

Complex palaeo-ice sheet dynamics in northeast Ireland during the retreat and reorganisation of the central British-Irish Ice Sheet

Alexander M. Clark^{a,b,*,1}, Bethan J. Davies^c, Sam Roberson^{d,e}, Simon P.E. Blockley^a,
Adrian P. Palmer^a, Magret Damaschke^b

^a Department of Geography, Royal Holloway University of London, Egham, Surrey, United Kingdom

^b British Geological Survey, Keyworth, Nottinghamshire, United Kingdom

^c School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, United Kingdom

^d Geological Survey of Northern Ireland, Belfast, United Kingdom

^e British Geological Survey, Edinburgh, United Kingdom

ARTICLE INFO

Keywords:

British-Irish Ice Sheet
Flow lineations
Photogrammetry digital surface model
Northern Ireland

ABSTRACT

Improving our understanding of the marine- to terrestrial-based transition of the last British-Irish Ice Sheet (BIIS) is crucial for assessing future ice sheet loss in analogous regions of contemporary ice sheets. Current palaeo-ice sheet reconstructions constrain the nature of BIIS wastage from its maximum extents well from c. 27 ka BP during a period of sea level rise and ice sheet instability. However, the drivers and influences of deglaciation from c. 20 ka BP as the BIIS separated into separate, terrestrial-based ice domes amid rapid, high-magnitude climate change remain a challenge to unravel. This study investigates palaeo-ice sheet dynamics in northeast Ireland pertaining to the reorganisation of the central BIIS to constrain and untangle these drivers. A 0.4 m horizontal resolution digital surface model was employed to map 12,979 glacial landforms over a 3905 km² study area in Northern Ireland. New sedimentological analyses are combined to interrogate palaeo-ice sheet dynamics through a relative chronological framework of six 'flow stages' that unravel the deglaciation of the central BIIS c. 20–15 ka. Intrinsic drivers such as meltwater drainage, ice sheet thinning, and ice divide migration heavily influenced the collapse of a major ice divide over northeast Ireland, as well as the initiation of an ephemeral ice stream at its margins. Irish ice dispersing from lowland and upland centres decayed during full stadial conditions as Scottish ice readvanced from a better nourished source, stabilising along the Irish coast. However, more absolute ages are required to better understand these complex, contrasting dynamical behaviours.

1. Introduction

The western margins of last British-Irish Ice Sheet (BIIS) rapidly retreated from their maximum extent on the continental shelf after c. 27 ka BP (Clark et al., 2022). Ice sheet dynamics, climate change, and high relative sea levels played an important role in early marine-based disintegration (Callard et al., 2018; Ó Cofaigh et al., 2021; Tarlati et al., 2020) and ice stream instability (Bradwell et al., 2021; Roberts et al., 2020) as major outlets with calving margins episodically receded to topographically restricted, semi-grounded positions c. 26–17 ka BP (Benetti et al., 2021; Callard et al., 2018; Chiverrell et al., 2018, 2013; Roberts et al., 2020).

Between the global Last Glacial Maximum (c. 20 ka BP, Clark et al.,

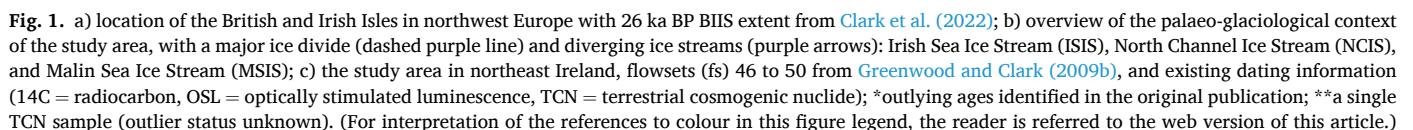
2009b) and the Late Glacial (c. 15 ka BP, Hoek, 2008; Lowe et al., 2008), the ice sheet evolved rapidly, reorganising and splitting into separate British and Irish ice sheets. Important advances in reconstructions of the last BIIS in recent years (Clark et al., 2022; Ely et al., 2024; Hughes et al., 2016) have highlighted the significance of intrinsic forcings, such as the influence of ice stream collapse on adjacent major ice centres, and external forcings, such as sea level rise and abrupt climate change. However, these remain poorly resolved in the northern Irish Ice Sheet prior to the Late Glacial, during a period of rapid climate and sea-level change. Tackling these questions is vital for understanding potential future trajectories of contemporary ice sheets, which will likely experience similarly complex behaviours as they shrink and split during their transition into more terrestrial-based ice masses.

* Corresponding author at: Department of Geography, Royal Holloway University of London, Egham, Surrey, United Kingdom.

E-mail address: alexander.clark@universityofgalway.ie (A.M. Clark).

¹ Present address: Department of Geography, University of Galway, Galway, Ireland.

Irish Sea and Malin Sea Ice Streams, which experienced rapid, unstable disintegration after c. 25–20 ka BP (Benetti et al., 2021; Tarlati et al., 2020; Van Landeghem and Chiverrell, 2020). A major ice divide straddling northeast Ireland and southwest Scotland then deteriorated after c.



20 ka BP, unzipping down the North Channel and separating the Irish and British sectors. This is thought to have preceded the rapid wastage of terrestrial-based ice from western (Bromley et al., 2026; Foreman et al., 2025, 2022) and central Ireland (Delaney et al., 2026) c. 17.5–16.7 ka BP, as well as multiple readvances of Scottish ice across the northern Irish Sea Basin (Chiverrell et al., 2018; Finlayson et al., 2014; Knight, 2004; McCabe and Williams, 2012; Merritt et al., 2018), before ice became restricted to upland centres c. 15 ka BP.

In this study, we produce a highly detailed geomorphological map of glacial landforms over a 3905 km² region of northeast Ireland. Process-form models produced from new geomorphological and sedimentological evidence are employed to investigate palaeo-ice sheet dynamics in unparalleled detail. A ‘flow stage’ reconstruction is presented using morphostratigraphic principles to better illuminate climatic, dynamic, and environmental drivers of as the BIIS approached complete demise. These high-resolution reconstructions are vital for informing and validating numerical models (Ely et al., 2024, 2021), especially during the period from c. 20–15 ka BP, when the Irish Ice Sheet drastically transformed from a marine-based to a terrestrial-based ice sheet during a period of rapid climatic, sea-level, and environmental change.

2. Study area

2.1. Geographical and geological context

Our study area encompasses a generally low-relief region of northeast Ireland between Belfast and the north coast of Northern Ireland with a rich geological and palaeoglaciological history (Fig. 1). Extensive early Palaeocene volcanism formed a series of resistant flood basalts c. 62–58 Ma that now form the Antrim Plateau (Cooper et al., 2026; Lyle and Thompson, 1983), lying >100 m ordnance datum (OD) between Belfast and the north coast of Co. Antrim (Fig. 1). These basalt strata directly overlie the less competent (Late Cretaceous) Ulster White Limestone Formation, now narrowly exposed exclusively on the southern and eastern boundaries of the plateau. Widespread faulting, (glacial) erosion, and preservation of dense intrusive dolerite plutons (Mitchell et al., 2010; Patterson, 1951; Preston, 1963) have helped shape the Antrim Hills, peaking at Trostan (550 m OD), and the Belfast Hills, peaking at Divis (478 m OD). The Antrim Hills descend into the glacially scoured Antrim Glens on the east coast and are bisected by the Braid and Six Mile Water valleys. The Belfast Hills provide a striking drop into the valley of the Lagan River which has been eroded into Triassic to Jurassic mudstones and sandstones.

Lough Neagh, the largest freshwater lake in the British and Irish Isles, occupies an extensive subsiding Oligocene basin comprising the Lough Neagh Clays Group (Mitchell, 2005), and is drained by the Lower River Bann into the Malin Sea through a wide valley between the Antrim Plateau and Sperrin Mountains. Lough Neagh Clays also rest unconformably on the 150 km-long Omagh-Tow Valley Fault (Anderson et al., 2016; Mitchell, 2005), which itself creates a relatively sharp topographic barrier east of Ballymoney now occupied by the Bush River (Fig. 1c).

A Dalradian (800–545 Ma) basement (Cooper and Johnston, 2005; Thomas et al., 2004) of brittle psammite and semipelite strata thrown by multiple faults are exposed over c. 390 km² in the north Antrim Hills. The Late Devonian Cushendun granodiorite (Cooper and Mitchell, 2005) pierces through these older formations as a subtle, rounded prominence, and is found as erratic cobbles along the east coast (Charlesworth, 1938; Hill and Prior, 1968).

2.2. Palaeoglaciological context

Our current understanding of palaeo-ice sheet dynamics in northeast Ireland is fundamentally informed by flowlines and flowsets (Fig. 1) of groups of drift-cored drumlins (Greenwood and Clark, 2009a, 2009b) mapped from 15 to 30 m LANDSAT 7 imagery (Greenwood and Clark,

2008), 233 glacial striae observed on bedrock surfaces (Smith et al., 2008; Smith and Knight, 2011), and erratic trains (Charlesworth, 1938; Syngé and Stephens, 1966). Higher resolution (10 m and 5 m) imagery has been used to provide more detailed insights into meltwater drainage routes (Stoker et al., 2021) and readvance extent (McCabe and Williams, 2012), albeit in more restricted regions. These works have been crucial in formalising key stages of deglaciation debated by earlier ground-based studies (Charlesworth, 1938; Creighton, 1974; Derryhouse, 1923; Hill and Prior, 1968). Nevertheless, insights into landform associations and their application for reconstructing palaeo-ice sheet dynamics are not well-understood.

