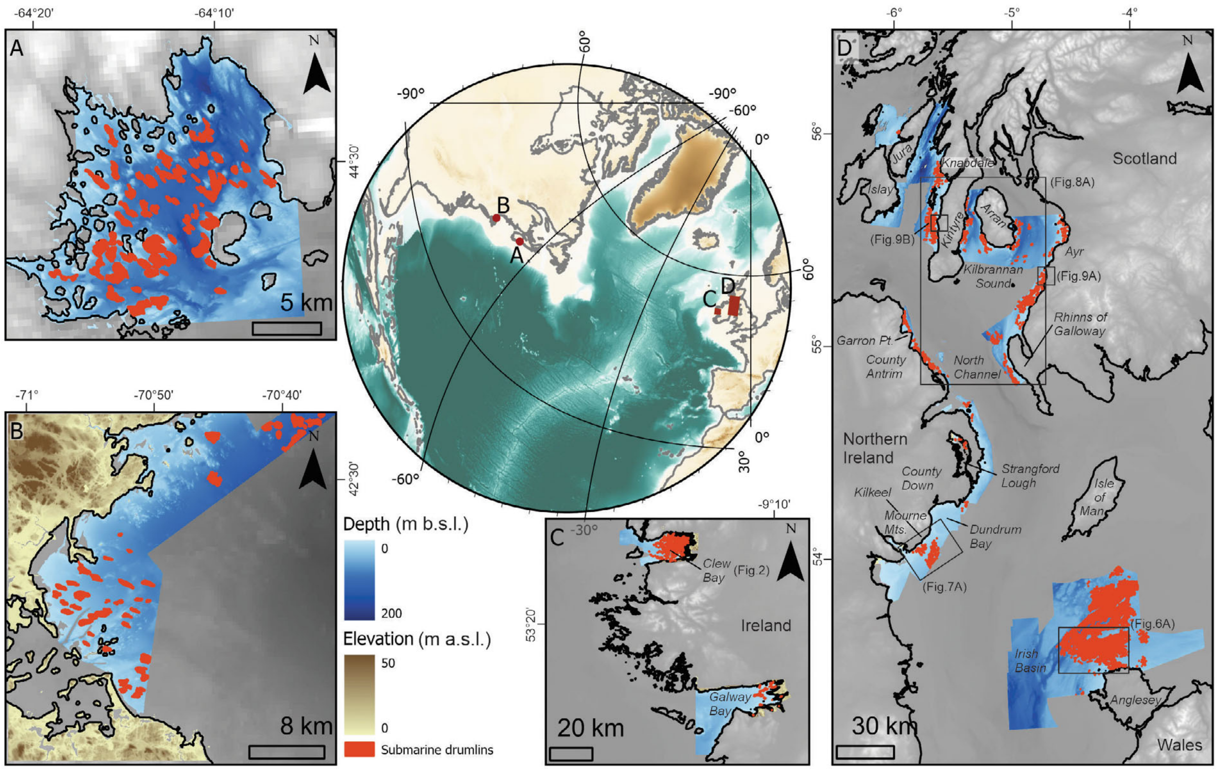


Fig. 1. General overview of the datasets utilized, the drumlins mapped in this study (red) and the location of other figures in the paper. The coastline for the globe and for insets A and B is sourced from the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) (Wessel & Smith 1996), while North Atlantic bathymetry is from GEBCO (GEBCO Bathymetric Compilation Group 2026). Depth scale is for the MBES data available, while elevation scale shows areas where Lidar data was available. A. Submerged drumlins in Mahone Bay, Canada. B. Drumlins in Massachusetts Bay (USA). C. Submerged drumlins in Clew and Donegal Bay west of Ireland. D. Mapped locations in the Irish Sea and western Scotland. The coastline presented in (C) and (D) is the UKHO Satellite Derived Coastline (UK Hydrographic Office © Crown Copyright 2019. Created using Google Earth Engine, contains modified Copernicus Sentinel data).

lin island to another. The rear drumlins can be enveloped by freestanding beach ridges in the formation of small flank lagoons. This front-to-rear transport corridor allows the relatively rapid landward or, more correctly, transverse-to-waves, movement of large volumes of sediment. In time these landward accumulations may aggregate and form the foci for more substantial barriers that run parallel to the shore.

The end geomorphological product of the coastal erosion of drumlins and subsequent sea-level rise are drowned, truncated (i.e. eroded and planated) drumlins (Oldale *et al.* 1994), previously also referred to as 'scars' (e.g. Carter & Orford 1988). Importantly, these features may provide useful information on relative sea-level (RSL) position at a point in time (Piper *et al.* 1983; Shaw *et al.* 2002; Plets *et al.* 2019), as they can be considered erosional terraces and gravel barriers (Vacchi *et al.* 2018). The literature for sea level modelling in palaeo-glaciated terrains (e.g. Baranskaya *et al.* 2018; Shennan *et al.* 2018; Vacchi *et al.* 2018; Bradley *et al.* 2023) has historically relied on onshore data points, because of the unavailability or poor quality of submarine data, and to our knowledge, seabed truncated drumlins have not been considered in the reconstructions.

Recent technological advances and increased collection of large swaths of high-resolution multibeam echosounder (MBES) bathymetry data provide a growing opportunity to better understand drowned offshore geomorphological records, as well as past sea level fluctuations. This auspiciously coincides with a period of heightened global interest in renewable energy, as nations increasingly explore offshore environments as potential sites for wind energy development. Within this study, we identify extensive areas of drowned truncated drumlins in the Irish Sea and on the western Scottish seaboard (Fig. 1C, D) and analyse these features for the first time in detail. We compare their morphology and assemblages to submerged truncated drumlins and coastal bluffs on the western coast of Ireland and North America previously described by other authors and investigate alternative formation mechanisms for the Scottish and Irish Sea examples. Moreover, we assess this record in the context of RSL in Britain and Ireland, and more generally discuss their relevance for general past RSL reconstructions.

Fig. 2. The actively retreating drumlin coast and archipelago in Clew Bay, Ireland. Drumlin sediments from multiple point sources are reworked by waves and longshore drift into prograding, cuspate spits, forming often gravel barriers that link drumlin islands. These barriers allow the development of depositional/lagoon environments connected by tidal channels. Many of the drumlin islands are linked, either by flanking barriers or gravel tombolos/tails. The progressive erosion of drumlin islands over time eventually leads to a flattened irregular platform with relict gravel tails or ridges. Maxar Technologies image dated 4/5/2007 courtesy of Google Earth.

Data and methods

Multibeam echosounder data

We collated and examined all the high-resolution, freely available MBES data from the UK and isolated regions where we could identify truncated drumlins. Four additional areas where truncated drumlins had been previously identified in the Republic of Ireland (Clew Bay and Galway Bay), USA (Massachusetts Bay) and Canada (Mahone Bay) were also analysed.

The UK MBES bathymetry data presented in this study were collected between 2012 and 2022 for the UK's Civil Hydrography Programme (CHP), managed by the Maritime & Coastguard Agency's (MCA) and delivered in partnership with the UK Hydrographic Office (UKHO) to update nautical charts and improve safety at sea in UK waters (https://www.gov.uk/guidance/uk-civil-hydrography-programme-chp). This study incorporates 21 Hydrographic Instruction survey areas: 1329, 1351, 1353, 1363, 1370, 1371, 1377, 1420, 1507, 1508, 1509, 1581, 1593, 1597, 1680, 1681, 1706, 1707, 1708, 1745 and 1747. MBES data for the North St. Georges Channel Marine Conservation Zone were collected by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) between 2012 and 2013 (https://data.cefas.co.uk/view/3652). Depending on the survey and water depth, the UK data have been gridded at 2 or 4 m per pixel. MBES bathymetry and LiDAR data for Clew and Galway Bay in Ireland were acquired for the INFOMAR Programme (https://www.infomar.ie/) and are gridded at 5 m per pixel. Data for Massachusetts Bay were obtained from the United States' National Ocean Service (NOS) Hydrographic Survey data viewer (https://www.ncei.noaa.gov/products/nos-hydrographic-survey), and include surveys H13993, H13994, H13995, H13996 and H13997, gridded at 2 or 5 m per pixel. Lidar data for this region were obtained by NV5 Geospatial (NV5) for the USGS in 2021 (https://www.mass.gov/info-details/massgis-data-lidar-terrain-data) and are available at 0.5 m per pixel. MBES bathymetry for Mahone Bay, Nova Scotia (Canada), were acquired by the Canadian Hydrographic Service (CHS) and are available for free in a spatial resolution of 10 m on the Non-Navigational (NONNA) Bathymetric Data Portal (https://cartes.gc.ca/data-gestion/nonna/index-fra.html). They include the tiles 4440N06420W, 4440N06430W, 4440N06440W, 4450N06420W and 4450N06430W.

MBES surveys were conducted from multiple vessels using different echosounding transducers. Post-acquisition data processing routines also vary by survey; however, many contractors on behalf of the CHP exploit the Combined Uncertainty and Bathymetry Estimator (CUBE) (Calder & Mayer 2003) module within Caris HIPS and SIPS along with manual swath editing. All depths are metres below Chart Datum (CD), approximately Lowest Astronomical Tide (LAT), referred to in the text as 'metres below sea-level (m b.s.l.)'.

Mapping method

In the United Kingdom and Ireland, drumlins were mapped first by re-gridding and merging all the bathymetry data to a 4 m per pixel mosaic, then by digitizing them with the help of CoMMa (Arosio *et al*. 2024), a rule-based ArcGIS Pro toolbox that extracts semi-automatically landform boundaries through bathymetric derivatives. A boundary-based delineation was applied on the bathymetry derivative 'relative deviation from mean value' (DEV) using an annulus with an inner radius of 5 and an outer radius of 50 cells. The cutoff value was set at 0.8, while features detected with a relief smaller than 1 m and width smaller than 20 m were rejected. A buffer of 40 m was applied to make sure that the entirety of the feature was included. Several mega-scale glacial lineations (MSGLs) and drumlins in the Irish Sea basin, whose morphology indicated a bedrock nature, were ignored. Manual editing was employed to improve and visually correct the result, eliminating landforms that were not drumlins and adjusting aggregated or not fully delineated features. Drumlins in Massachusetts and Mahone Bay were mapped manually. Depth statistics were extracted using a modified version of the CoMMa Descriptor tool, obtaining minimum, maximum, mean, median and percentile 90 and 75 depth for each drumlin. The 90th percentile (p90) of the depth range within each delineated drumlin is used as a reference in the following analysis, as it represents the top portion of each landform but not the maximum (i.e. shallowest, the peak of the landform) value. A summary of the relevant statistics is given in Table 1, while the full list is given in Table S1. Moreover, drumlins were classified into three distinct classes: truncated, ambiguous and pristine. The classification was based on careful visual assessment (Fig. 3), and comparison to truncated drumlins described in previous studies (Fig. 4), as semi-automated morphometric analysis was insufficient to capture the range of alterations that affected the landforms. The first class, 'truncated', encompasses all the landforms that deviate from a normal, curved or sloping drumlin profile with clear stoss and lee sides (Spagnolo *et al*. 2012) (Fig. 3B). The truncated forms often possess a clear flat top but might also have irregular or more complex morphologies. The second class includes landforms whose morphology remains ambiguous, while the drumlins belonging to the third class 'pristine' show characteristic mounded tops with no apparent modification (Fig. 3A).

In the text, especially the Results, the terms 'flat-topped drumlins', 'drumlin plateaus' and 'platforms' are used interchangeably throughout to refer to drumlins with a flat or planar summit. These terms are employed in a purely morphological sense and do not imply any interpretation of their genesis. The term 'truncated drumlin' is used more specifically at a second stage (Results interpretation and Discussion) to denote drumlins that have been interpreted as planated by wave erosion.

Results

We have identified submarine flat-topped drumlins in three main regions in the United Kingdom, often within larger drumlin swarms: north of Anglesey, along the eastern Northern Irish coast and in southwestern Scotland (Fig. 1C, D). For the depth and distribution analysis (Table 1, Fig. 5), the Irish and Scottish drumlin regions were further subdivided into zones—S Down, N Down and Antrim in Ireland; Rhinns of Galloway, Ayr S, Ayr N, Kilbrannan Sound, Kintyre W, Knapdale and Jura in Scotland, for ease of description and for later comparison to RSL studies and GIA modelling (e.g. see zones in Brooks *et al*. 2008; Shennan *et al*. 2018). The drumlins are mostly found close to the present-day coastline, on shallow seabed away from modern depocentres, although more may exist below the Holocene sedimentary cover, especially offshore east Northern Ireland (S Down). The drumlin top surfaces are, in their most simple occurrence, planar, horizontal or slightly sloping, often rubbly and preserve some appearance of the original teardrop or lemniscate shape typical of a drumlin. Often the morphology is more complex, and the surfaces are superimposed by other relict features or reworked deposits, or again they are merged with other truncated drumlins, creating composite irregular platforms (Fig. 4A). Due to the complexity of the geomorphic record, in the next section we present the flat-topped drumlin assemblages by location, from south to north. For each location: firstly, we contextualize the landforms within the regional glacial history; then we describe the forms and their occurrence in relation to depth; and finally justify our interpretation as wave-produced truncation on the basis of our observations, context and comparison to modern examples.

Table 1. Depth statistics for each class in each zone including maximum depth (p75 and p90), and mean depth statistics for the deepest and shallowest groups of 10 landforms (p90). Mean distance from Rannoch Moor (* approximately Lat 56.6303; Long −4.6933, WGS84 UTM 29N), the centre of glacial isostasy in Britain and Ireland, is also given. All depths shown are metres below Chart Datum (approximately Lowest Astronomical Tide).

Region	Class	#	Max depth (p90) (m b.s.l.)	Max depth (p75) (m b.s.l.)	Mean depth (p90) 10 lowest (m b.s.l.)	Std depth (p90) 10 lowest (m)	Mean depth (p90) 10 shallowest (m b.s.l.)	Std depth (p90) 10 shallowest (m)	Average distance from Rannoch Moor (km)
Anglesey	Pristine	3757	97.7	98.9	94.6	2.2	32.9	2.9	333
	Truncated	919	61.2	61.5	55.3	3.8	25.3	1.8	
	Ambiguous	1101	85.5	86.2	74.3	6.7	40.9	4.0	
South Down	Truncated	174	38.6	38.8	35.9	1.3	8.9	3.4	298
North Down	Pristine	1	38.7	40.3	38.7		38.7		230
	Truncated	30	30.7	32.0	23.5	3.6	−1.3	0.4	
	Ambiguous	1	27.7	28.7	27.7		27.7		
Antrim	Pristine	73	47.6	48.1	43.2	2.2	27.0	2.1	197
	Truncated	44	24.8	25.5	22.7	1.3	12.2	2.7	
	Ambiguous	25	37.6	38.2	30.6	3.2	22.8	1.3	
Rhinns of Galloway	Pristine	53	97.7	99.9	75.6	10.5	33.6	5.4	193
	Truncated	3	22.1	23.8	22.0	0.1	22.0	0.1	
	Ambiguous	7	53.5	54.5	38.6	9.7	38.6	9.7	
South Ayr	Pristine	39	35.0	35.3	30.5	3.0	18.8	0.7	161
	Truncated	88	18.5	19.5	16.8	1.2	3.5	1.1	
	Ambiguous	16	24.7	25.4	20.7	2.4	17.6	1.0	
North Ayr	Pristine	70	80.9	84.4	71.5	4.3	19.3	2.3	129
	Truncated	28	17.6	18.2	12.2	2.6	3.7	1.6	
	Ambiguous	6	18.0	19.9	9.7	6.2	9.7	6.2	
Kilbrannan Sound	Pristine	82	67.1	68.6	59.9	5.8	19.3	2.5	132
	Truncated	15	17.2	17.8	13.5	1.9	9.6	3.0	
	Ambiguous	18	37.7	38.5	28.0	6.7	17.3	1.4	
West Kintyre	Pristine	45	48.5	50.4	43.6	3.4	24.3	1.5	137
	Truncated	62	27.5	29.5	23.3	2.3	11.6	0.9	
	Ambiguous	17	39.8	40.6	30.6	4.7	23.9	2.1	
Knapdale	Pristine	11	26.0	28.3	20.7	3.5	19.1	4.4	112
	Truncated	25	15.7	17.0	12.9	1.5	8.1	0.9	
	Ambiguous	4	25.1	26.8	16.4	5.9	16.4	5.9	
Jura	Truncated	2	10.3	11.0	10.1	0.2	10.1	0.2	107

Irish Sea: north of Anglesey

Regional context. – An extensive record of subglacially streamlined bedforms lies within the central axial sector of the Irish Sea Basin (ISB) (Fig. 6), offshore from north-west Wales and adjacent to Anglesey, occupying part of the former flow corridor of the Irish Sea Ice Stream (ISIS) (Van Landeghem & Chiverrell 2020; British Geological Survey 2022). It is a shallow to moderately deep marine basin, with water depths between ~28 and 92 m b.s.l., deepening westwards to >100 m b.s.l. and shoaling towards the Isle of Man and the eastern ISB. The record shows many overlapping glacial landform footprints, representing four phases of ice flow and reorganization during the Late Weichselian. A first phase includes MSGLs focussed on the deeper parts of the basin, representing erosive ice streaming with axis-parallel flow. A subsequent slowdown and reorganization are reflected by numerous ribbed moraines and their transition into drumlins, indicating cumulative strain in the till sheet following the dynamic reorganization of the ice mass resulting in the widespread migration of ice divides. The later phases are documented by widespread fluting, generated during a renewed acceleration and realignment of flow, and ice-marginal and recessional moraines recording final retreat, oscillation and eventual shutdown of the ice stream (Van Landeghem & Chiverrell 2020). Drumlins form a coherent belt within the corridors of the former Irish Sea Ice Stream; they are approximately 150–250 m long, 50–100 m wide and 10–15 m proud of the surrounding seabed. In more central parts of the exposed drumlin field elongation ratios are commonly below ~1.5:1, whereas on the steeper western slopes of the basin they increase to values approaching 5:1. Cross-sectional profiles of complete forms show relatively steep flanks, commonly exceeding 30° and a tapered form towards the down-ice end. Their long axes are aligned broadly west to south-west, with azimuths between roughly 225° and 255°. They were not subsequently buried by extensive glacifluvial or marine sediments, implying relatively limited sediment supply and rapid retreat following their formation.

Description of drumlin morphologies. – Numerous (919) sediment drumlin in the swarms present clear flat tops, while another 1101 present ambiguous signs of possible

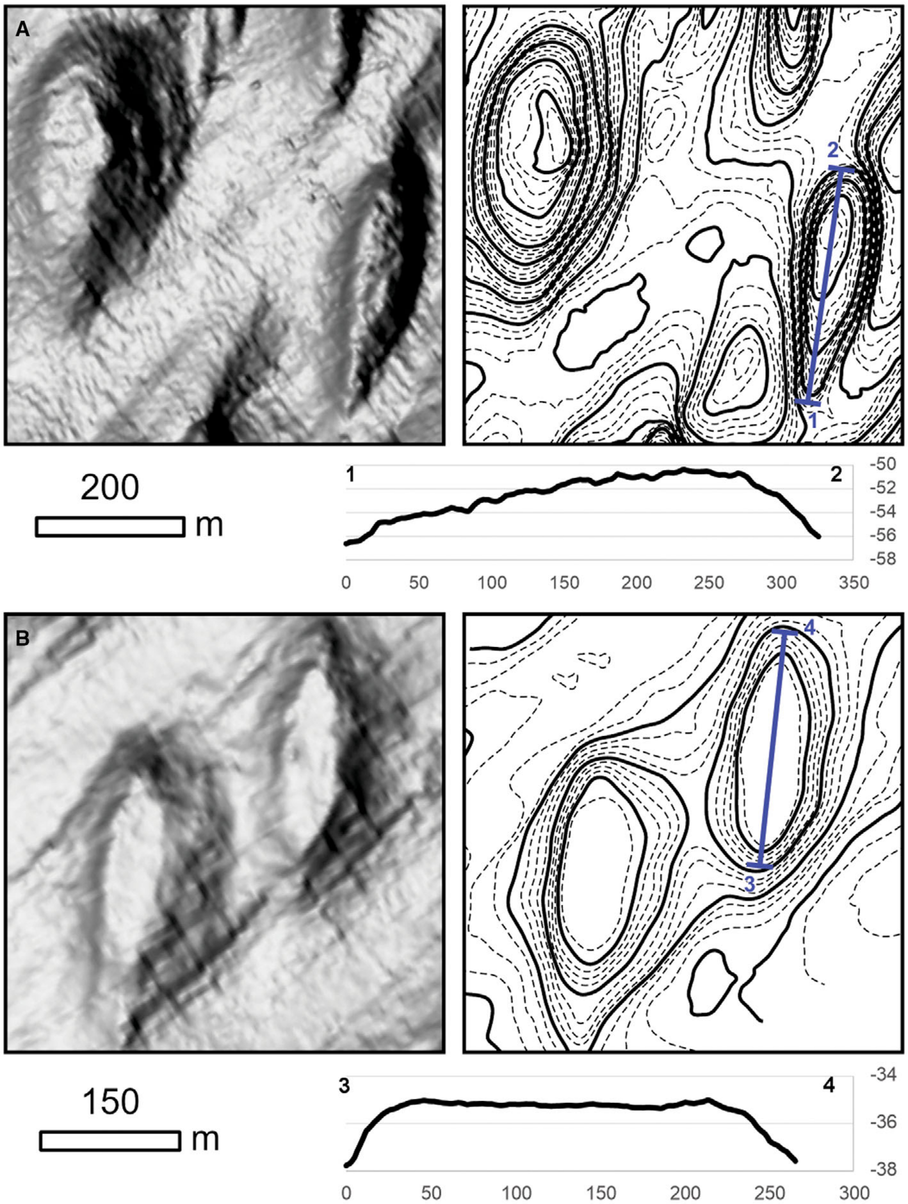
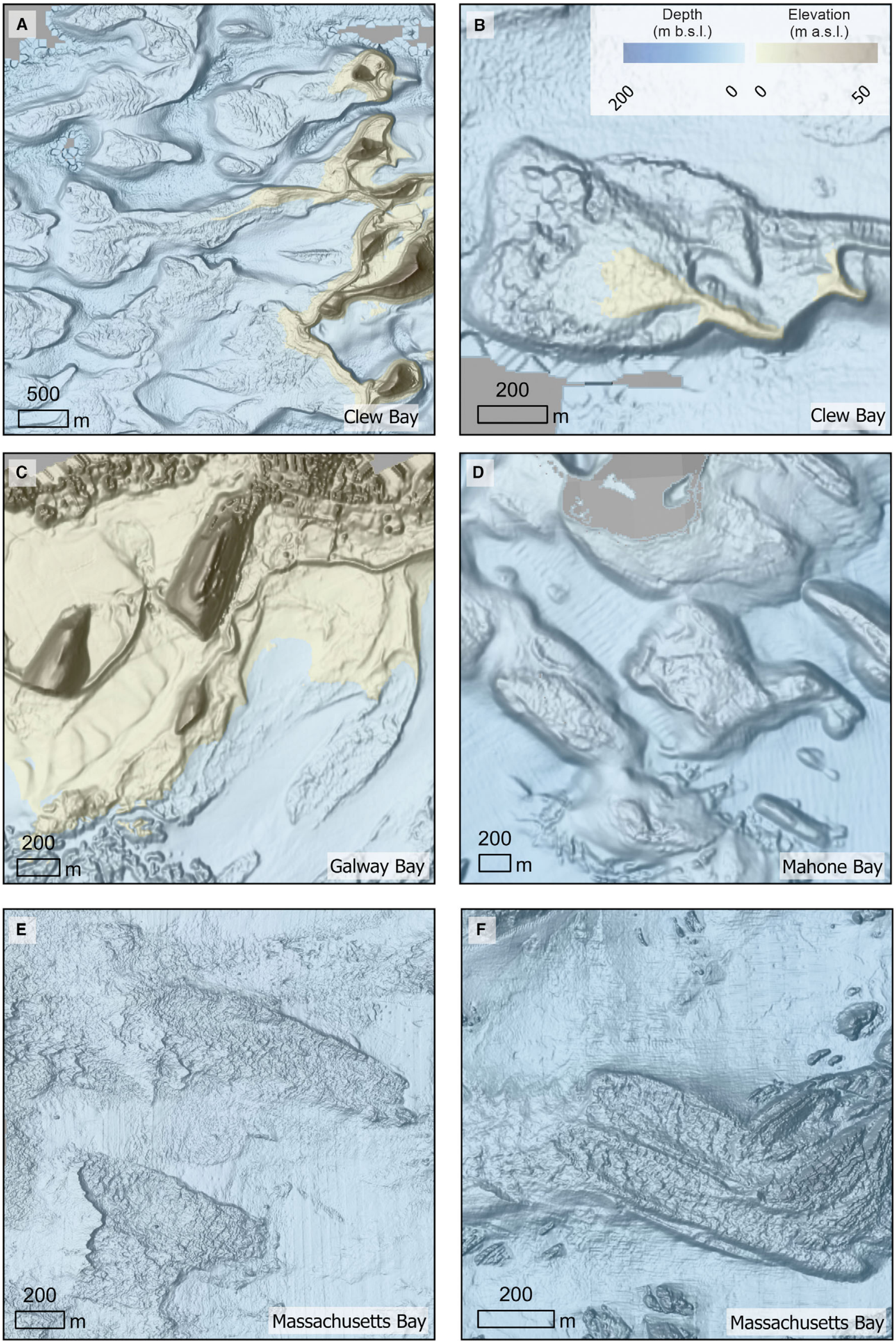