The relative timing of the most significant stages of deglaciation in northeast Ireland (and how they relate to nearby regions) as proposed by Greenwood and Clark (2009a) is shown in Fig. 1c and is the generally accepted paradigm. These flowsets are in turn anchored in absolute time by a sparse suite of dates (Fig. 1c). The flow of ice northeast from Lough Neagh (fs50) and south from the Malin Sea (fs46) are generally considered the oldest flow stages in the region, with deglacial terrestrial cosmogenic nuclide and OSL ages of c. 17.5–23.6 ka BP (Fig. 1c, Benetti et al., 2021; Bowen et al., 2002). Radiocarbon minimum-bounding constraints from Belfast Lough (Plets et al., 2019), Sluggan Bog (Lowe et al., 2004; Walker et al., 2012), and Rough Island (McCabe et al., 1998) suggest deglaciation and marine transgression following fs50 and overprinting flow stages of the ‘East Antrim Coastal Readvance’ (fs47–49, Finlayson et al., 2014; McCabe and Williams, 2012) must have occurred by c. 14.3–15.7 ka BP.

Dated landform-derived flowsets have been incorporated into model-data comparison exercises and computer model experiments (Clark et al., 2022; Ely et al., 2024). However, these reconstructions are typically attached with large spatiotemporal uncertainties (Clark et al., 2022) as existing chronological and geomorphological datasets struggle to accord. Landforms associated with many flow stages are often truncated, fragmentary, or isolated such that interconnected palaeo-ice sheet dynamics are often assumed based on what might be broadly glaciologically feasible (e.g. Knight, 2004; Stephens et al., 1975). This highlights the need for a more detailed understanding of the geomorphology and morphostratigraphy of this key area for unravelling the nature of deglaciation of the central BIIS.

3. Materials and methods

Digital mapping of glacial landforms across our 3905 km² study area used a 0.4 m horizontal resolution photogrammetry digital surface model (DSM) produced in 2017–2020 by the Ordnance Survey of Northern Ireland. A maximum horizontal resolution of 0.4 m is maintained with a root mean square error of 0.66 m (Ordnance Survey of Northern Ireland, 2024a). This resolution is achieved through photogrammetric analysis of orthophotos with pixel sizes of 25 cm, 16 cm, or 10 cm and a root mean square error of 0.26 m (Ordnance Survey of Northern Ireland, 2024b). A photogrammetry DSM cannot detect the ground surface beneath tree canopies, meaning forest cover inevitably disguises some glacial landforms. However, dense forest covers only ~3% of our study region and so presents little hinderance.

We employed a focussed thematic mapping approach in the study region, concentrating on digitally mapping glacial landforms supplemented by selective ground-truthing where possible (see Chandler et al., 2018). Landform identification and description (Table 1) were informed by our understanding of glacial landform formation processes, as well as previous investigations of similar landforms in the region and elsewhere in Ireland (e.g. Delaney et al., 2018; Greenwood and Clark, 2008; McCabe and Williams, 2012).

Sedimentary analyses at key exposures associated with glacial landforms (where possible) were obtained during field surveys from June 2022 to June 2024. Clast shape (Benn and Ballantyne, 1993; Sneed and Folk, 1958) and lithology data were obtained from key sedimentary units which were logged and photographed. C₄₀ and RA indices (Benn

and Ballantyne, 1994), RWR index (Lukas et al., 2013), and mean roundedness quantifications are used to investigate transport pathways through a glacier and more effectively discriminate between sedimentary environments (following Benn and Lukas, 2021).

Landform maps and sedimentological analyses are combined to develop sediment-landform assemblage associations which aid the development of process-form models for investigating palaeo-ice sheet dynamics at the ice-bed interface. We then apply a morphostratigraphic approach to the study of the relative timing of palaeo-ice sheet events. This provides insights into the complex evolution of the central BIIS through time through the production of updated and revised flow stages (e.g. Delaney et al., 2018; Greenwood et al., 2024; Greenwood and Clark, 2009a). Efforts to anchor these flow stages on absolute time-scales using a multi-proxy geochronological approach are underway and will be the focus of future papers.

4. Results and interpretations

4.1. Glacial geomorphology and sedimentology

Digital mapping of the study area allowed us to identify and map a total of 12,979 individual glacial landforms (Fig. 2). This is the largest compendium of glacial landforms in the region to date compared to previous datasets compiled through digital mapping (Greenwood and Clark, 2008), all belonging to a total of 25 landform and sediment types (Table 1). High-resolution mapping has allowed for detailed metrics (e.g. height, width, elevation, elongation ratio, sinuosity) to be accurately obtained which are useful for understanding ice-bed interface and ice-margin dynamics (e.g. Clark et al., 2009a; Spagnolo et al., 2014; Vérité et al., 2023).

4.2. Subglacial assemblage

4.2.1. Streamlined topography

A series of streamlined, plucked, and somewhat elongated topographic features were identified (Fig. 3a, b) and broadly characterised as 'streamlined topography'. Flat-topped, stepped bedrock features are interpreted as roches moutonnées. These features range in size from meso-scale c. 30 m wide forms (Fig. 3a) to macro-scale c. 670 m wide forms plucked from basalt or dolerite bedrock in the Antrim Hills c. 130–430 m OD. Their concentration at higher elevations is consistent with other regions of Ireland (Ballantyne et al., 2007; Meehan, 1999; Wilson, 2004) and implies abrasion and quarrying occurred under thin, warm-based ice with fluctuating meltwater pressures (Iverson, 1991; Sugden, 1992).

Kilometre-scale asymmetrical streamlined features with some degree of alignment were also identified and interpreted as 'streamlined shields' (Fig. 3b). These 44 bedforms comprise wide hills with steep stoss sides and relatively shallow lee sides, similar to mega-rock drumlins (Krabbendam et al., 2016) but less elongated. Though originally identified here by McCabe and Williams (2012), they are not described elsewhere in Ireland. They may indicate the persistence of thick and erosive ice (e.g. Hall et al., 2013), potentially over multiple glacial cycles. There also appears to be a geological control on their morphology, with stoss sides typically marking the edge of a basalt escarpment and their lee side slopes emphasised by dipping basalt strata (Fig. 3b).

4.2.2. Glacially modified valley heads

Concave valley backwalls (Fig. 3c) located at the highest elevations of the study area are interpreted as glacially modified valley heads. These features are exclusively present at elevations of 350–490 m OD on the flanks of the highest peaks in the north Antrim Hills. They differ from purely fluvial valley heads by their relatively tall (30–120 m) 6–25° backwall slopes and amphitheatre-like morphologies. Moreover, subtle morainic features are present 1.7–2.2 km downslope of these backwalls (Fig. 3c). By contrast, fluvial valleys in the area are absent of such

moraines and slope very consistently at <10°. However, glacially modified valley head slopes fail to reach the ~30° minimum for classification as a 'cirque' (Evans, 2006; Haynes, 1968) and typical bowl-shaped depressions at the foot of these slopes are absent or obscured.

Glaciers typically scour valley heads over repeated glaciations primarily through quarrying (Hooke, 1991; MacGregor et al., 2009; Rapp, 1984) to form cirques. However, glacial scouring in the Antrim Hills appears to have been a less significant or more transient process as environmental, climatic, and glaciological conditions and feedback mechanisms (e.g. Barr et al., 2019; Delmas et al., 2014; Evans, 2006; Hooke, 1991; Oien and Kurjański, 2026) were not conducive to cirque excavation. Consequently, these glacially modified valley heads may represent particularly short-lived phases of glaciation in the Antrim Hills.

4.2.3. Ribbed moraines

A variety of broad, sinuous, low-lying ridges are interpreted as subglacial ribbed (Rogen) moraines. These 394 bedforms exhibit a range of sinuous, chevron-shaped, rounded, and circular forms (see Dunlop and Clark, 2006), occasionally superimposed by flutings (Fig. 4a) or tightly packed drumlinoid forms (Fig. 4b). They are typically located on gently sloping valley sides where they are often scattered amongst, and superimposed by, drumlin swarms.

Ribbed moraines form over decades as cold-based ice frozen to its bed fractures and moulds underlying till sheets as it begins to transition to a warm-based ice mass (Ely et al., 2023; Hätterstrand and Kleman, 1999). Ribbed moraine morphology and spatial distribution in the study region implies a range of formation mechanisms operated during spatially complex transitions in thermal regime under a morphological continuum (Vérité et al., 2023), rather than just formation under cold-based ice (Lundqvist, 1989) at the head of ice sheet outlets. Mega-scale glacial lineations and megaflutes are found overlying subglacial ribs (e.g. Greenwood et al., 2024) adjacent to less sinuous ribs on topographic highs, revealing sharp lateral gradients in ice sheet velocity and thermal regime (Vérité et al., 2021) influenced by topography. Increased flow velocity or a shift in ice column shear stress patterns result in the 'drumlinised' ribbed forms (Clark and Meehan, 2001; Greenwood et al., 2017) found throughout the study area.

4.2.4. Drumlins

A suite of 3025 elongated mounds 100–1300 m long and 40–345 m wide were interpreted as drumlins. Drumlins are commonly located in valley settings where they typically cluster in *en echelon* patterns (e.g. Hill, 1973) or large chains transverse and oblique to inferred ice flow direction (Fig. 4c), especially in wide valley and plateau settings where they also often deflect around minor topographic highs. Drumlins in more confined valleys are strongly topographically restricted, oriented aligned to valley sides, and may terminate in latero-frontal moraines, raised glaciofluvial deposits, or esker swarms.