Fig. 3. Shape comparison of pristine (A) and truncated (B) drumlins from the dataset in this study. Notice the deviation of the truncated drumlins from the typical curved profile. Height (y) and length (x) of the drumlins are presented in metres.

alteration. Reworking and planation are tentatively observed at and above ~61.2 m b.s.l. (Fig. 5), although flat-topped drumlin assemblages (mean p90 depth of the deepest 10 planated landforms) are primarily observed from ~55.3±3.8 m b.s.l. and become clearer moving to shallower seabed (~50 m b.s.l.). Below 61.2 m no planation—apart from a few ambiguous occurrences—is recorded. Drumlin planation is

Fig. 4. Six examples of truncated drumlins in actively retreating coastal bluffs previously described and studied by other authors in terrestrial settings. A and B. Clew Bay; INFOMAR Lidar Data. The drumlin archipelago in Clew Bay has been described and studied by various authors, for example, Carter *et al.* (1989) and Knight (2016). The location of A corresponds to Fig. 2 and better shows the drowned drumlin platforms, gravel tails, ridges and tidal channels. Panel (B) shows an irregular relict drumlin with gravel tails pointing landwards. C. Galway Bay, INFOMAR LiDAR data, showing the retreating coastline described by Rink *et al.* (2024) associated with an eroded drumlin rubbly platform on the right. D. Mahone Bay, NONNA bathymetry data, showing truncated drumlins previously described by Piper *et al.* (1983). E and F. Massachusetts Bay, USA; NOAA bathymetry data. Eroding drumlin bluffs in this region have been extensively described by previous authors (e.g. Rosen & Leach 1987; Oldale *et al.* 1994; Himmelstoss *et al.* 2006; Black *et al.* 2025).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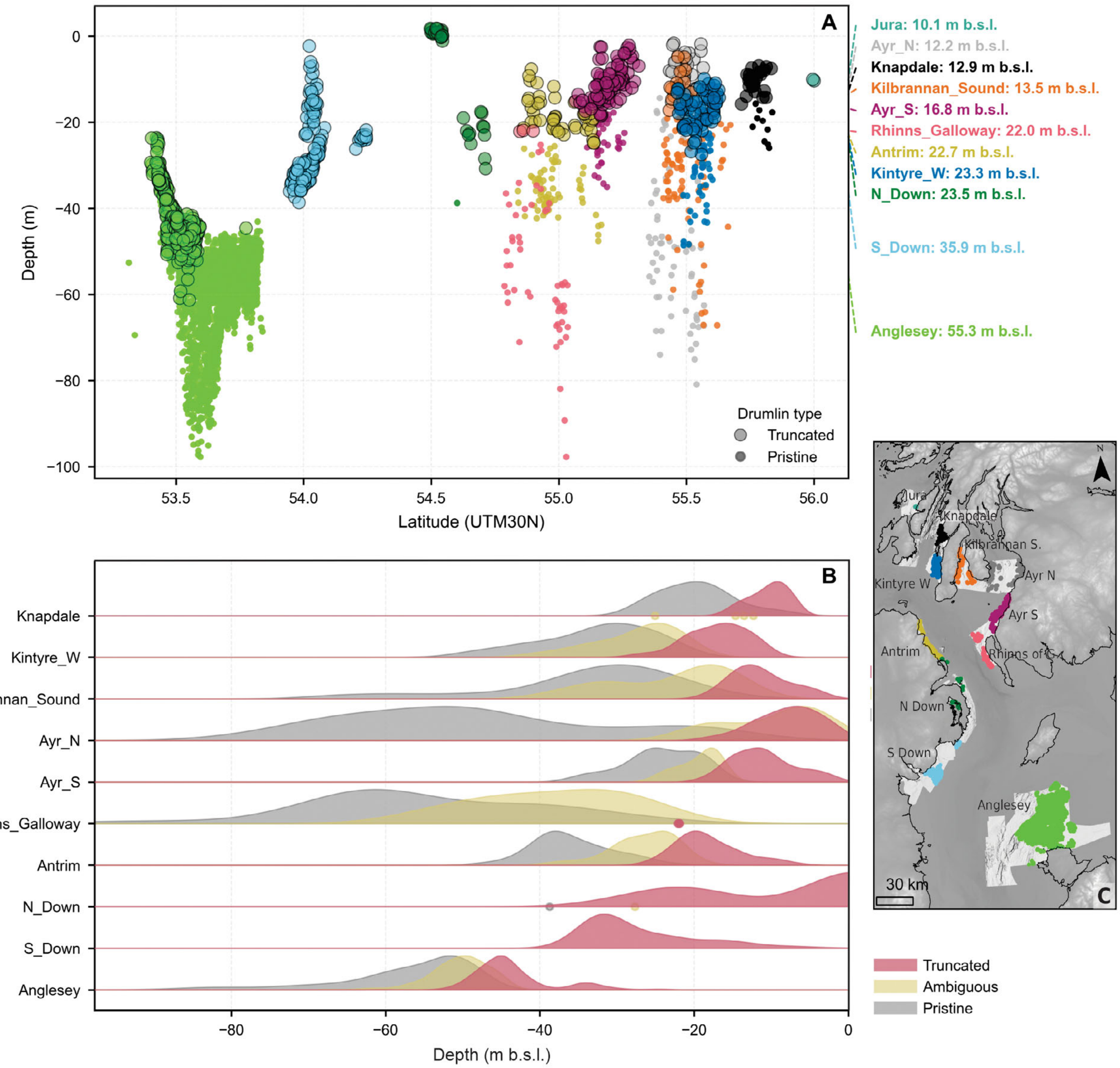

Fig. 5. Depth distribution of the truncated platforms analysed in this study for each zone (Anglesey, S Down, N Down, Antrim, Rhinns of Galloway, Ayr S, Ayr N, Kilbrannan Sound, Kintyre W, Knapdale and Jura). The reference depth of each landform plotted in A and B is the 90th percentile (p90) of the depth range extracted for that landform. A. Plotted depths for all truncated and pristine landforms in each sub-region. The depth values shown on the right are the mean p90 depths of the deepest 10 truncated drumlins for each zone. Notice the progressively shallower depths of truncated forms moving closer to Rannoch Moor, the centre of glacial isostasy in Britain and Ireland during the Late Glacial. B. Relative abundance plot of the three landform classes (truncated, ambiguous and pristine) for each subregion. C. Map showing the location of the zones. The coastline presented in C is the UKHO Satellite Derived Coastline (UK Hydrographic Office © Crown Copyright 2019. Created using Google Earth Engine, contains modified Copernicus Sentinel data).

observed up to ~1 km away from the modern northern Anglesey coastline, where completely horizontal and almost featureless drumlin plateaus are observed (Fig. 6E). The featureless plateaus are rare, however, as across the region, drumlins present planation combined with sinuous or curvilinear ridges extending from the flanks and either forming appendages (e.g. Fig. 6C) or creating bridges to other truncated forms (e.g. Fig. 6D). Ridge dimensions vary, but are usually only a few metres high, and between 100 and 300 m wide. The orientations are predominantly eastwards or south-eastwards, with some directed SW–NE when connecting multiple flat-topped drumlins. On the shoal extending on the side of the ISB, on the northern and western part of the study area (see Fig. 6A and zoom-in on Fig. 6B), between 65 and 45 m b.s.l., grooves about 0.5–1 m deep and ~20 m wide traverse the seabed surrounding the landforms, leaving rectilinear, curvilinear and tightly meandering marks directed predominantly E-W. These features are not observed in other parts of the study area.

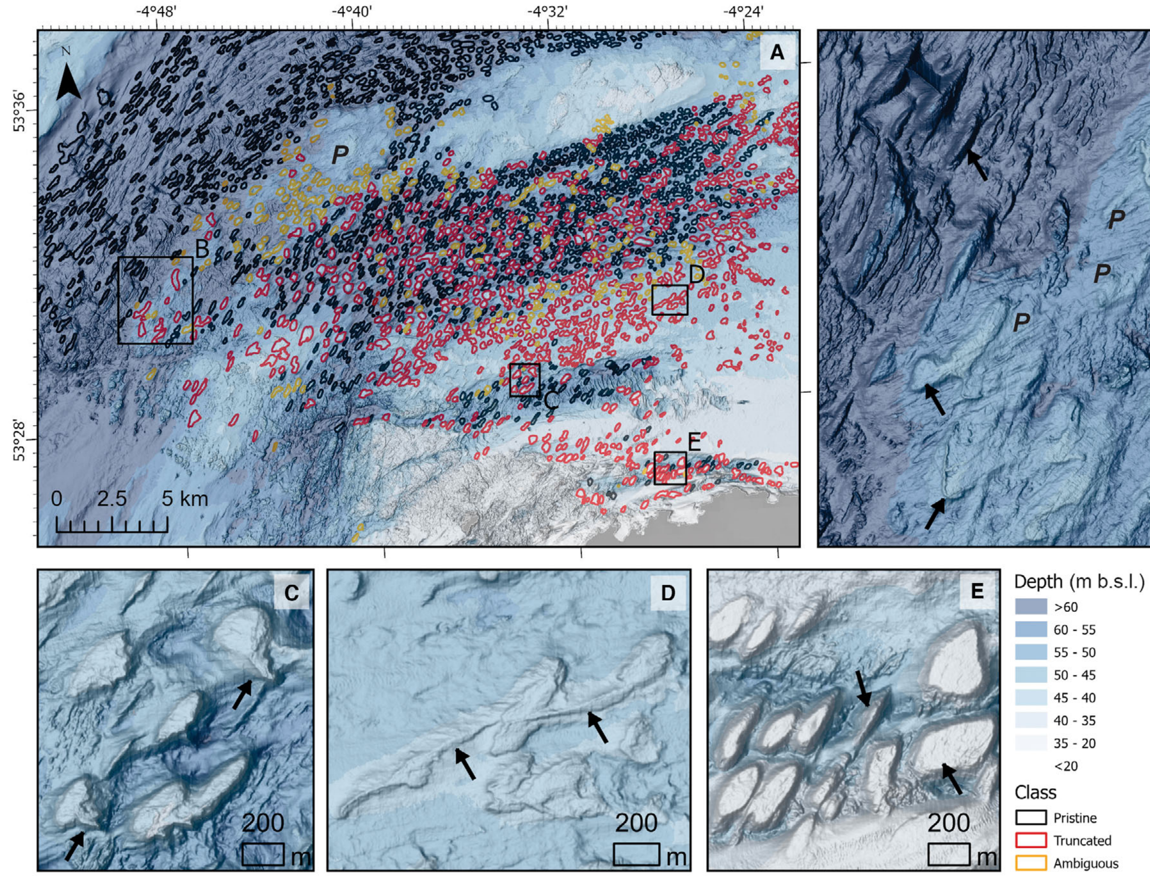

Fig. 6. A. Overview of the mapped landforms in the Anglesey area, showing the correlation between water depth and truncated drumlins. The letter 'P' indicates diffused presence of iceberg ploughmarks. B. First occurrences of flat-topped drumlins in the deeper parts of the area, showing transition from pristine drumlins (top arrow), to planated drumlin with tail connecting to a second planated form (mid arrow) and irregular fine ridges on top of drumlin-shaped platform, previously interpreted as moraine ridge, and here re-interpreted as relict gravel barrier. The letter 'P' is positioned next to examples of iceberg ploughmarks. C. Set of flat-topped drumlins with flanking ridges (indicated by arrows) interpreted as cuspate spits. D. Flat-topped drumlins; the arrows point to elongated, sinuous ridges that connect the relict landforms; the ridges are interpreted as a gravel tail or tombolo. E. Perfectly planated drumlins in a confined rock basin close to the Anglesey coastline, associated with a pristine form (left arrow) in the deeper part of the basin. The latter drumlin was too deep for wave action to indent it.

Interpretation. – Flat-topped drumlins north of Anglesey and in the ISB are interpreted as drumlins truncated by wave erosion as those observed in Galway, Boston or Clew Bay. The coexistence of pristine and truncated forms at shallower depths (Fig. 6E) may be explained by drumlins that occur within large seabed depressions (as occurring in Mahone Bay, Fig. 4D), causing them to be quickly submerged and avoid erosion at higher relative sea levels. While sinuous and curvilinear ridges in this area were in many instances previously interpreted as moraines (British Geological Survey 2022), or in adjacent areas similar features were identified as eskers (Van Landeghem *et al.* 2009; Van Landeghem & Chiverrell 2020), the morphological characteristics and position of the ridges in this study are for the most clearly comparable to those observed in western Ireland (cf. Fig. 4A–C with Fig. 6), where gravel bars and curved spits develop on the stoss side of bluffs, or along longshore transport. Ridges oriented SW–NE developing over the planated surfaces may be interpreted as gravel lags, like the 'pladdies' of Strangford Lough in Ireland (Greenwood & Orford 2008). An interpretation as uneroded segments of terminal moraines or eskers is less likely, firstly because the ridges overlap flat, truncated surfaces and moraines or eskers would have also been flattened together with the drumlins (Fig. 6B). Secondly, the ridges are closely associated with the truncated forms, originating from and connecting different drumlin platforms, suggesting that the drumlins formed the source sediment for the ridges (as is the case in the Clew Bay locality described by Carter & Orford (1988)).