Drumlins form and grow beneath polythermal and warm-based ice masses, moulding subglacial transverse ridges into elongated mounds oriented in the direction of ice flow where basal till is allowed to deform (Ely et al., 2023; Ely et al., 2018; Fowler, 2000; Stokes et al., 2013). Drumlin distributions and concentrations in our study region imply erosive warm-based ice persisted throughout deglaciation but was thin enough to be influenced by gently undulating underlying topography. Consistent elongation ratios of around 3.1 ± 0.9 (1σ) fall within the typical range of drumlins found in Britain (Clark et al., 2009a), and may be partly controlled by the heterogeneity of the underlying bedrock geology and subsequent production of basalt-dominated glacial till (Creighton, 1974). Drumlins are on average up to twice as elongated as those formed from low-permeability, laterally variable Ordovician greywacke-dominated tills in neighbouring Co. Down to the southeast (Hill, 1973; Vernon, 1966). Drumlin width measurements, and therefore elongation ratios, are not available for most drumlins in Ireland (Clark et al., 2009a; Greenwood and Clark, 2008), precluding further

Table 1

Inventory of landforms mapped and sediments logged in the study area, with descriptions of key features and morphometries.

Landform or sediment	Occurrences	Description
Subglacial assemblage		
Aligned streamlined topography	649	Bedrock-cored lineations. Typically 10–1000 m in length and only up to a few metres tall, though the largest features are up to 2.7 km long and 55 m tall. Development of the largest features appears to be facilitated by the erosion of large faults.
Roche Moutonnées	31	Subtle step-like bedrock features with meso-scale forms in the order of ~30 m wide and ~1–5 m tall (Fig. 3a), and macro-scale forms up to ~670 m wide and tens of metres tall. Restricted to the Antrim Hills at 130–430 m OD over basaltic bedrock. No striations on the upper polished surface.
Streamlined Shields	44	Shield-like forms (Fig. 3b) are typically 0.5–4.5 km wide (a axis) and 0.2–0.8 km deep (b axis) and found at a range of elevations (43–415 m OD). 93% comprise basaltic bedrock.
Glacially Modified Valley Heads	7	Curvilinear bedrock exposures descending into basin-like depressions at valley heads. Short/ shallow, concave forms are harboured at maximum elevations of 450 m OD (north flank of Trostan) to 490 m OD (northern and eastern flanks of Slievenanee). Steeper horseshoe-shaped valley heads present at 350–450 m OD on the northern flanks of Slieveanorra (Fig. 3c).
Ribbed (Rogen) Moraine	394	Usually found on minor topographic highs and gently sloping valley sides (Fig. 4), most commonly at elevations of 50–60 m OD, 90–115 m OD, and 140–145 m OD.
Drumlins	3025	Tear- and cigar-shaped mounds are most common, with more elliptical forms also quite frequent (Fig. 4c). Mounds typically peak in height towards the centre or up-ice end. Drumlins are 103–1301 m long (424 m mean average) and 39–346 m wide (142 m mean average) with elongation ratios of 1.4–9.2 (3.1 ± 0.9 1 σ). Elevational distribution between 13 and 344 m OD; 99% of drumlins are found <258 m OD.
Crag and Tails	25	Around 148–636 m long (368.7 m mean average) and 45–196 m wide (110.3 m mean average), with elongation ratios of 1.8–6.8 (3.4 ± 1.2 1 σ).
Megaflutes	90	Around 700 m long and 77 m wide on average with elongation ratios of 5–21. Usually not tapered at one or both ends. Found superimposed on or adjacent to ‘evolved’ ribbed moraine morphologies (Fig. 4a) and down-ice from bedrock prominences (Fig. 4d).
Mega-Scale Glacial Lineations	71	Highly elongated mounds reaching up to 2.2 km in length (Fig. 4d). Larger features may reach ~10 m tall and appear to be bisected by channels.
Uncategorised Glacial Lineations	280	Subdued linear mounds with drumlin-like morphologies but with subtle slope breaks, 81–785 m long (313 m mean average).
Subglacial Traction Till	2	Typically clast-rich with a silty matrix. Clasts are predominantly sub-angular (26–30%) to sub-rounded (12–24%); C ₄₀ of 8–22%, RA of 4–16%, RWR of 2–6%; striations on 0–3% of clasts (Fig. 5b)
Ice-marginal assemblage		
Complex/Composite Ridge(s)	1 complex of 16 ridges	Ridges are 5–72 m tall and 0.3–2.0 km wide and frequently cut by channels. Small moraine ridge crests and hummocks are superimposed on the widest ridges (Fig. 6a). Ridges at lower elevations (<50 m OD) lie adjacent to or underneath relatively flat-topped deposits.
Latero-Frontal Moraines	6 complexes of 123 ridges	Curvilinear features reaching 10–15 m tall and 300–650 m wide (cross-profile) at their frontal sections and 5–10 m and 50–150 m wide on their lateral sections. Occasionally superimposed by minor transverse ridges and hummocks or cut by meltwater channels (Fig. 6b).
Moraine Ridges (uncategorised)	1328	A range of raised, undulating, sharp- and round-crested, aligned ridges reaching up to 10 km ² in area (Fig. 6b, c). Ridges are typically 1–50 m tall and reach hundreds of metres wide.
Moraine Ridge Crests	2178	Apex of moraine ridges, where identified. Most ridge crests are fragmented, typically occurring as 15–350 m-long features which may form parts of longer chains reaching 1–3 km in length. Very few crests >1 km in length have been preserved and are typically clustered amongst the widest (~800–1600 m) moraine ridges.
Minor Transverse Ridges	357	Very subtle (~0.5–2.0 m tall), straight (sinuosity index of <0.1) ridges, often forming larger chains of ridges creating a corrugated appearance (Fig. 5a).
Hummocky Moraines	2005	Clast-rich with silty matrix. Clasts are exclusively angular to sub-rounded; C ₄₀ of 12%, RA of 16%, RWR of 0%; no striations. See Fig. 5b
Glaciofluvial assemblage		
Meltwater Channels	1628	Always found in groups, typically arranged in valley-aligned corridors (Fig. 6b), small amorphous clusters, or form larger aligned ridges. Occasionally superimposed on larger moraine ridges (e.g. complex ridges, Fig. 6a).
		Deep, abandoned channels with a variety of sinuous morphologies on valley beds and sides (Fig. 7a). Decimetre- to metre-scale N-channels found carved into bedrock (Fig. 7b) and gravelly channel infills (Fig. 7c) discovered in the field.
		Meltwater channels are classed as marginal (n = 910, 16–1789 m long, SI = 1.00–1.40), subglacial (n = 605, 46–4110 m long, SI = 1.00–1.54), or pro-glacial (n = 113, 109–6534 m long, SI = 1.01–1.33). Channels mainly form over Palaeocene basalt bedrock/ till (86%) or Dalradian schistose bedrock/ till (10%); channel length and sinuosity are very similar across these bedrock and substrate types.
Eskers	282	A variety of ridge lengths (30 m to 1.8 km, 300 m mean average) identified. Sinuosity Index is very consistent (1.0–1.2), except one example (7.5). Always found <200 m OD (93% are <120 m OD). Rarely found parallel or oblique to underlying slope dip direction. Single-crested and multi-crested examples mapped in the Lower Bann valley.
Raised Glaciofluvial Landforms	322	Flat-topped and gently undulating, occasionally dipping landforms typically found in valley-bottom settings near present water courses (Figs. 7d, e, 8a). Often comprise massive or rippled sands or laterally discontinuous gravel facies (Fig. 8b). Landforms are 972 m ² to 5.3 km ² in area with almost all sitting at 6–230 m OD.
Glaciolacustrine assemblage		
Deltas	30	Best preserved in the Carey Valley where they are flat-topped and have steep slopes. Meltwater channels and kettle holes are present on the surface of some deltas.
Fans	1	A 2 km ² feature in the Lower Bann valley with a narrow (~250 m) southwestern end that fans out into a 2.2 km-wide form. Features a 0.6% surface gradient sloping generally northeast.
Lake Bottom Deposits	10	Generally flat-topped or gently dipping, low-relief landforms up to 2.9 km ² in area confined to valley bottom settings. Contain fine-grained (often laminated) lake bottom deposits (e.g. Derryhouse, 1923; Kilroe, 1913).

(continued on next page)

Table 1 (continued)

Landform or sediment	Occurrences	Description
Uncategorised Raised Glaciolacustrine Deposits	42	Flat-topped or gently dipping, low-relief landforms reaching up to 1.8 km ² in area typically identified on valley sides. Superficial geology maps suggest they comprise fine-grained material. Likely a mixture of deltas and lake bottom deposits.
Shorelines	41	Subtle ridges of 0.1–1.3 km in length and 0.5–12.5 m in height, or shallow (a few metres) but wide (10–100 m) erosional benches. Generally restricted to the northern and eastern shores of Lough Neagh, most commonly at elevations of 14–18 m OD.

comparisons.

4.2.5. Crag and tails

Asymmetric elongated mounds with bedrock-cored summits, steep stoss sides and shallow lee sides are interpreted as crag and tails. These mounds are of a similar size and shape to drumlins (Table 1) and are typically found amongst drumlin fields.

Crag and tails can form from kilometre-wide stepped bedrock surfaces (Krabbendam and Bradwell, 2011; Livingstone et al., 2015) and volcanic intrusions (Evans and Hansom, 1996; Sissons, 1971). The small collection of 25 crag and tails in our study region appear to have similar origins, except at smaller scales. Their distribution amongst drumlin fields is typical in other formerly glaciated regions (Greenwood and Clark, 2008; Hall and Riding, 2016; Norris et al., 2017) and suggests they formed during the same or similar stage of persistent warm-based ice cover.

4.2.6. Megaflutes

Small clusters of highly elongated, low-relief mounds (90 in total) are interpreted as megaflutes. These bedforms are predominantly found either superimposed on highly sinuous ribbed moraines (Fig. 4a), or down-ice of substantial bedrock prominences amongst other highly elongated subglacial bedforms (Fig. 4d). Where they form clusters, ridge-to-ridge spacing varies from 70 m to 275 m; more isolated megaflutes can be separated by ~450–850 m amongst drumlin swarms. Megaflutes are occasionally bisected by meltwater channels but otherwise show no signs of overriding or modification.

Megaflutes are considered a geomorphological evolution of drumlin forms, rather than larger versions of flutes formed in cavities on the lee side of subglacial obstacles (Boulton, 1976; Gordon et al., 1992; Rose, 1989). Elongation ratios of 5–22 in our study region are comparable to ranges (around 6–25) found in regions of former high-velocity flow (Bradwell et al., 2008; Everest et al., 2005; Geldard et al., 2024), distinguishable from typical drumlin elongation ratios of 1.7–4.1 (Clark et al., 2009a). These properties suggest they may have primarily formed during fast flow conditions either distal to an ice divide, under a palaeo-ice stream, or under a surge-type glacier (Bradwell et al., 2008; Delaney et al., 2018; Evans et al., 2008, 2005; Everest et al., 2005; Eyles, 2012; Van Landeghem and Chiverrell, 2020; Vêrité et al., 2021). Megaflute distribution in the Lower Bann valley (Fig. 4a) is particularly reminiscent of formation and modification under a palaeo-ice stream (Vêrité et al., 2021). However, their location down-ice of large bedrock prominences (Figs. 3b, 4d) suggests their formation is also influenced by elevated stoss-side friction from kilometre-scale subglacial obstacles (Boulton, 1976; Geldard et al., 2024).

4.2.7. Mega-scale glacial lineations

Kilometre-scale, highly elongated mounds are interpreted as mega-scale glacial lineations (MSGs). Like megaflutes, MSGs are occasionally found superimposed on evolved ribbed moraines (Fig. 4a) or amongst swarms of other elongated bedforms such as drumlins (Fig. 4d). MSGs are distinguished from megaflutes by their size (mostly >1 km in length and >70–100 m in width) and elongation ratios (generally >15). However, it is recognised that there may be some overlap in definition and metrics between the two bedforms. MSGs are frequently located up-ice of bulldozed moraine ridges and superimposed by glaciofluvial

glaciolacustrine landforms in topographic lows.

MSGs are gradually moulded from less elongated bedforms (Ely et al., 2023; Spagnolo et al., 2014) during persistent, high-velocity flow facilitated by plastic bed deformation, typically under ice streaming conditions (Clark, 1993; Clark and Stokes, 2013; Spagnolo et al., 2016; Stokes and Clark, 2001). Along with the presence of megaflutes, MSGs in the study region support the persistence of episodes of high-velocity flow during deglaciation of a warm-based ice mass, especially in topographic lows, assisted by deforming beds (Fig. 4a).

4.3. Ice-marginal assemblage

4.3.1. Minor transverse ridges

A total of 357 low-relief, round-crested, <2 m tall, 100–270 m long ridges found in large, corrugated clusters or chains (Fig. 5a) are interpreted as minor transverse ridges. Ridges are often associated with larger (latero-)frontal moraines, especially where they form down-ice of highly elongated bedforms (e.g. megaflutes). The sedimentology of similar squeezed ridges in north Antrim (Fig. 5b, c) aligns well with thrust basal debris (Bennett et al., 1997) modified in polythermal ice (Hambrey and Glasser, 2012), differing from properties of nearby traction till (Fig. 5b, d).

Based on their sedimentological properties and presence at the termini of megaflute and drumlin swarms, minor transverse ridges in our study area were likely bulldozed or thrust at the margins of high-velocity lobes, similar to those at the former ice stream (Evans and Campbell, 1992; Evans, 2000; Evans et al., 2014, 2008) and surge-type glacier margins (Evans et al., 1999). Unlike those examples, their formation in our study area is not restricted to areas adjacent to or superimposed on larger morainic features, cementing these landforms as cryptic indicators of a glacial margin position. Though McCabe and Williams (2012) briefly note the presence of subtle corrugated forms near Lough Neagh (Fig. 5a), our study is the first to comprehensively map minor transverse ridges anywhere on the island of Ireland.

4.3.2. Hummocky moraine

Relatively disorganised, round-topped, small, circular mounds are interpreted as hummocky moraines. Hummocks are often found within larger groups of moraine ridges and sometimes form chains broadly oriented perpendicular to the inferred ice margin (Fig. 6a). Hummocky moraines are also common in valley bottom settings lying amongst raised glaciofluvial deposits and eskers (Fig. 6b), even where evidence of defined terminal moraine ridge crests is absent.

Chains of hummocks on larger moraine ridges in our study area are particularly consistent with hummocky moraines formed at polythermal ice margins (Fig. 6a) where ice may have dumped or bulldozed material at a margin undergoing a thermal regime shift (Benn, 1992; Delaney et al., 2023; Evans, 2009; Hambrey and Huddart, 1995; Knudsen et al., 2006). Their association with glaciofluvial landforms in short corridors (e.g. Delaney et al., 2023; Peterson et al., 2017; Utting et al., 2009) on the Antrim Plateau (Fig. 6b) suggests some concentrations of hummocky moraines formed in the subglacial realm during large meltwater events (Peterson and Johnson, 2018).

4.3.3. Complex/composite ridge

Moraine ridges 5–72 m tall and 300–2000 m wide (cross-profile) form

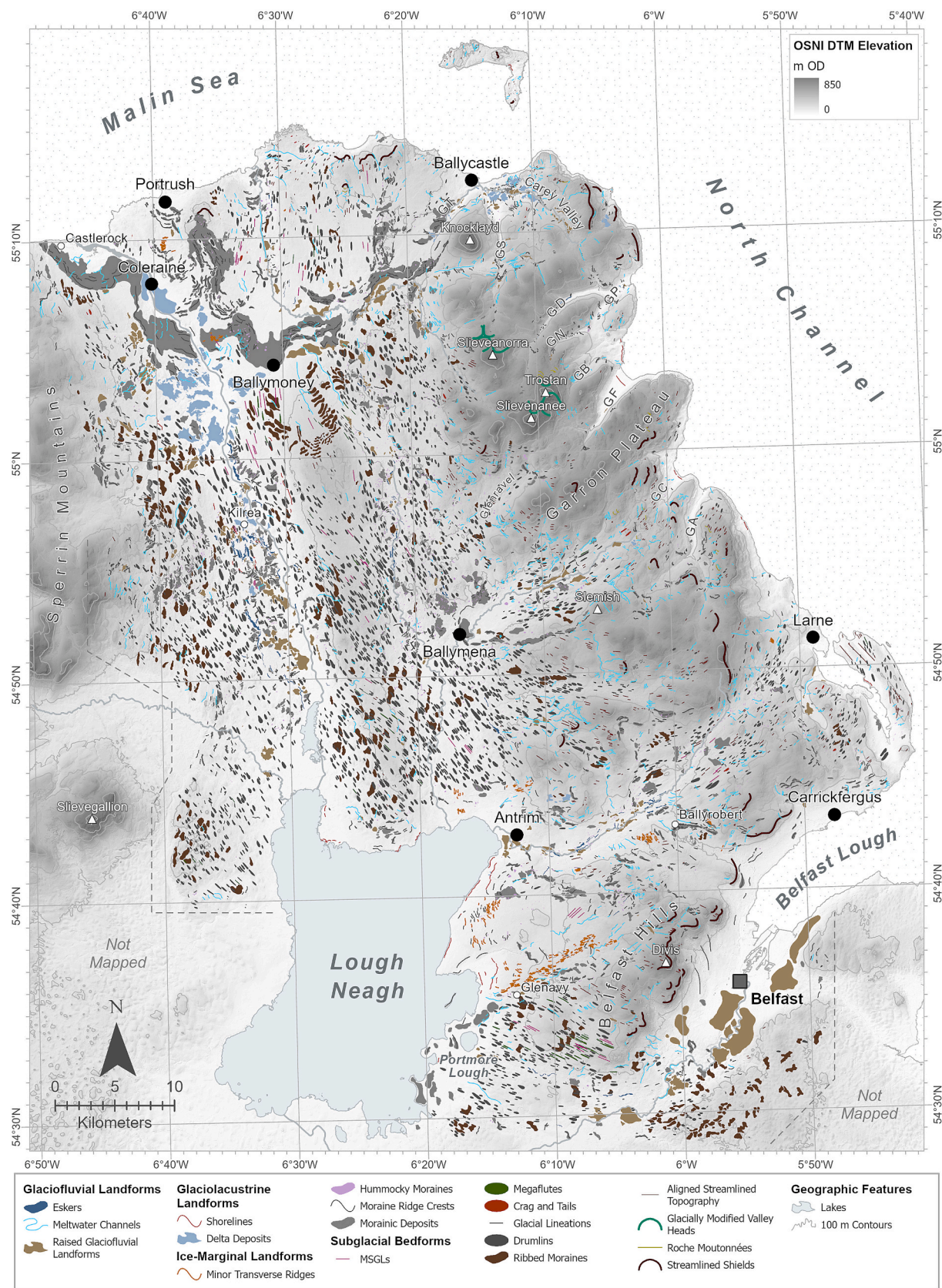


Fig. 2. Glacial geomorphological map of the study area in northeast Ireland. Based upon Crown Intellectual Property and reproduced with the permission of Land & Property Services under delegated authority from the Keeper of Public Records, © Crown copyright and database right (2026) MOU577.X.