From the bathymetry data it is clear that a 'drumlin archipelago' existed at lower sea levels in the region (Fig. 4A). However, due to the complex glacial history of the ISB, the existence of palaeo-embayments and the lack of detailed information on tidal range and wave climate, a clear understanding of wave propagation and bluff retreat around Anglesey is difficult to reconstruct from the truncated surfaces alone. The grooves that incise the northwestern shoals are interpreted as iceberg ploughmarks, and are observed elsewhere in the region (Van Landeghem & Chiverrell 2020). Presence of ploughmarks around, but not over, the truncated drumlins suggest a glacimarine setting before an initial sea-level fall, and then drumlin erosion and drowning associated with subsequent sea level rise.

Eastern Irish coast: from S Down to Antrim

Regional context. – Extensive studies have been carried out on ice dynamics during the last glacial cycle and drumlin geomorphology in Northern Ireland (e.g. Greenwood & Clark 2009; McCabe & Williams 2012; Merritt *et al*. 2018), more recently supplemented by high-resolution geomorphological mapping and offshore investigations that refine regional ice-flow reconstructions (Williamson 2021). Along the Antrim coastline numerous drumlins are organized into discrete, cross-cutting flow-sets that record multiple phases of ice flow reorganization (Greenwood & Clark 2009; McCabe & Williams 2012). Inland, an older assemblage of SSE–NNW drumlins and NE–SW ribbed moraine records ice dispersal from a major lowland ice dome and associated ice divide over northeast Ireland. Recent mapping indicates that subsequent ice-flow reorganization involved progressive collapse and migration of this divide, producing several successive flow stages (Sam Robertson pers. comm.) before relatively thin Scottish ice advanced southwestwards along topographically constrained valleys of east Antrim (East Antrim Coastal Readvance (~16.5 ka BP); McCabe & Williams 2012). Another flow-set on Island Magee (fs49 in Greenwood & Clark 2009) is associated with maximum extent and ice advance in the Irish Sea Basin, with offshore drumlin swarms indicating extension beneath the North Channel and continuation as a broadly coast-parallel southeastward flow (Williamson 2021). In County Down, ice flowing southwards from local onshore sources was diverted around the Mourne massif, generating arcuate flow-sets that wrap around both the northern and southern flanks of the mountains (Merritt *et al*. 2018). On the Mourne plain south of the mountains, Merritt *et al*. (2018) mapped a few crestlines of low drumlins directed SW–NE (Robertson 2024). The Kilkeel coastal sediments record instead a complex sequence of overriding, deformation and reworking beneath grounded ice. Most notably, deep, SE-aligned troughs are incised into till (Ballymartin Member) by subglacial drainage and ice modification; the troughs were later infilled in glacimarine conditions, truncated by an ice sheet during the Clogher Head Readvance, creating a line of cobbles (Main Stone Pavement) where truncation occurs, and further covered by glacifluvial outwash (Merritt *et al*. 2018).

Description of drumlin morphologies. – Drumlins, including flat-topped features, previously observed by other authors (Plets *et al*. 2019; Williamson 2021; Arosio *et al*. 2023), are mapped along the entire narrow strip of shallow seabed offshore the east coast of Northern Ireland, from 0 to ~60 m b.s.l., where high-resolution MBES data are available. Along the Antrim coast, two drumlin swarms are mapped, separated by Garron Point (see Fig. 1); the northernmost is directed approximately perpendicular to the coastline, SW–NE, while the southern follows the strike of the coastline, showing an SSE-wards flow. For both groups, a maximum depth of planation occurrence can be established, where the first signs of flattening are observed from 30.7 m b.s.l. (Table 1), with stronger evidence, including sinuous low ridges on the top or edge of the plateaus, from 23.5±3.6 m b.s.l. in North Down and 22.7±1.3 m b.s.l. in Antrim (Table 1). Below these depths, drumlins mostly preserve their typical rounded summit; however, many are incised by 0.5–1 m deep and 20–30 m wide rectilinear or curved grooves.

The most complex geomorphological record is found south and north of Dundrum Bay (zone: S Down), especially southeast of Kilkeel (Fig. 7A). Here the bathymetry is characterized by a gently sloping seabed, irregularly carved by dead-end channel-like features close to the coastline (Fig. 7E), teardrop-shaped plateaus (Fig. 7C) and hummocky terrain with fine elongated ridges in the mid-section. Some elongated ridges in the mid-section extend linearly and continuously for 5–6 km in the deepest part of the bathymetry data; a fragmented and irregular topography appears, with isolated platforms distinguished by a peculiar polygonal shape, almost regular at times (Fig. 7D). Both polygonal and teardrop-shaped platforms measure from 100 m to >1 km in length, between 50 and 750 m in width and from 2 to 4.5 m in height. The top surface of all plateaus can be well approximated by a common surface gently dipping towards the SE ~1–2°. Steeper slopes are common on the SW sides of the plateaus, often associated with fine ~1 m high ridges that run along the perimeter of the side (Fig. 7C, D). However, sharp margins occur also on the NE sides, sometimes cutting abruptly the gently dipping surface. A group of these features presents an almost triangular shape, with one of the vertices aligned towards the SW and corresponding to the steeper slope.

Flat-topped features extend across the entire depth range of the Kilkeel area, from ~35.9 m b.s.l. (Fig. 5), and no pristine drumlins are mapped; therefore, a maximum planation depth cannot be established.

Interpretation. – Overall, the flat-topped landforms overlaid by relict ridges along the northeastern Irish coast are interpreted as drumlins truncated by wave erosion. Offshore Antrim, the northern group of drumlins is tentatively associated with the onshore late-stage

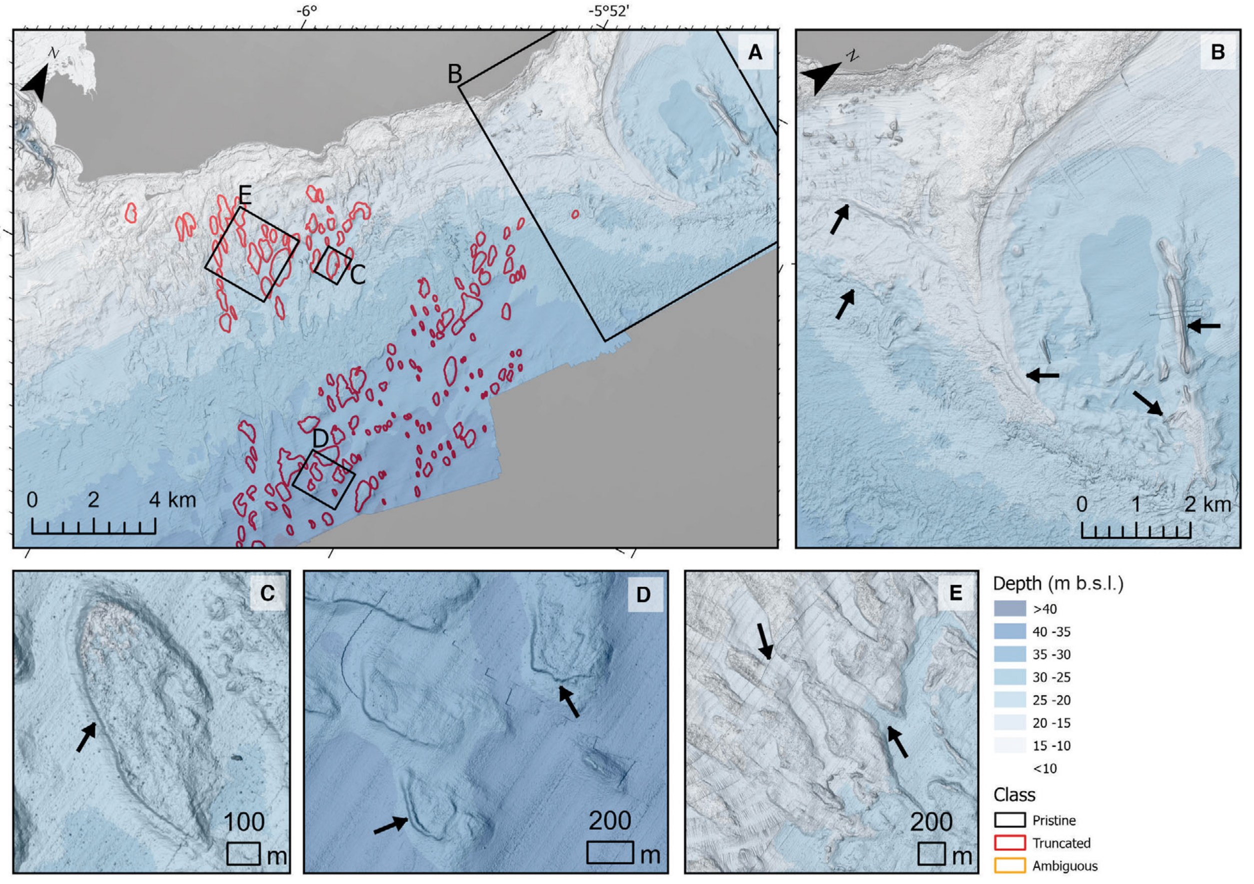

Fig. 7. A. Overview of the mapped landforms in the Kilkeel area, showing an assemblage of truncated drumlins and drowned coastal geomorphology. B. Palaeo-shorelines and palaeo-lagoon. The arrows, counterclockwise from left to right, indicate: two palaeo-shorelines at ~15 and 21 m b.s.l.; a narrow, drowned headland or spit with beach ridge on top of the Dunmore Head Moraine (Merritt *et al.* 2018); a fine sequence of regressive beach ridges; and finally a barrier island, south of which a fine tidal inlet is also visible (Goslin & Clemmensen 2017). C. Truncated teardrop-shaped plateau, interpreted as a truncated drumlin, with a fine ridge along the western side (arrow). D. Polygonal plateaus, interpreted as truncated drumlins, gently sloping eastwards with ridges along the western side (arrow), reminiscent of the 'pladdies' of Strangford Lough (Greenwood & Orford 2008). E. Irregular topography of flat-topped, teardrop-shaped connected plateaus surrounded by channels, comparable to the bathymetry in Clew Bay (Fig. 4A).

flow-set of McCabe & Williams (2012), while the southern group is congruent to fs49 of Greenwood & Clark (2009). Truncated morphologies are reminiscent of those present in Massachusetts Bay (Fig. 4E, F), with ridges along the side (coarse debris 'armour' after Carter & Orford (1988)).

The architecture of teardrop-shaped plateaus overlaid by curved ridges and delimited by channels observed offshore Kilkeel (Fig. 7A, E) is very similar to the relict drumlin footprint and tidal channel assemblages of Clew Bay (Fig. 4A). This interpretation is also supported by additional relict coastal features found in the Dundrum area, including palaeo-shorelines at 15 and 21 m b.s.l. (Fig. 7B) and a palaeo-lagoon delimited by the eroded offshore continuation of the Dunmore Head Moraine to the south (see fig. 3 in Merritt *et al.* 2018) and a drowned barrier island and tidal inlet indicating RSLs of about 20 m b.s.l. (Fig. 7B). It is difficult to assess the link between the Kilkeel submarine plateau-and-channel morphology and the incised Ballymartin Member till (Merritt *et al.* 2018). While some of the features might be explained by Merritt *et al.*'s model, the exposed assemblage offshore Kilkeel is congruent with other coastally eroded drumlin terrains. Only ground-truthing including sediment cores and onshore to offshore stratigraphic profiles may help reach a conclusion.