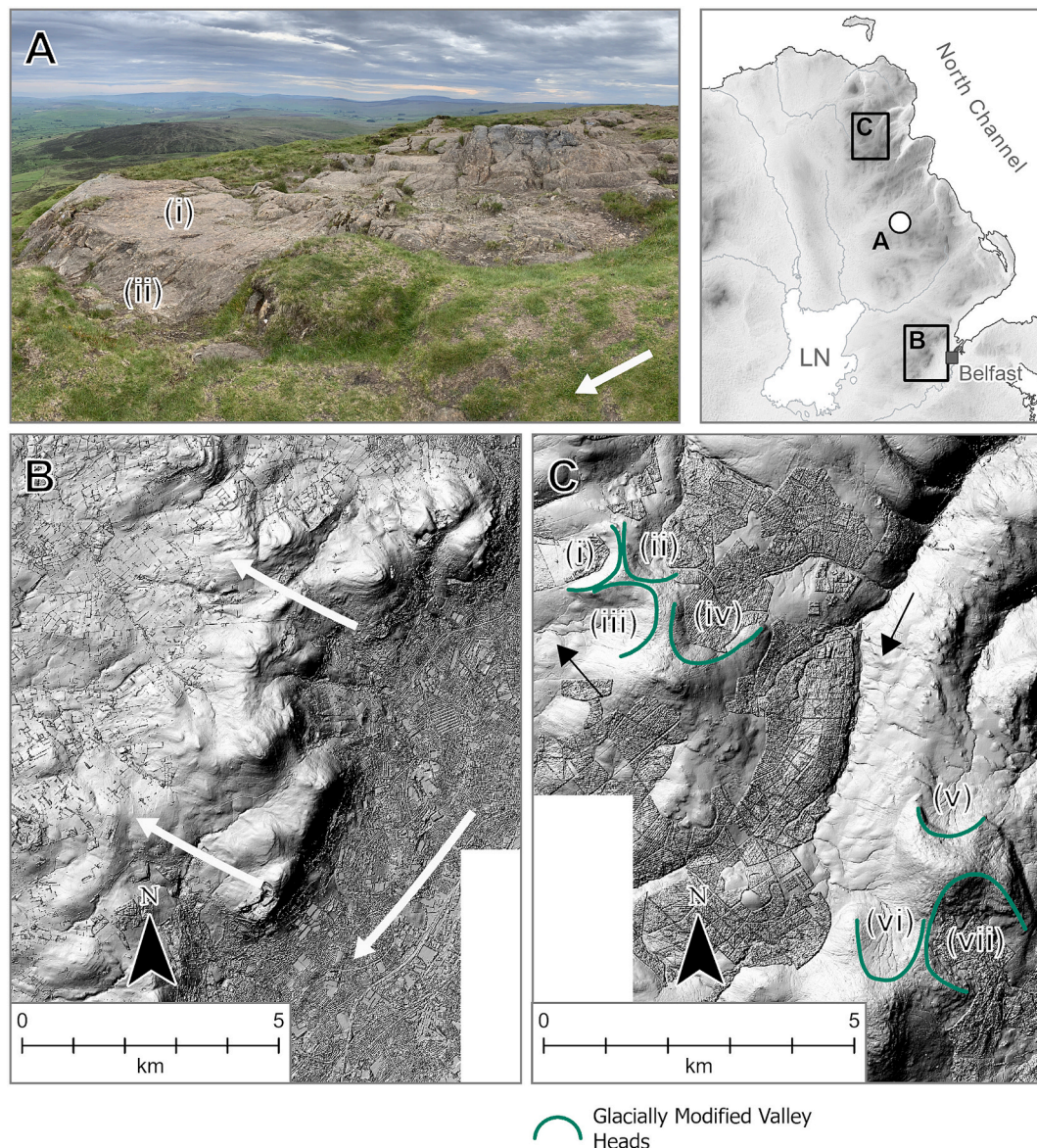


Fig. 3. a) metre-scale roches moutonnées on Slemish, near Ballymena, Co. Antrim showing polished (i) and plucked (ii) surfaces; b) streamlined shield-like forms of the Belfast Hills immediately west of Belfast; c) glacially modified valley heads (i-vii) in the Antrim Hills. White arrows indicate palaeo-ice flow direction. Illumination from the northwest and 5× vertical exaggeration in b) and c). Based upon Crown Intellectual Property and reproduced with the permission of Land & Property Services under delegated authority from the Keeper of Public Records, © Crown copyright and database right (2026) MOU577.X.

a sinuous concave feature spanning c. 46 km between Castlerock and Ballycastle (Fig. 2). These 16 ridges occupy c. 61 km² of land immediately south of evolved ribbed moraines, drumlins, megaflutes, and MSGs. Ridge morphology displays east-west variation between round-topped, broad, sharp-crested, channel-breached, and hummocky forms (Fig. 6a).

Morainic landform-sediment assemblages are consistent with widespread glaciotectonic deformation of a glacier foreland under high stresses from ice sheets with a variety of thermal regimes (Boulton et al., 1999; Hambrey and Huddart, 1995; Hart, 1990; Hart and Boulton, 1991; Hiemstra et al., 2015; Huddart and Hambrey, 1996). The size of this feature and scale of glaciotectonic deformation is consistent with definitions of large complex (or composite) ridges (Aber et al., 1989; Bennett, 2001). We broadly associate these ridges to the previously documented Armoy Moraine complex (Charlesworth, 1938; Derryhouse, 1923; Knight, 2004; Shaw and Carter, 1980), which is known to contain erratic clasts from Cushendun granodiorite in north-east Antrim and Ailsa Craig in the Firth of Clyde (Charlesworth, 1938;

Hill and Prior, 1968; Synge and Stephens, 1966) sourced ~90 km and ~30 km to the east, respectively.

Subglacial and ice-marginal sediment-landform assemblages associated with and north of the Armoy Moraine suggest a very large, high-velocity outlet lobe originating from the Malin Sea impinged on the north Antrim coast. Assemblages at least partly resemble those from surge-type lobes (Chandler et al., 2020; Lovell et al., 2018; Sutherland et al., 2019) and terrestrial ice stream margins (Evans et al., 2014; Stokes and Clark, 2001).

4.3.4. Latero-frontal moraines

Complexes of lobate moraine ridges are interpreted as latero-frontal moraines. They are topographically confined to valley settings or lows between bedrock pinning points (Fig. 6b, c) at the termini of drumlin swarms, where they may also be flanked by meltwater channels (Fig. 6b). Latero-frontal moraines are generally ~100 m wide (cross-profile) and sharp-crested, though some reach up to 400 m wide (cross-profile) superimposed by chains of hummocks following the ridge

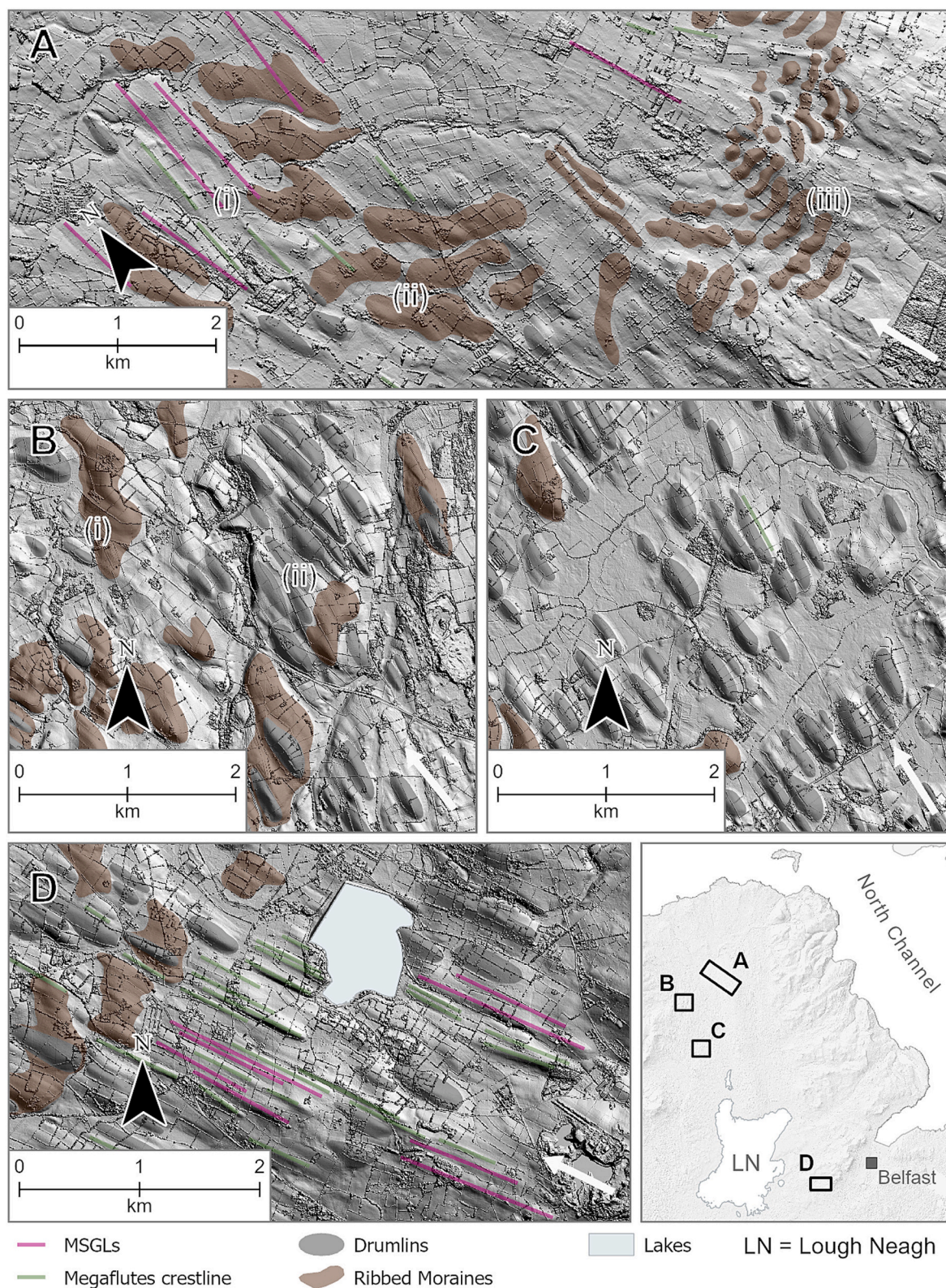


Fig. 4. a) low-lying, sinuous ribbed moraines superimposed by elongated bedforms (i), sinuous ribbed moraines showing a high degree of 'evolution' (ii), and collections of circular ribbed moraines (iii); b) prominent ribbed moraine with a small degree of streamlining/ drumlinisation (i), and highly streamlined/ drumlinised ribbed moraines (ii); c) drumlin swarm in the Lower Bann valley; d) megaflutes and MSGLs on the southwestern flanks of the Belfast Hills southeast of Glenavy. White arrows indicate palaeo-ice flow direction. Illumination from the northeast and 5× vertical exaggeration in a)–d). Based upon Crown Intellectual Property and reproduced with the permission of Land & Property Services under delegated authority from the Keeper of Public Records, © Crown copyright and database right (2026) MOU577.X.

crests (e.g. Benn, 1992).

Latero-frontal moraine distribution in the study area suggests major standstills occurred once ice thinned and became confined to valley settings, especially on the east coast. Adjacent minor transverse ridges indicate bulldozing of proglacial sediments was underway in some cases. Hummocky chains on moraine ridges adjacent to minor transverse ridges suggest there may have been a change in thermal regime at the ice margins, consistent with formation by polythermal ice (Benn, 1992; Delaney et al., 2023; Hambrey et al., 1997).

4.4. Glaciofluvial assemblage

4.4.1. Meltwater channels

Narrow, deep, and sinuous channels incised through bedrock and superficial sediments are interpreted as former meltwater channels. Channels cut through bedrock (possibly exploiting faults) at high elevations are deep and relatively straight. Those at lower elevations cutting through substrate (usually till) are typically more sinuous and run sub-horizontally along valley sides (Fig. 7a), with those at or towards the base of valleys being sinuous, wide, and oriented mainly downslope.

Lateral meltwater channels are cut into valley sides along both cold-based (Atkins and Dickinson, 2007; Kleman et al., 1992) and polythermal ice masses where ice is less permeable (Syverson and Mickelson, 2009). Their concentration in the valleys of the Antrim Hills (Fig. 2, 7a) often adjacent to moraine ridges reveals lobes originating from the North Channel were likely polythermal, and highly constrained by topography with somewhat gentle (2.7–7.6%) slopes.

Subglacial channels in our study area are primarily either valley-aligned or oriented sub-horizontally on gentle relief. Channels occur as both isolated examples and anastomosing systems (Fig. 7a) spanning hundreds of metres to kilometres in length, whilst small N-channels can be found cut into bedrock at the decimetre scale (Fig. 7b). Subglacial channel deposits (Fig. 7c) of clast-supported sandy gravels amongst fissile till units indicate high-energy channelised flow conditions may punctuate periods of distributed subglacial meltwater flow. The River Bush and Lower River Bann now potentially occupy large subglacial tunnel valleys (Fig. 2), introducing the possibility of outburst-type drainage events under certain conditions (Hooke and Jennings, 2006; Kirkham et al., 2024; Piotrowski, 1997).

Proglacial meltwater channels are uncommon (~7% of dataset). Many are long, sinuous, and occasionally form anastomosing networks in valley bottom settings, occasionally cutting through morainic deposits (Fig. 6a, b) and over deltaic landforms (Fig. 8). They are often associated with latero-frontal moraine complexes (Fig. 6b) where they may reach 200–700 m long. Proglacial meltwater channels are therefore likely predominantly associated with relatively long-lasting standstill events of warm-based or polythermal lobes.

4.4.2. Eskers

Sharp-crested, steep-sided and ‘beady’ sinuous ridges are interpreted as eskers. The 282 esker ridges mapped in our study area exhibit a range of morphologies and clustering patterns: i) ‘distributary’-type esker systems with short (typically 50–500 m), sometimes highly-sinuous ridges found in small clusters adjacent to raised glaciofluvial or glaciolacustrine landforms (Fig. 7d); ii) multi-crested, sometimes ‘beady’, eskers with wide (100–200 m), relatively shallow-sloping bases (Fig. 7d), interpreted as esker enlargements; iii) isolated, single-crested, relatively long (3–5 km) and narrow (10–50 m wide) eskers or esker chains (Fig. 7e).

Distributary-type or ‘deranged’ eskers and esker enlargements in the Lower Bann valley likely formed during a rapid and unstable ice margin retreat phase (e.g. Hewitt and Creyts, 2019; Storrar et al., 2015), potentially in standing water (Brennand, 2000) as occasionally also evidenced by their proximity to glaciolacustrine deposits. They contrast with the long, single-crested esker chains found nearby probably related to a more stable ice margin retreat phase as meltwater was transported

through the supraglacial and englacial environment (Perkins et al., 2016). Eskers in our study area therefore reveal contrasts and shifts in the stability of ice margins and meltwater flux in the subglacial and englacial environment, possibly also linked to associations with glacial lakes.

4.4.3. Raised glaciofluvial landforms

Flat-topped and gently undulating landforms typically lying adjacent to present river courses are broadly categorised as raised glaciofluvial landforms. This category primarily includes glaciofluvial terraces with relatively flat, sheet-like surfaces (Fig. 8a). Landforms with more of an undulating (‘kamiform’) relief may have formed as buried ice blocks eventually melted.

Glaciofluvial terraces in the Antrim Hills c. 170–180 m OD (Fig. 8a) comprise well-sorted sand with thrust faults and matrix-supported gravels (of local lithologies), gravel lenses overlying weathered bedrock (Fig. 8b), and massive and crudely stratified matrix-supported gravels overlying diamicton. The former are consistent with ice-distal sandar in mountain environments sourced from polythermal glaciers (Glasser et al., 2009; Hambrey and Glasser, 2012), whilst the latter are likely ice-proximal glaciofluvial deposits overlying subglacial till. These outwash deposits reveal variable flow energies as the landscape becomes ice-free, with thrust faulting perhaps representative of post-depositional shunting of the landform by a distal active ice mass.

Low-lying (<10 m OD) sheet-like deposits comprise massive to crudely stratified, matrix-supported, poorly sorted, primarily sub-angular to sub-rounded sandy gravels with occasional lenses of clast-supported rounded gravels (Fig. 8c), all of which contain mostly or entirely local basalts. Clasts in these deposits show clear evidence of subglacial transportation (Fig. 8d) before being transported into the proglacial environment as ice-proximal deposits. Frequent lenses of rounded coarse gravels in some sedimentary units (Fig. 8b, c) are indicative of braided channel infills, probably in a more ice-intermediate environment. In places, these outwash deposits overly glaciolacustrine units, revealing a complex depositional history of flat-topped, low-lying landforms in the study area.

4.5. Glaciolacustrine assemblage

4.5.1. Deltas, fans, and other glaciolacustrine landforms

A variety of flat-topped and gently sloping landforms are interpreted as subaqueous glaciolacustrine deltas or fans. They are best preserved in the Carey Valley (Fig. 8a), Glenshesk, and the Tow valley in northeast Antrim, where deltaic landforms sit between 24 and 125 m OD. Shallow channels occasionally weave across their flat surfaces. Sub-aqueous debris flows, delta bottomsets and foresets associated with the c. 100–125 m OD deltas in the Carey Valley (Fig. 8a) indicate an input source from the east or southeast was responsible for delta-building at these higher elevations (Benetti et al., 2021; McCabe and Eyles, 1988). Deltas here do not commonly lie adjacent to prominent moraine ridges.