Western Scotland: from Rhinns of Galloway to Jura

Regional context. – Fields of southwest trending streamlined landforms, including drumlins, are well-documented along onshore coastal areas of southwestern Scotland (Fig. 8), including the Rhinns of Galloway, the Ayrshire coast and the Kintyre peninsula (Salt & Evans 2004; Finlayson *et al.* 2010, 2014; Phillips *et al.* 2010). These landforms have also previously been shown to extend offshore into the Sound of Jura (Dove *et al.* 2015). Onshore, borehole records and sediment

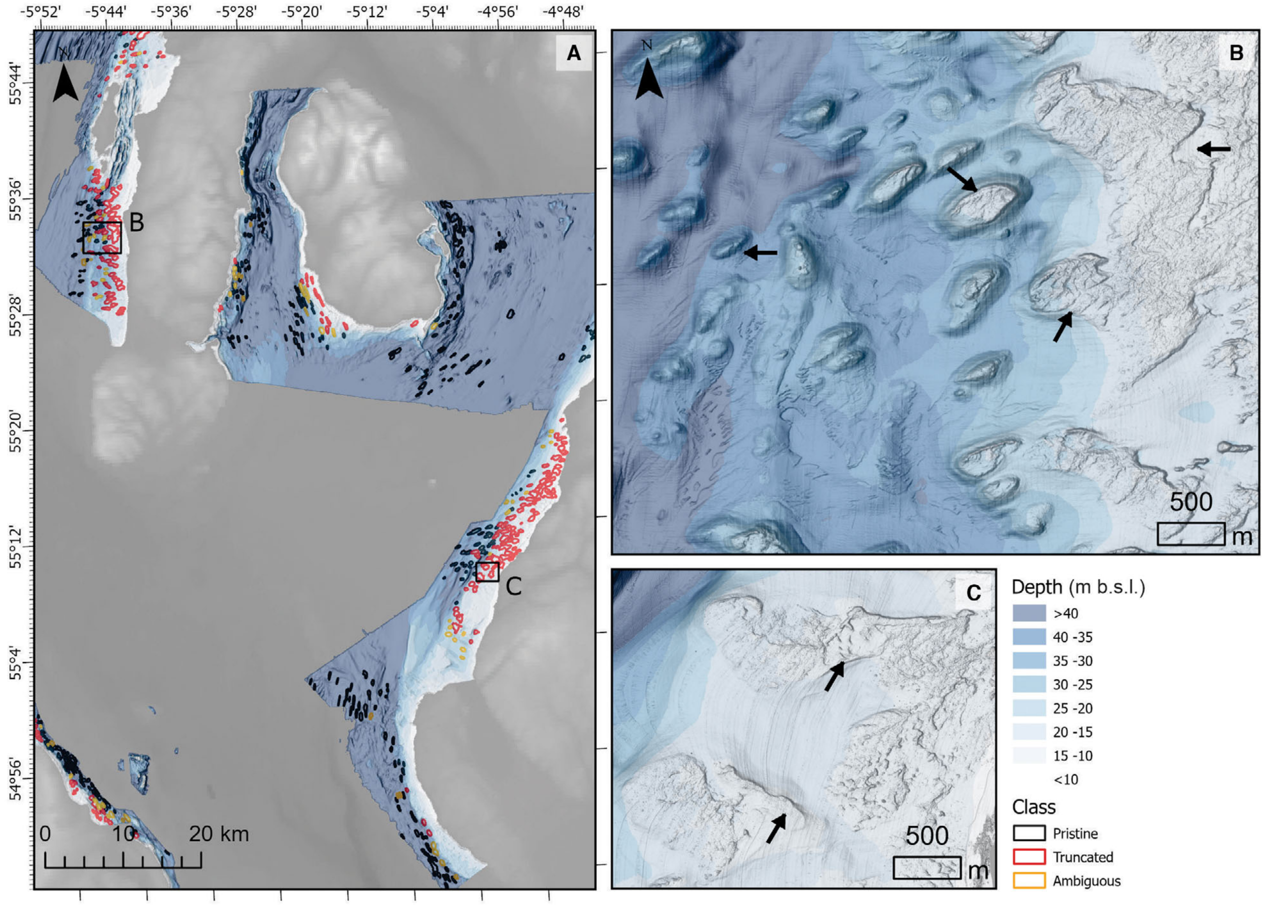

Fig. 8. A. Overview of the mapped landforms in western Scotland. B. Transition between pristine drumlins (arrow on the left), truncated drumlins with irregular topography and fine ridges (mid two arrows) and ‘coalesced’ truncated drumlins platform (or Rogen moraine) (right arrow) sloping towards the south-west and bound by a short cliff to the north-east. C. Irregular truncated drumlin platforms characterized by barrier-like ridges as observed elsewhere in the data (bottom arrow) and small arcuate ridges (top arrow) that might be current-induced bedform remnants.

exposures reveal that the drumlins are predominantly composed of glacigenic sediment (Finlayson *et al.* 2010, 2014), although some features within the Sound of Jura have been interpreted to be bedrock-dominated, with crag-and-tails locally present with the assemblages. Collectively these drumlins and associated streamlined bedforms were interpreted to have formed during phases of south-westerly ice flow during the latter stages of the last, Late Devensian, glaciation to affect the area.

Description of drumlin morphologies. – Here we further describe assemblages of offshore drumlins near the coast in the Sound of Jura, the shallow seabed along the Ayrshire and the Rhinns of Galloway, with a focus on the range of morphologies: flat-topped (truncated) and rounded (pristine) morphologies present and the depth at which transition from one form to the other occurs. Excluding the two isolated drumlin-shaped plateaus west of the Isle of Jura, across the entire study area of western Scotland the full range of drumlin forms (pristine to truncated) is preserved, allowing the identification of the depth range for drumlin modification. In the Kilbrannan Sound and Ayrshire region, drumlin planation is established between 18.5 and 17.6 m b.s.l. (Fig. 5, Table 1). Offshore the Rhinns of Galloway, drumlin classification proved difficult, with morphologies not clearly attributable to original form, bedrock structure or exogenous modification. This uncertainty reflects in only three positively identified truncated forms (Table 1), and a bigger spread for ambiguous drumlin surfaces (Fig. 5B). The situation is instead much clearer west of Kintyre, where planation is established at 23.3±2.3 m b.s.l., with potential erosion as deep as 27.5 m b.s.l. (Fig. 5, Table 1).

The morphology of flat-topped drumlins on the western coast of Kintyre, and on the eastern shallows of Ayrshire, in strips of seabed that extend for ~6 km from the modern coastline, is the richest in features. In these areas we observe assemblages of isolated, grouped or coalescing subaqueous platforms of various sizes and morphologies. The majority of the isolated plateaus possess an elongated or irregular teardrop shape, with the point directed towards the southwest. Dimensions vary considerably, with the largest landform measuring ~900 m in length and 400 m across, while the smaller are only ~150 × 100 m. Most of the flat-topped drumlins are about 10–15 m tall, although to the north, the biggest rise 30–35 m above the surrounding seabed.

The plateaus are gently sloping towards the SW or WSW, and several present a curved ridge between 1 and 4 m high and a few tens of m wide on their NW or NNW perimeter. The ridges follow the edge of the plateaus and are therefore oriented SW–NE or WSW-ENE, their curvature becoming more accentuated and their height more prominent, towards the east. On shallow seabed (from 20 to 5 m b.s.l.), only a hint of the original drumlin shape is visible, as the footprints coalesce in wide and irregular platforms adjacent to the coastline bound by abrupt cliff edges on the northeastern side followed by shallow channels (Fig. 8B). The platforms slope gently from the coastline towards the SW at about 4 m km^{-1} and are characterized by a very irregular topography consisting of variously configured ridges and hummocks. Relict curved ridges are occasionally still visible on northwestern margins.

Interpretation. – Flat-topped drumlins and platforms in this region are best interpreted as landforms dissected and truncated by coastal processes. While most of the truncated landforms are drumlins, 'coalesced' platform features might have been originally Rogen (ribbed) moraines, being these landforms also found in association with drumlins, representing slower ice movement in the glacial streamlined landforms spectrum (Eyles *et al.* 2016). Some truncated forms near Kilberry were previously interpreted as proglacial deltas by Arosio *et al.* (2018); however, this new study better explains them as wave-eroded drumlins.

As for the Anglesey and Irish record, these Scottish landforms are clearly morphologically equivalent to those present in the USA or Canada (Fig. 4D–F), but even more notably to the submerged relict drumlin footprints of Clew Bay (Figs 2, 4A). Here submerged 'coalesced' platforms interrupted by tidal channels and depositional basins correspond closely to the platforms, shallow cliffs and channels offshore Ayrshire or west of Kintyre (Fig. 8B, C). These assemblages are also characterized by side ridges that are either the coarse debris armours described by Carter & Orford (1988), or leeside gravel barriers and spits as those observed in truncated drumlins in Galway Bay (Fig. 4C). Short and arcuate ridges observed on truncated drumlins and platforms offshore Ayrshire (Fig. 8C) may be interpreted as submarine bedforms, potentially tidally related, as those observed in Massachusetts Bay (Fig. 4E, F) or as remnants of exposed lag rocks and boulder shoals of eroded materials comparable to the 'pladdies' of Strangford Lough.

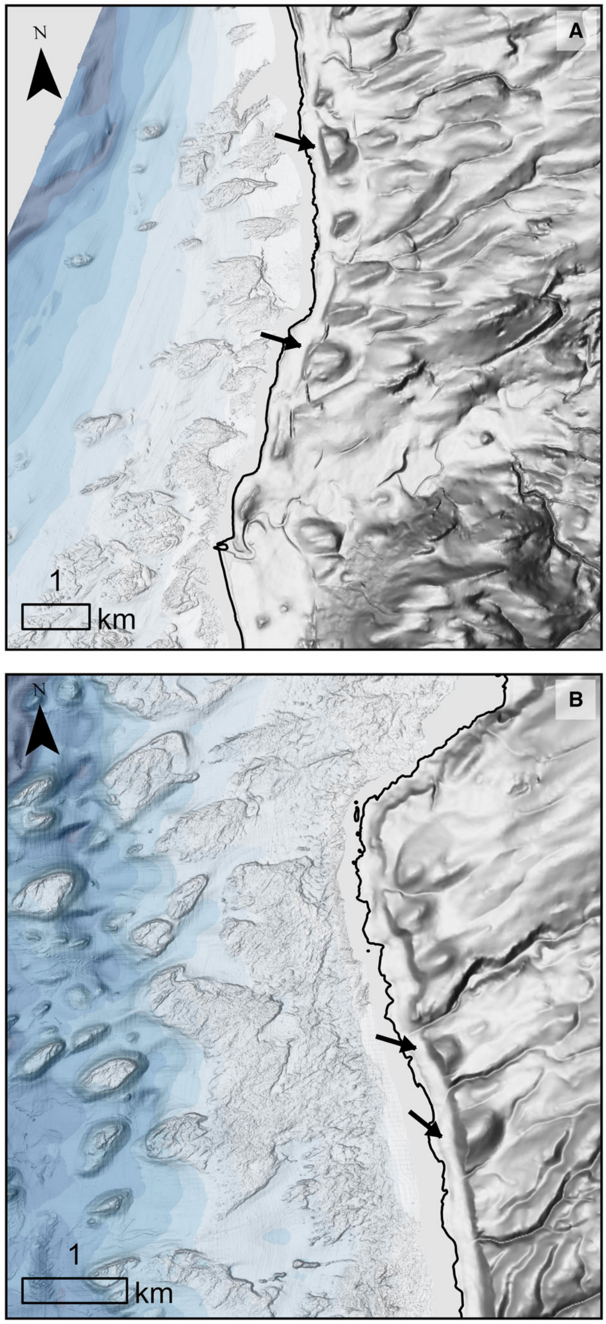

Fig. 9. Retreating bluffs in western Scotland observed in the Firth of Clyde (A) and west of the Kintyre peninsula (B). The location of these figures is given in Fig. 1D. Drumlin cliffs are visible on the onshore DEM (arrows); however, a full connection between onshore and marine forms was not possible due to the lower resolution of the onshore data and the presence of the white ribbon. The coastline presented in C is the UKHO Satellite Derived Coastline (UK Hydrographic Office © Crown Copyright 2019. Created using Google Earth Engine, contains modified Copernicus Sentinel data).

Finally, combined images of NextMap and MBES data in Fig. 9 show clearly the relationship of the offshore record offshore Ayrshire with onshore drumlins, whose lower reaches are removed where the coast has retreated.

Discussion

Drumlin truncation mechanics and preservation potential

In the Results section, we have shown several pieces of evidence, including coastal landform assemblages, comparison to well-studied equivalents and association to coastal bluffs, that strongly advocate for the formation of the truncated drumlins as wave-cut landforms. However, it is worth assessing the plausibility of alternative modes of formation.

Overall, three other mechanisms can be considered as causes for drumlin planation in the context of this study, which do not require the sea-level to be at least as low as the platforms observed rendering invalid further considerations for RSL reconstruction: (i) truncation by ice readvance due to ice reorganization and changes in flow, (ii) intense subglacial meltwater activity or floods and (iii) erosion and planation by wave or tidal action in a subtidal setting. The first two, glacially-related alternatives can be quickly refuted, as both mechanisms do not truncate but rather reorganize drumlin structure and produce palimpsests or other subglacial landforms altogether (e.g. Stea & Brown 1989; Eyles *et al*. 2016; Peterson Becher & Johnson 2021). The latter explanation is also unlikely for two main reasons. Firstly, the record shows in several places (e.g. Dundrum Bay or Anglesey) fine intertidal or supratidal structures best interpreted as flanking and beach ridges, spits and tombolos overlying truncated platforms. These features require lower RSL and cannot be formed by subtidal processes. Secondly, truncated drumlins are observed at depths that exceed the range of plausible wave-induced erosion in the Irish Sea and the Sound of Jura. Recent work demonstrates that the depth of sediment disturbance is better described by a grain-size and wave-climate-dependent effective wave base (EWB), rather than the standard oceanographic wave base (OWB, approximated as half the deep-water wavelength, ~20–35 m for wave periods of ~5–7 s in the Irish Sea) (Flemming 2024). Under storm conditions in a marginal sea such as the Irish Sea, EWB may extend significantly deeper than the OWB, potentially reaching several tens of metres. However, even allowing for such variability, wave-induced orbital motions at these depths are primarily capable of mobilizing unconsolidated sediments rather than eroding or planing cohesive subglacial landforms. The truncated drumlins occur at depths of 40–70 m, where, although some sediment movement may be possible during high-energy events, the generation of regionally extensive, laterally continuous planation surfaces would require sustained and spatially uniform shear stresses that wave processes are unlikely to provide (Flemming 2024). Furthermore, if wave-base erosion could produce such landform-scale planation, more extensive and laterally continuous submerged erosion surfaces would be expected to have formed during the relatively stable sea-level conditions of the Mid- to Late Holocene (e.g. Fig. 10), which is not observed. Similar conclusions were reached for the drumlins in Massachusetts Bay by Oldale *et al*. (1994). On the basis of these considerations and taking into account more likely a single mechanism of formation for this group of landforms, we conclude that wave-cutting is the best possible mechanism of formation.

Erosion of drumlin bluffs along formerly glaciated terrains is controlled primarily by whether water levels are sufficiently high to permit direct wave attack at the bluff toe. Variations in till composition are apparently not statistically significant (Carter *et al*. 1990; Himmelstoss *et al*. 2006; Greenwood & Orford 2007), although more abundant coarse cobble and boulder supplies forming thicker armouring might locally reduce erosion rates. Observations from monitored drumlin cliffs in Strangford Lough, Ireland, show that effective erosion by waves is threshold-dependent, occurring mainly when predicted high water exceeds mean high-water spring level and coincides with strong, sustained winds, allowing waves to reach and undercut the bluff base (Greenwood & Orford 2007). Studies from Boston Harbour confirm this dual-process framework: when extreme water levels (astronomical tide plus storm surge) reach the bluff toe, erosion proceeds via wave notching, oversteepening and subsequent mass failure. In contrast, at higher bluffs where water levels do not reach the base, retreat occurs through rainfall-driven slope wash and geotechnically induced failures within sandy till (Black *et al*. 2025).

While subtidal erosion is implausible for the establishment of truncated drumlins, after drowning the landforms could undergo further downcutting due to such processes. In general and unfortunately, rates of erosion of subtidal cohesive shore platforms composed of materials such as glacial till, clay and mud are generally poorly constrained (Brew 2004).

The concept of Morphodynamic Depth of Closure (MDoC; Ortiz & Ashton 2016) provides a physically based framework for estimating the offshore limit of significant profile adjustment over centennial to millennial timescales. Plets *et al*. (2019) adopted this concept to define an uncertainty envelope for the depth over which long-term wave-induced sediment transport and morphodynamic reworking may affect submerged palaeoshoreline indicators. However, MDoC was developed for mobile sandy shorefaces in which bed evolution is governed by cross-shore sediment transport and its formulation does not account for erosion of cohesive, armoured substrates. Therefore, while MDoC supports the expectation that morphodynamic activity decreases rapidly offshore, it cannot presently be applied in this study to quantitatively predict erosion depths or erosion rates for cohesive till platforms.

Erosion operates through a combination of wave-induced shear, abrasion by mobile sediment and progressive weakening of the substrate, with erodibility con-

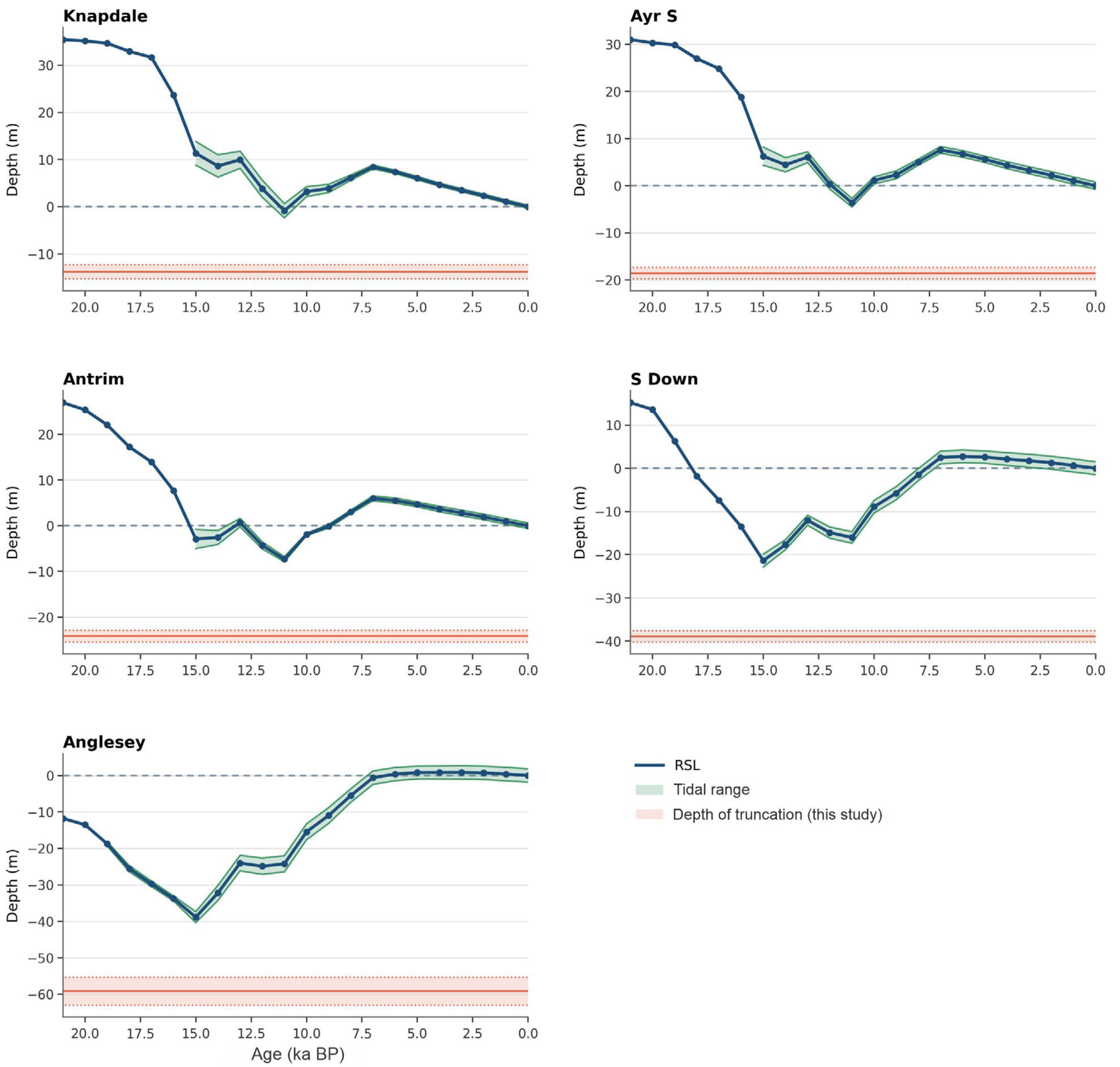

Fig. 10. Comparison of RSL curves extracted from PALTIDE for five selected locations against maximum depth of truncation (converted to MSL) observed in this study. Anglesey: −4.60415; 53.5248. S Down: −5.85415; 54.0664. Antrim: −5.85415; 54.9855. Ayr S: −4.9375; 55.27145. Knapdale: −5.6875; 55.7904.

trolled by geotechnical properties of the geological substrate and a critical shear stress threshold; however, erosion is commonly concentrated along structural weaknesses and as aggregate detachment rather than particle-by-particle removal. Abrasion can significantly enhance erosion where sediment is mobile, but cohesive sediment cover—and gravel 'armouring'—may inhibit it (Brew 2004). Both empirical observations and theoretical models demonstrate that erosion rates decline rapidly offshore as wave energy dissipation and wave–bed interaction diminish (Trenhaile 2002). For example, field measurements on cohesive (clay-rich) platforms show mean vertical erosion rates of ~17–18 mm a^{-1}, declining offshore from >30 mm a^{-1} near the cliff to <8 mm a^{-1} on the outer platform, demonstrating a strong decrease in downwearing with increasing water depth (Moses & Robinson 2021). Consequently, cohesive platforms experience most vertical erosion near MSL and become effectively inactive when submerged. This is consistent with sediment budgets indicating that platform downwearing contributes only a minor proportion (~7%–8%) of total coastal erosion relative to cliff retreat (Moses & Robinson 2021), implying that marine transgression typically removes only a limited thickness of stiff glacial till before preservation dominates.

In conclusion, coastal erosion leads to the development of broad wave-cut drumlin platforms, armoured by coarse sediment including cobbles and boulders in the foreshore, which dissipate wave energy and result in a progressive decrease in the rate of cliff retreat at stable sea levels. However, in transgressive settings, the truncated drumlin is drowned, allowing continuation of cliff erosion (e.g. Piper *et al.* 1983: fig. 2). As drumlins are progressively eroded and submerged, the wave-planed and armoured surfaces are left stranded and drowned by continued transgression (Carter *et al.* 1990), allowing the waves to indent formerly sheltered landforms. Progressive RSL rise and planation leads in the long term to a set of truncated drumlins whose top surface broadly fits a plane-sloping seawards (Piper *et al.* 1983), as observed in Dundrum Bay, and in western Scotland.

Truncated drumlins as terrestrial-limiting indicator

Following the erosion model presented above, truncated drumlin platforms are interpreted as the cumulative product of wave erosion during one or more shoreline occupations, with their preservation as submarine landforms requiring a final drowning during transgression. In a transgressive setting, the entire platforms of submarine truncated drumlins do not represent fixed palaeodatums such as mean sea level (MSL), but instead they are best interpreted as time-transgressive features formed within the nearshore zone of effective wave action. In particular, the maximum and minimum depths of truncated drumlin platforms represent the earliest and latest stages of sea-level position across the erosional history of the landform, respectively. In regions with non-monotonic RSL histories, the deepest preserved truncation still provides a limiting constraint on the minimum RSL attained prior to final drowning.

Assuming that the superficial (i.e. seabed) geomorphological imprint left by Late Pleistocene ice sheets, including subglacial lineations and moraines, predominantly records the most recent Weichselian glaciation (Stewart *et al.* 2021; Clark *et al.* 2022; Arosio *et al.* 2023), and that, as it has been discussed above, the plateaus have not undergone any more significant undercutting after drowning, within any given area, the depth range between pristine submarine drumlins and the first (deepest) evidence of wave erosion or fully developed truncated drumlins defines a depth bracket for the local minimum RSL in that region at some point after the last deglaciation. Where pristine submarine drumlins are absent, the deepest preserved drumlin platform provides only a limiting depth, indicating that RSL must have been lower than that elevation at the time of formation. On its own, this indicator does not constrain the absolute age of the palaeo-shoreline and requires independent contextual information for chronological interpretation. The lowest indication of truncated drumlins may therefore be treated as terrestrial-limiting indicators. Finally, only sediment drumlins can be considered for this analysis, and bedrock, or bedrock-cored drumlins, may lead to ambiguities or apparent pristine outliers.

Implications for RSL reconstructions in the Irish Sea and western Scotland

Following the principles outlined above, some initial considerations can be made on the implications of the truncated drumlins on our current understanding of palaeo-RSL in the study region. Figure 10 compares the depths of drumlin truncation observed in this study with RSL and palaeotidal outputs from the LGM to the present at 1000-year intervals downloaded from PALTIDE, an easily accessible portal for RSL-related data on the northwest European shelf (Scourse *et al.* 2024). PALTIDE uses the Britain-focused GIA model of Bradley *et al.* (2011) for RSL and palaeotopography, while the tidal component is sourced from regional ROMS hydrodynamic simulations following Ward *et al.* (2016), forced at the boundaries by a global tidal model based on the Princeton Ocean Model. PALTIDE's RSL curves are not the newest generation of Britain–Ireland GIA outputs. Since 2011, substantial advances, particularly through the BRITICE-CHRONO programme (Clark *et al.* 2022) and the expanded RSL database compiled by Shennan *et al.* (2018), have led to a new modelling framework (Bradley *et al.* 2023) which moves beyond the traditional practice of tuning ice thickness to fit RSL data, instead using empirically constrained ice-margin chronologies and testing physically plausible ice geometries. At any rate, for the purpose of our comparison, PALTIDE data remain useful for capturing the first-order patterns and magnitudes of RSL change, and for assessing broad palaeotidal dynamics. As the bathymetry data used in this study are referenced to Chart Datum (CD), while the model outputs are relative to MSL, in the following sections depths are adjusted by 0.1 to 3.8 m to account for the difference between CD and MSL in the locations. The adjustments are based on Vertical Offshore Reference Frame (VORF) data provided by the UK Hydrographic Office. Dates, unless specified, are in calendar ka BP.