By contrast, hyperconcentrated flow deposits on the north Antrim coast (Fig. 8c) imply high-energy, friction-dominated plastic flow over short distances from a submerged ice margin (Mulder and Alexander, 2001; Todd, 1989). Overlying sub-aerial glaciofluvial sediments indicate a primary control on glaciolacustrine delta formation, such as water depth or ice margin position (Fyfe, 1990), became unfavourable. Landform-sediment assemblages here therefore reveal: i) multiple stable lake levels potentially during a prolonged phase of deglaciation at the higher elevation ice sheet fringes, contrasted by; ii) more transient glacial lake development at lower elevation outlet lobe frontal margins, potentially during a period of more rapid ice sheet wastage.

In the Lower Bann valley, delta surfaces are identified around Kilrea with surface elevations of ~30–50 m OD, with some comprising laminated clays (Dwerryhouse, 1923). A series of flat-topped or gently sloping landforms are also identified in contact with the southern flanks of the Armoey Moraine and up to ~6 km to the south. Some landforms

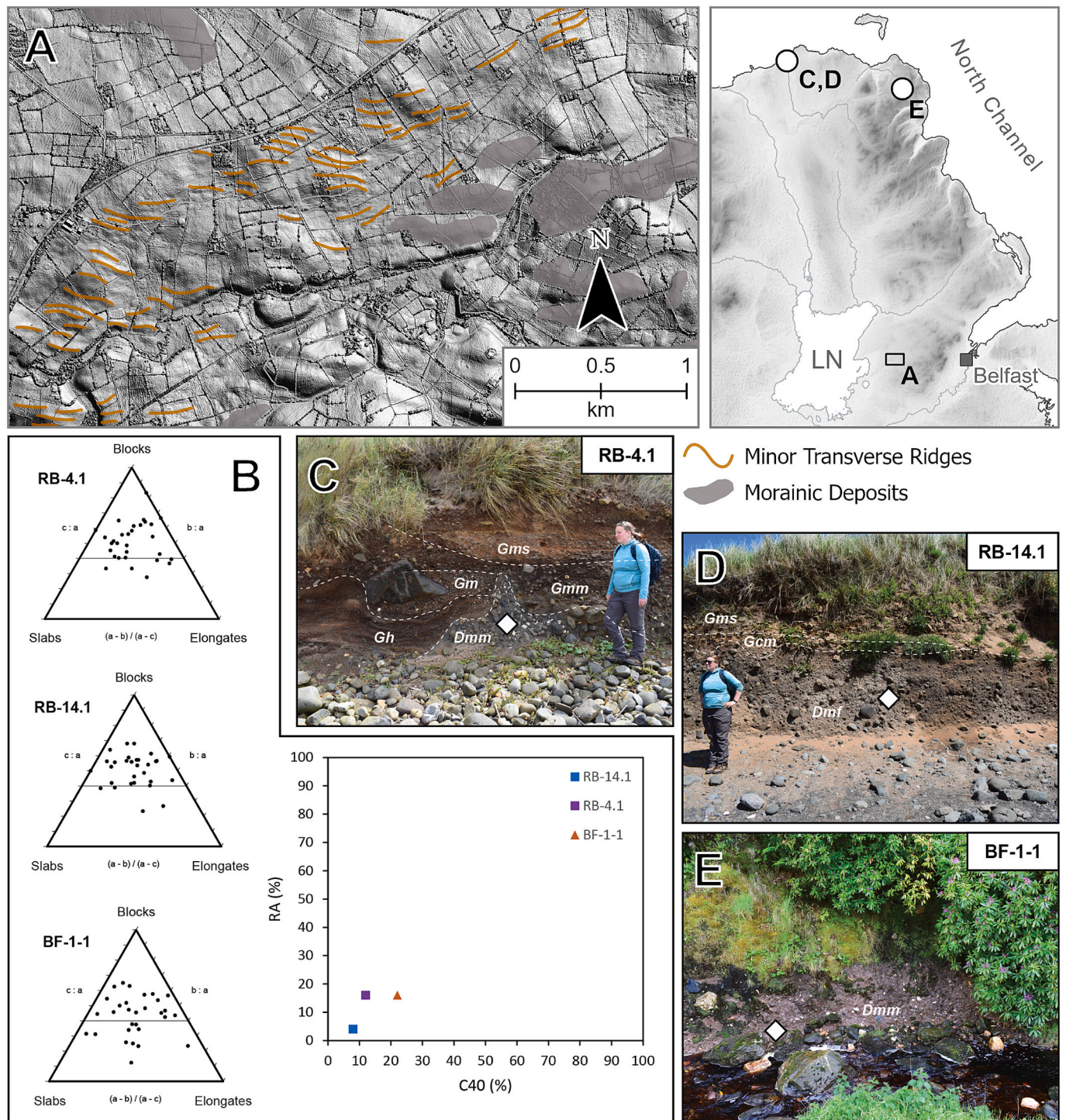


Fig. 5. a) minor transverse ridges near Glenavy, Co. Antrim (illumination from the northeast, 10× vertical exaggeration); b) clast form results from diamicton associated with a suspected minor transverse ridge (RB-4.1) compared with other glacial diamicton in the study area (RB-14.1 and BF-1-1); c) photo of a minor transverse ridge cross-section; d) and e) subglacial traction tills at Runkerry Beach and Ballypatrick Forest, Co. Antrim. Lithofacies codes: massive diamicton (Dmm), fissile diamicton (Dmf), laminated gravels (Gh), massive gravels (Gm), massive, matrix-supported, poorly sorted gravels (Gmm), faintly stratified gravels (Gms), massive, clast-supported gravels (Gcm). Based upon Crown Intellectual Property and reproduced with the permission of Land & Property Services under delegated authority from the Keeper of Public Records, © Crown copyright and database right (2026) MOU577.X.

contain laminated clays (Creighton, 1974; Dardis, 1990a; Kilroe, 1913) occasionally interrupted by dipping gravel facies (Dardis, 1990a). These landforms are interpreted as either deltas, sub-aqueous fans, or lake bottom deposits depending on landform morphology and sediment assemblages where possible. These landforms frequently lie adjacent to moraine ridges and branching esker chains. The surface elevations and

distribution of these landforms imply a series of interlobate glacial lakes were dammed up to ~50 m OD by ice as far south as Kilrea and as far north as the Armoyle Moraine, potentially with progressively lower lake levels persisting throughout deglaciation.

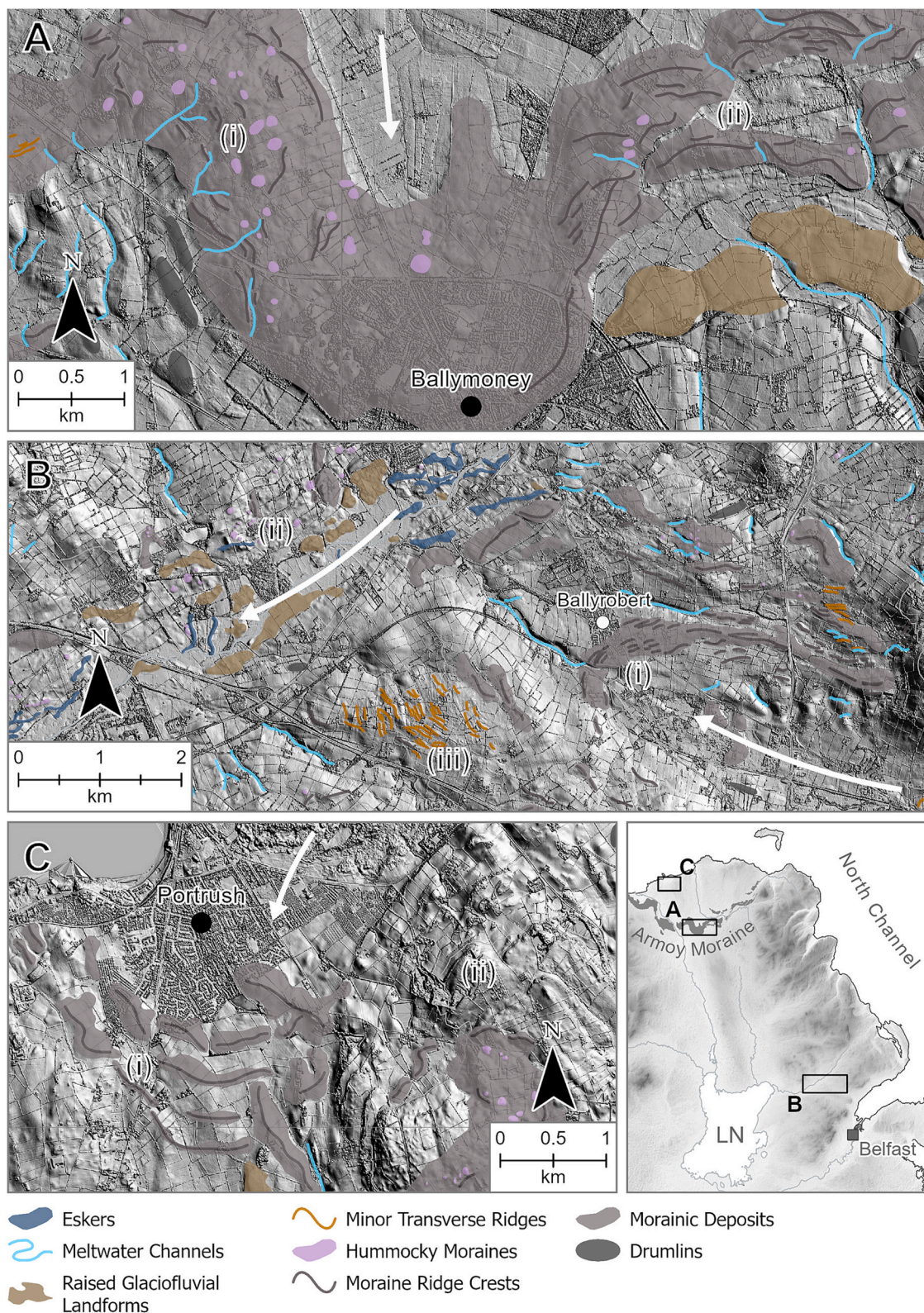


Fig. 6. a) Armoy Moraine ridge at Ballymoney with hummocky (i) and sharp-crested (ii) ridge morphologies; b) latero-frontal moraine ridge at Ballyrobert (i), hummocky topography amongst raised glaciofluvial landforms in the Six Mile Water valley (ii), and minor transverse ridges (iii) adjacent to the Ballyrobert moraine; c) latero-frontal moraines south of Portrush, Co. Antrim (i) showing somewhat regular spacing, formed by a lobe pinned against the nearby bedrock-cored topographic high (ii). White arrows indicate palaeo-ice flow direction. Illumination from the northwest in a) and northeast in b) and c), 8× vertical exaggeration in a)–c). Based upon Crown Intellectual Property and reproduced with the permission of Land & Property Services under delegated authority from the Keeper of Public Records, © Crown copyright and database right (2026) MOU577.X.