Anglesey. – Latest reconstructions of the British-Irish Ice Sheet (BIIS) during the last deglaciation indicate that the ISB between the Isle of Man and Anglesey was ice-free roughly between 21 and 20 ka BP (Clark *et al.* 2022). The ice margin was marine terminating, as suggested by iceberg ploughmarks shown in this study and ploughmarks and De Geer moraines presented in Van Landeghem *et al.* (2009) and Van Landeghem & Chiverrell (2020). Assuming an initial RSL regression after deglaciation (Fig. 10), truncated drumlins in Anglesey indicate that coastal erosion in the region as deep as at least ~58 m below MSL was ongoing, possibly during the Windermere Interstadial. This agrees with the observation of ploughmarks only in the deeper part of the truncated drumlin record, but not on the shallower (above ~47.5 m below MSL) southern shoals. After an initial submarine setting, the seabed was exposed by RSL regression and eroded by coastal processes. The PALTIDE curve does not reach as deep (~40 m below MSL at 15 ka BP), but it is consistent within uncertainty to the truncation depth observed in this study. Older RSL reconstructions, summarized in (Roberts *et al*. 2011), roughly correspond with our observations, with RSL in North Wales between 50 and 70 m below MSL at about 14–16 ka BP.

Northern Irish coastline. – Glaciomarine muds were deposited during the Cooley Point Interstadial (between 16.5 and 15 ka BP) in the troughs at Kilkeel following retreat of ice from the coast and while RSL stood at up to about 30 m above sea level, suggesting a marine-terminating front (McCabe *et al*. 2005; Merritt *et al*. 2018). After deglaciation, RSL regression happened through the Killard Point Stadial (~14.7 ka BP), with transgression taking place during the Younger Dryas and Early Holocene. Sea level trends from the GIA modelling indicate RSL reaching minima of ~20 m below MSL in S Down, and almost 10 m below MSL offshore Antrim (Fig. 10), not too different from the more recent model outputs shown in Shennan *et al*. (2018). Our results for Kilkeel do not fit well with these reconstructions, as planation occurs as deep as 38 m below MSL, although some uncertainty remains in the interpretation of the deeper features. Similarly, planation along the Antrim coast occurs at ~25 m below MSL, indicating a discrepancy of 10 m with the models. Similar discrepancies had already been presented by Westley *et al*. (2011), especially related to the results of Kelley *et al*. (2006). In this study, Kelley and coauthors report a lowstand in Belfast Lough at about 30 m below OD, recorded by fossils in a shoreline deposit dated at ~13.4 ka BP. The deposition followed a period of rapid isostatic uplift associated with a RSL fall of 6–7 cm a^{-1}. More recently, Plets *et al*. (2019) combined seismic stratigraphy, dated cores and wave-ravinement surfaces to reconstruct two RSL lowstands reaching approximately 38–40 m below MSL, separated by periods of transgression and relative stillstand. Their interpretation of truncated drumlins and ravinement surfaces closely agrees with the deeper planation depths observed in this study, lending independent support to a lower deglacial RSL than predicted by several GIA models.

Western Scotland. – A similar predicament is encountered also in western Scotland, where drumlin truncation occurs on average 10–15 m below the RSL minima predicted by the GIA models (Fig. 10 and Shennan *et al*. 2018). RSL higher than modern MSL is predicted for most of the Weichselian, and the minima (modern MSL at Knapdale in the Sound of Jura and 2–3 m below MSL at Ayr S and the Rhinns of Galloway) are reached during the Younger Dryas or beginning of the Holocene. Sea-level index points or marine/terrestrial-limiting points are scarce for that period in the region (Shennan *et al*. 2018). For Knapdale in the Sound of Jura, Shennan *et al*. (2006) found no stratigraphic evidence to demonstrate whether there was a fall to an early Holocene minimum followed by a rise to a Mid-Holocene highstand or if there was relatively little change from ~10 ka BP. Marine erosion in western Scotland during the cold climate of the Younger Dryas resulted also in the production of the Main Lateglacial Shoreline (MLS) (Dawson 1982, 1984). The MLS consists of fragments of rock-cut platforms backed by a cliff found at a maximum of approximately 10–11 m OD near Oban, and declining away, with gradients of ~0.16 m km^{-1} towards the west, southwest and south, passing below present sea level around northeast Islay, western Mull, Kintyre and Arran. The area of submergence broadly agrees with the distribution of truncated drumlins observed in this study, although the gradient of the MLS is less steep than that of the drumlins. More recently, Smith *et al*. (2024) demonstrated through Gaussian trend surface analysis that the MLS forms an elongate, north–south-oriented uplift dome centred northwest of Loch Lomond, and show that this centre of maximum uplift differs from that of younger Holocene shorelines, providing strong evidence for a shifting of the locus of maximum uplift southeastwards after the Lateglacial. In addition, their residual analysis highlights that MLS deformation is not a simple planar tilt but exhibits regional asymmetry and local anomalies, implying more complex crustal responses than previously assumed, which can lead to the discrepancies between shoreline and truncated drumlin-based reconstructions and the numerical GIA models.

Conclusions

This study provides evidence that flat-topped, submerged drumlins in the Irish Sea and western Scotland are the result of coastal erosion during periods of lower RSL from the Lateglacial to the Early Holocene, followed by drowning during marine transgression. Alternative mechanisms such as glacial reworking or subtidal erosion are unlikely to account for the observed geomorphology. The depth distribution of truncated sediment drumlins offers a framework for identifying past sea-level minima, although these features should be interpreted as time-transgressive rather than fixed shoreline markers. Truncated drumlins do not provide direct chronological control and therefore cannot, on their own, be used to reconstruct revised RSL curves. However, they provide independent minimum limiting constraints on former RSL position over broad areas of the continental shelf. Such constraints complement traditional SLIPs by extending observations offshore into regions where dated sedimentary archives are scarce. Comparisons with existing GIA models reveal notable mismatches, indicating that current reconstructions may underestimate past sea-level lowstands in parts of Britain and Ireland. Overall, truncated drumlins represent an underutilized but effective proxy for reconstructing palaeo-sea levels, and their inclusion as an additional dataset for future GIA model calibration can significantly refine our understanding of post-glacial coastal evolution, particularly with respect to the magnitude and spatial pattern of post-glacial rebound and associated RSL minima.

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Author contributions. – RA: Conceptualization, validation, methodology, formal analysis and writing original draft. AF: Conceptualization, validation, funding acquisition and writing original draft. GM: Conceptualization, validation and writing—review and editing. DD: Validation and writing—review and editing.

Data availability statement. – Bathymetry data utilized in this study are freely downloadable at the websites indicated in the 'Data and methods' section. An Excel table containing the centroid coordinates of each drumlin and the statistics extracted is provided as Supporting Information.

References

Arosio, R., Dove, D., Ó Cofaigh, C. & Howe, J. A. 2018: Submarine deglacial sediment and geomorphological record of southwestern Scotland after the Last Glacial Maximum. *Marine Geology 403*, 62–79. https://doi.org/10.1016/j.margeo.2018.04.012.

Arosio, R., Gafeira, J., De Clippele, L. H., Wheeler, A. J., Huvenne, V. A. I., Sacchetti, F., Conti, L. A. & Lim, A. 2024: CoMMa: a GIS geomorphometry toolbox to map and measure confined landforms. *Geomorphology 458*, 109227. https://doi.org/10.1016/j.geomorph.2024.109227.

Arosio, R., Wheeler, A. J., Sacchetti, F., Guinan, J., Benetti, S., O'Keeffe, E., Van Landeghem, K. J. J., Conti, L. A., Furey, T. & Lim, A. 2023: The geomorphology of Ireland's continental shelf. *Journal of Maps 19*, 2283192. https://doi.org/10.1080/17445647.2023.2283192.

Ballantyne, C. K. 2002: Paraglacial geomorphology. *Quaternary Science Reviews 21*, 1935–2017. https://doi.org/10.1016/S0277-3791(02)00005-7.

Baranskaya, A. V., Khan, N. S., Romanenko, F. A., Roy, K., Peltier, W. R. & Horton, B. P. 2018: A postglacial relative sea-level database for the Russian Arctic coast. *Quaternary Science Reviews 199*, 188–205. https://doi.org/10.1016/j.quascirev.2018.07.033.

Black, S. K., Hughes, Z. J. & FitzGerald, D. M. 2025: Controls on coastal bluff erosion of a drowned drumlin field: Boston Harbor, Massachusetts. *Geomorphology 468*, 109490. https://doi.org/10.1016/j.geomorph.2024.109490.

Bradley, S. L., Ely, J. C., Clark, C. D., Edwards, R. J. & Shennan, I. 2023: Reconstruction of the palaeo-sea level of Britain and Ireland arising from empirical constraints of ice extent: implications for regional sea level forecasts and North American ice sheet volume. *Journal of Quaternary Science 38*, 791–805. https://doi.org/10.1002/jqs.3523.

Bradley, S. L., Milne, G. A., Shennan, I. & Edwards, R. 2011: An improved glacial isostatic adjustment model for the British Isles. *Journal of Quaternary Science 26*, 541–552. https://doi.org/10.1002/jqs.1481.

Brew, D. S. 2004: *Understanding and Predicting Beach Morphological Change Processes Associated with the Erosion of Cohesive Foreshores – Scoping Report*. 95 pp. Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme, Defra.

British Geological Survey 2022: *BGS Seabed Geology 10k: Anglesey Version 1.0. British Geological Survey. (Dataset)*. https://doi.org/10.5285/d2f2f8e8-8e97-40fb-9207-875563d0fec0.

Brooks, A. J., Bradley, S. L., Edwards, R. J., Milne, G. A., Horton, B. & Shennan, I. 2008: Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling. *Journal of Quaternary Science 23*, 175–192. https://doi.org/10.1002/jqs.1119.

Calder, B. R. & Mayer, L. A. 2003: Automatic processing of high-rate, high-density multibeam echosounder data. *Geochemistry, Geophysics, Geosystems 4*, 1046. https://doi.org/10.1029/2002GC000486.

Carter, R. W. G., Forbes, D. L., Jennings, S. C., Orford, J. D., Shaw, J. & Taylor, R. B. 1989: Barrier and lagoon coast evolution under differing relative sea-level regimes: examples from Ireland and Nova Scotia. *Marine Geology 88*, 221–242. https://doi.org/10.1016/0025-3227(89)90099-6.

Carter, R. W. G. & Orford, J. D. 1988: Conceptual model of coarse clastic barrier formation from multiple sediment sources. *Geographical Review 78*, 221. https://doi.org/10.2307/214179.

Carter, R. W. G., Orford, J. D., Forbes, D. L. & Taylor, R. B. 1990: Morphosedimentary development of drumlin-flank barriers with rapidly rising sea level, Story Head, Nova Scotia. *Sedimentary Geology 69*, 117–138. https://doi.org/10.1016/0037-0738(90)90104-2.

Carter, R. W. G., Orford, J. D., Jennings, S. C., Shaw, J. & Smith, J. P. 1992: Recent evolution of a paraglacial estuary under conditions of rapid sea-level rise: Chezzetcook Inlet, Nova Scotia. *Proceedings of the Geologists' Association 103*, 167–185. https://doi.org/10.1016/S0016-7878(08)80228-3.

Clark, C. D. & 37 others 2022: Growth and retreat of the last British–Irish Ice Sheet, 31 000 to 15 000 years ago: the BRITICE-CHRONO reconstruction. *Boreas 51*, 699–758. https://doi.org/10.1111/bor.12594.

Dawson, A. G. 1982: Late glacial sea-level changes and ice-limits in Islay, Jura and Scarba, Scottish Inner Hebrides. *Scottish Journal of Geology 18*, 253–265. https://doi.org/10.1144/sjg18040253.

Dawson, A. G. 1984: Quaternary sea-level changes in Western Scotland. *Quaternary Science Reviews 3*, 345–368. https://doi.org/10.1016/0277-3791(84)90012-X.

Dove, D., Arosio, R., Finlayson, A., Bradwell, T. & Howe, J. A. 2015: Submarine glacial landforms record Late Pleistocene ice-sheet dynamics, inner Hebrides, Scotland. *Quaternary Science Reviews 123*, 76–90. https://doi.org/10.1016/j.quascirev.2015.06.012.

Eyles, N., Putkinen, N., Sookhan, S. & Arbelaez-Moreno, L. 2016: Erosional origin of drumlins and megaridges. *Sedimentary Geology 338*, 2–23. https://doi.org/10.1016/j.sedgeo.2016.01.006.

Finlayson, A., Fabel, D., Bradwell, T. & Sugden, D. 2014: Growth and decay of a marine terminating sector of the last British–Irish Ice

Sheet: a geomorphological reconstruction. *Quaternary Science Reviews 83*, 28–45. https://doi.org/10.1016/j.quascirev.2013.10.009.
Finlayson, A., Merritt, J., Browne, M., Merritt, J., McMillan, A. & Whitbread, K. 2010: Ice sheet advance, dynamics, and decay configurations: evidence from west central Scotland. *Quaternary Science Reviews 29*, 969–988. https://doi.org/10.1016/j.quascirev.2009.12.016.
Flemming, B. W. 2024: The concept of wave base: fact and fiction. *Geo-Marine Letters 44*, 14. https://doi.org/10.1007/s00367-024-00776-3.
Forbes, D. L. & Syvitski, J. P. M. 1995: Paraglacial coasts. *In* Carter, R. W. G. & Woodroffe, C. D. (eds.): *Coastal Evolution*, 373–424. Cambridge University Press, Cambridge.
GEBCO Bathymetric Compilation Group 2026 2026: *The GEBCO_2026 Grid – A Continuous Terrain Model for Oceans and land at 15 arc-second intervals.* https://doi.org/10.5285/4F68D5C7-45EB-F999-E063-7086ABC036FA.
Goslin, J. & Clemmensen, L. B. 2017: Proxy records of Holocene storm events in coastal barrier systems: storm-wave induced markers. *Quaternary Science Reviews 174*, 80–119. https://doi.org/10.1016/j.quascirev.2017.08.026.
Greenwood, S. L. & Clark, C. D. 2009: Reconstructing the last Irish Ice Sheet 2: a geomorphologically-driven model of ice sheet growth, retreat and dynamics. *Quaternary Science Reviews 28*, 3101–3123. https://doi.org/10.1016/j.quascirev.2009.09.014.
Greenwood, R. O. & Orford, J. D. 2007: Factors controlling the retreat of drumlin coastal cliffs in a low energy marine environment—Strangford Lough, Northern Ireland. *Journal of Coastal Research 232*, 285–297. https://doi.org/10.2112/04-0417.1.
Greenwood, R. O. & Orford, J. D. 2008: Temporal patterns and processes of retreat of drumlin coastal cliffs—Strangford Lough, Northern Ireland. *Geomorphology 94*, 153–169. https://doi.org/10.1016/j.geomorph.2007.05.004.
Guilcher, A. 1962: Morphologie de la Baie de Clew (Comté de Mayo, Irlande). Note préliminaire. *Bulletin de l'Association de géographes français 39*, 53–65. https://doi.org/10.3406/bagf.1962.5581.
Himmelstoss, E. A., FitzGerald, D. M., Rosen, P. S. & Allen, J. R. 2006: Bluff evolution along coastal drumlins: Boston Harbor Islands, Massachusetts. *Journal of Coastal Research 225*, 1230–1240. https://doi.org/10.2112/06A-0005.1.
Kelley, J. T., Cooper, J. A. G., Jackson, D. W. T., Belknap, D. F. & Quinn, R. J. 2006: Sea-level change and inner shelf stratigraphy off Northern Ireland. *Marine Geology 232*, 1–15. https://doi.org/10.1016/j.margeo.2006.04.002.
Knight, J. 2016: Subglacial processes from drumlins in Clew Bay, western Ireland. *Earth Surface Processes and Landforms 41*, 277–288. https://doi.org/10.1002/esp.3865.
Knight, J. & Harrison, S. 2019: Paraglacial evolution of the Irish landscape. *Irish Geography 51*, 171–186. https://doi.org/10.55650/igj.2018.1370.
Lebrec, U., Riera, R., Paumard, V., O'Leary, M. J. & Lang, S. C. 2022: Morphology and distribution of submerged palaeoshorelines: insights from the North West Shelf of Australia. *Earth Science Reviews 224*, 103864. https://doi.org/10.1016/j.earscirev.2021.103864.
McCabe, A. M., Clark, P. U. & Clark, J. 2005: AMS 14C dating of deglacial events in the Irish Sea Basin and other sectors of the British–Irish ice sheet. *Quaternary Science Reviews 24*, 1673–1690. https://doi.org/10.1016/j.quascirev.2004.06.019.
McCabe, A. M. & Williams, G. D. 2012: Timing of the East Antrim Coastal Readvance: phase relationships between lowland Irish and upland Scottish ice sheets during the Last Glacial Termination. *Quaternary Science Reviews 58*, 18–29. https://doi.org/10.1016/j.quascirev.2012.10.012.
Merritt, J. W., Roberson, S. & Cooper, M. R. 2018: A critical review and re-investigation of the Pleistocene deposits between Cranfield Point and Kilkeel, Northern Ireland: implications for regional sea-level models and glacial reconstructions of the northern Irish Sea basin. *Proceedings of the Geologists' Association 129*, 583–609. https://doi.org/10.1016/j.pgeola.2018.04.001.
Moses, C. & Robinson, D. A. 2021: Intertidal cohesive foreshores: erosion rates and processes illustrated by a shore platform at Warden Point, Kent, UK. *Marine Geology 442*, 106658. https://doi.org/10.1016/j.margeo.2021.106658.
Oldale, R. N., Knebel, H. J. & Bothner, M. H. 1994: Submerged and eroded drumlins off northeastern Massachusetts. *Geomorphology 9*, 301–309. https://doi.org/10.1016/0169-555X(94)90051-5.
Ortiz, A. C. & Ashton, A. D. 2016: Exploring shoreface dynamics and a mechanistic explanation for a morphodynamic depth of closure. *Journal of Geophysical Research: Earth Surface 121*, 442–464. https://doi.org/10.1002/2015JF003699.
Peterson Becher, G. & Johnson, M. D. 2021: Sedimentology and internal structure of murtoos – V-shaped landforms indicative of a dynamic subglacial hydrological system. *Geomorphology 380*, 107644. https://doi.org/10.1016/j.geomorph.2021.107644.
Phillips, E., Everest, J. & Diaz-Doce, D. 2010: Bedrock controls on subglacial landform distribution and geomorphological processes: evidence from the Late Devensian Irish Sea Ice Stream. *Sedimentary Geology 232*, 98–118. https://doi.org/10.1016/j.sedgeo.2009.11.004.
Pinet, P. R. & McClennen, C. E. 1997: Drumlin-Bluff and Baymouth-barrier erosion along the southeastern shore of Lake Ontario, New York. *In* Rayne, T. W. & Bailey, B. J. (eds.): *Field Trip Guide for the 69th Annual Meeting of the New York State Geological Association*, 17–36. Hamilton College, Clinton.
Piper, D. J. W., Letson, J. R. J., De Iure, A. M. & Barrie, C. Q. 1983: Sediment accumulation in low-sedimentation, wave-dominated, glaciated inlets. *Sedimentary Geology 36*, 195–215. https://doi.org/10.1016/0037-0738(83)90009-X.
Plets, R. M. K., Callard, S. L., Cooper, J. A. G., Kelley, J. T., Belknap, D. F., Edwards, R. J., Long, A. J., Quinn, R. J. & Jackson, D. W. T. 2019: Late Quaternary sea-level change and evolution of Belfast Lough, Northern Ireland: new offshore evidence and implications for sea-level reconstruction. *Journal of Quaternary Science 34*, 285–298. https://doi.org/10.1002/jqs.3100.
Rink, G. M., Farrell, E. J. & Bromley, G. R. M. 2024: Quantifying aperiodic cliff top and cliff face retreat rates for an eroding drumlin on Ireland's Atlantic Coast using structure-from-motion. *Geosciences 14*, 165. https://doi.org/10.3390/geosciences14060165.
Roberts, M. J., Scourse, J. D., Bennell, J. D., Huws, D. G., Jago, C. F. & Long, B. T. 2011: Late Devensian and Holocene relative sea-level change in North Wales, UK. *Journal of Quaternary Science 26*, 141–155. https://doi.org/10.1002/jqs.1443.
Robertson, S. 2024: Newry – Northern Ireland Sheet 60/61/71. Quaternary Deposits.
Rosen, P. S. & Leach, K. 1987: Sediment accumulation forms, Thompson Island, Boston Harbor, Massachusetts. *In* Fitzgerald, D. M. & Rosen, P. S. (eds.): *Glaciated Coasts*, 233–250. Academic Press, San Diego.
Salt, K. E. & Evans, D. J. A. 2004: Superimposed subglacially streamlined landforms of southwest Scotland. *Scottish Geographical Journal 120*, 133–147. https://doi.org/10.1080/00369220418737197.
Scourse, J., Ward, S., Wainwright, A., Bradley, S., Wilson, J. K. & Guo, J. 2024: An interactive visualization and data portal tool (PALTIDE) for relative sea level and palaeotidal simulations of the northwest European shelf seas since the Last Glacial Maximum. *Journal of Quaternary Science 39*, 831–838. https://doi.org/10.1002/jqs.3615.
Shaw, J., Piper, D. J. W. & Taylor, R. B. 2002: The Geology of the Bras d'Or Lakes, Nova Scotia. *Proceedings of the Nova Scotian Institute of Science (NSIS) 42*, 21 pp. https://doi.org/10.15273/pnsis.v42i1.3595.
Shennan, I., Bradley, S. L. & Edwards, R. 2018: Relative sea-level changes and crustal movements in Britain and Ireland since the Last Glacial Maximum. *Quaternary Science Reviews 188*, 143–159. https://doi.org/10.1016/j.quascirev.2018.03.031.
Shennan, I., Hamilton, S., Hillier, C., Hunter, A., Woodall, R., Bradley, S., Milne, G., Brooks, A. & Bassett, S. 2006: Relative sea-level observations in western Scotland since the Last Glacial Maximum for testing models of glacial isostatic land movements and ice-sheet reconstructions. *Journal of Quaternary Science 21*, 601–613. https://doi.org/10.1002/jqs.1048.
Smith, D. E., Firth, C. R. & Rose, J. 2024: Patterns of glacio-isostatic adjustment in mainland Scotland: new data from western central Scotland, proximal to the zone of maximum rebound. *Boreas 53*, 262–281. https://doi.org/10.1111/bor.12650.

Spagnolo, M., Clark, C. D. & Hughes, A. L. C. 2012: Drumlin relief. *Geomorphology 153–154*, 179–191. https://doi.org/10.1016/j.geomorph.2012.02.023.

Stea, R. R. & Brown, Y. 1989: Variation in drumlin orientation, form and stratigraphy relating to successive ice flows in southern and central Nova Scotia. *Sedimentary Geology 62*, 223–240. https://doi.org/10.1016/0037-0738(89)90117-6.

Stewart, H. A., Bradwell, T., Carter, G. D. O., Dove, D. & Gafeira, J. 2021: Geomorphology of the Continental Shelf. *In* Ballantyne, C. K. & Gordon, J. E. (eds.): *Landscapes and Landforms of Scotland*, 117–134. World Geomorphological Landscapes. Springer International Publishing, Cham.

Trenhaile, A. S. 2002: Rock coasts, with particular emphasis on shore platforms. *Geomorphology 48*, 7–22. https://doi.org/10.1016/S0169-555X(02)00173-3.

Vacchi, M., Engelhart, S. E., Nikitina, D., Ashe, E. L., Peltier, W. R., Roy, K., Kopp, R. E. & Horton, B. P. 2018: Postglacial relative sea-level histories along the eastern Canadian coastline. *Quaternary Science Reviews 201*, 124–146. https://doi.org/10.1016/j.quascirev.2018.09.043.

Van Landeghem, K. J. J. & Chiverrell, R. C. 2020: Bed erosion during fast ice streaming regulated the retreat dynamics of the Irish Sea Ice Stream. *Quaternary Science Reviews 245*, 106526. https://doi.org/10.1016/j.quascirev.2020.106526.

Van Landeghem, K. J. J., Wheeler, A. J. & Mitchell, N. C. 2009: Seafloor evidence for palaeo-ice streaming and calving of the grounded Irish Sea Ice Stream: implications for the interpretation of its final deglaciation phase. *Boreas 38*, 119–131. https://doi.org/10.1111/j.1502-3885.2008.00041.x.

Ward, S. L., Neill, S. P., Scourse, J. D., Bradley, S. L. & Uehara, K. 2016: Sensitivity of palaeotidal models of the northwest European shelf seas to glacial isostatic adjustment since the Last Glacial Maximum. *Quaternary Science Reviews 151*, 198–211. https://doi.org/10.1016/j.quascirev.2016.08.034.

Wessel, P. & Smith, W. H. F. 1996: A global, self-consistent, hierarchical, high-resolution shoreline database. *Journal of Geophysical Research: Solid Earth 101*, 8741–8743. https://doi.org/10.1029/96JB00104.

Westley, K., Quinn, R., Forsythe, W., Plets, R., Bell, T., Benetti, S., McGrath, F. & Robinson, R. 2011: Mapping Submerged Landscapes Using Multibeam Bathymetric Data: a case study from the north coast of Ireland: mapping submerged landscapes using multibeam bathymetric data. *International Journal of Nautical Archaeology 40*, 99–112. https://doi.org/10.1111/j.1095-9270.2010.00272.x.

Williamson, S. 2021: *Geomorphological Investigation of Submarine Glacial Landforms off the Northeast of Ireland*. Master's thesis, University of Ghent, 49 pp.

Supporting Information

Additional Supporting Information to this article is available at http://www.boreas.dk.

Table S1. Complete statistics calculated for the drumlin dataset.