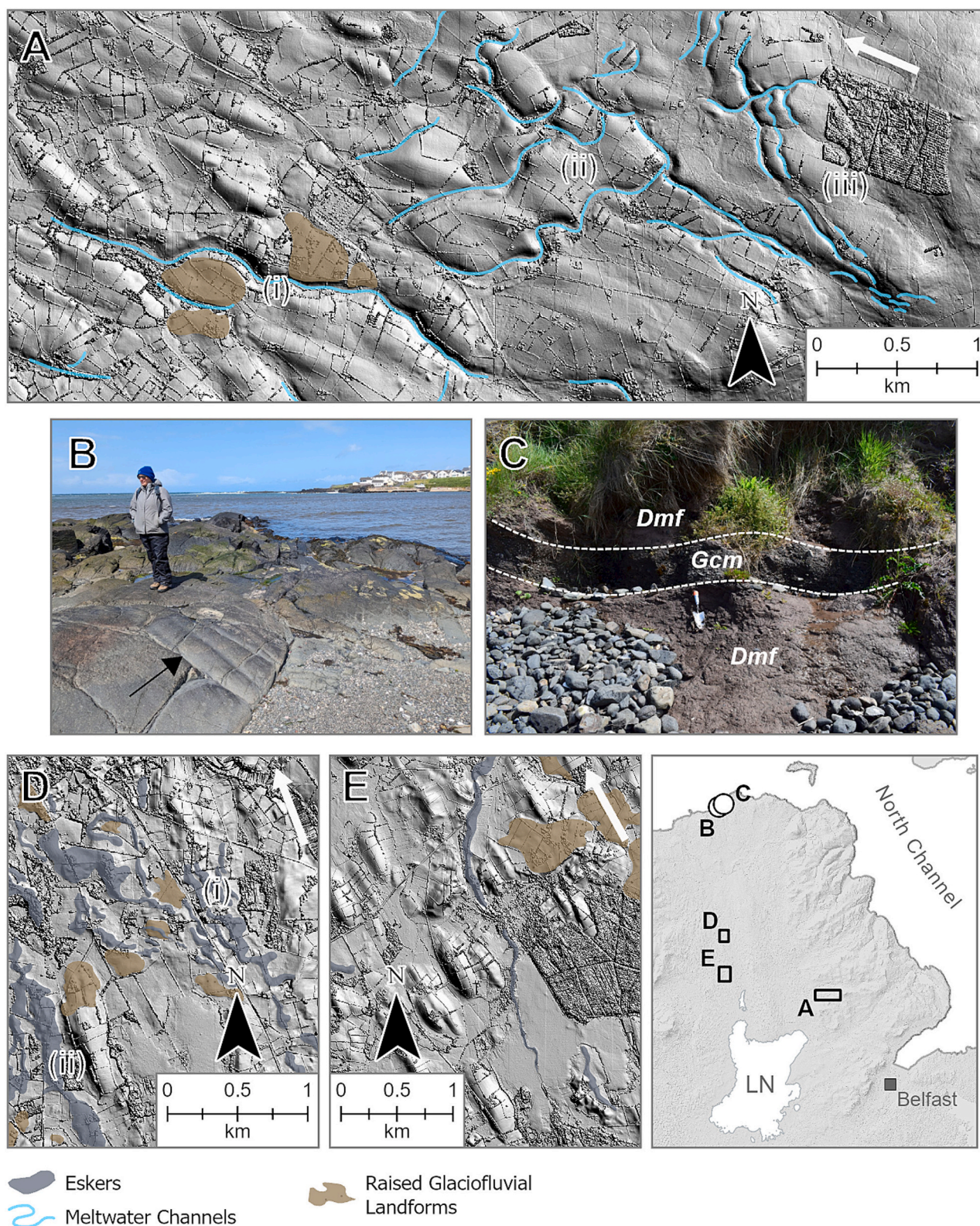
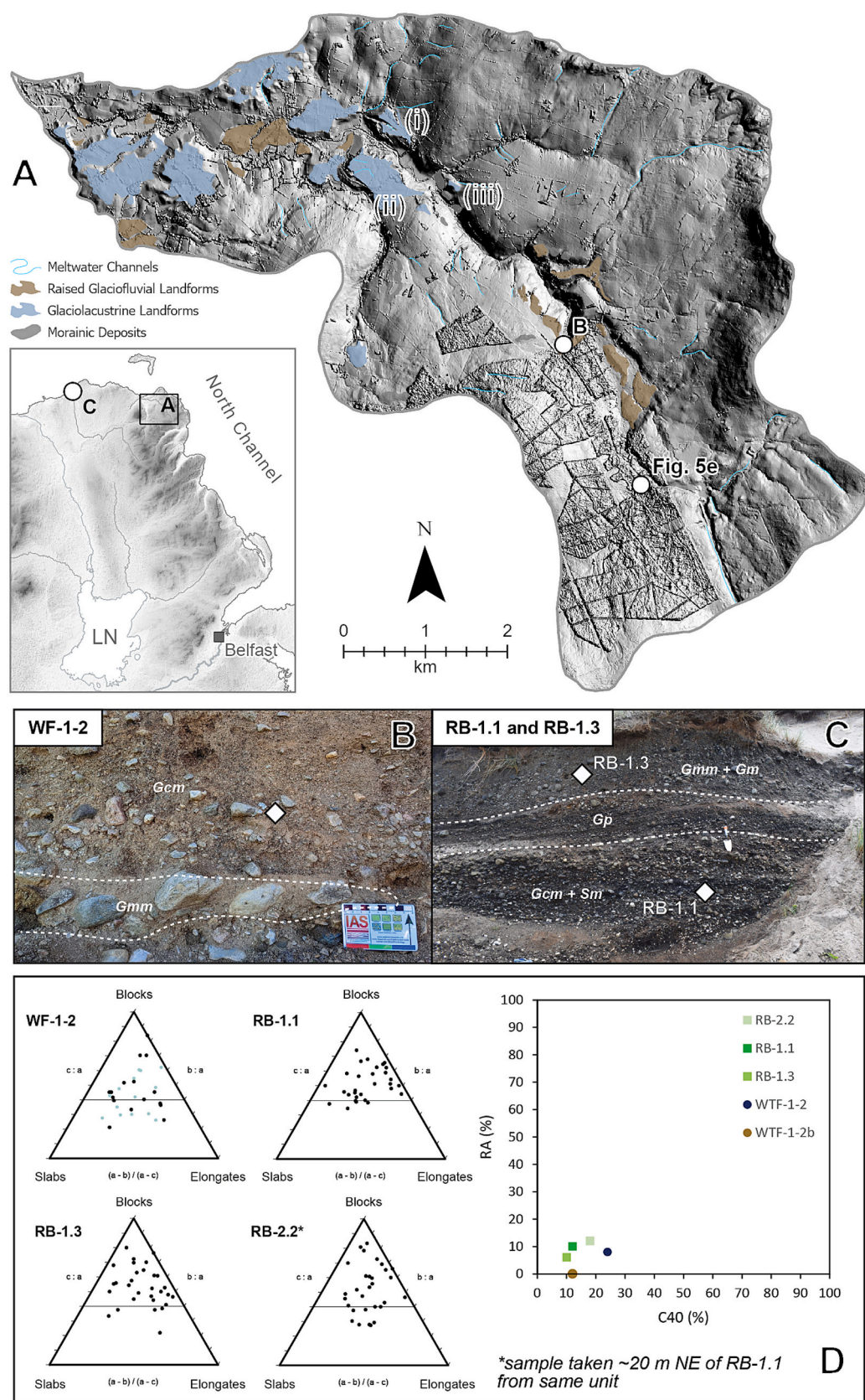


Fig. 7. a) subglacial (i, ii) and ice-marginal (iii) meltwater channels in the south Antrim Hills; b) N-channels cut north-south through basalt bedrock; c) subglacial meltwater channel deposit within fissile subglacial till; d) distributary/ deranged esker systems (i) and esker enlargements (ii) near Kilrea, Co. Londonderry; e) single-chain esker system weaving amongst drumlins north of Lough Neagh. White arrows indicate palaeo-ice flow direction. Illumination from the northeast and 5× vertical exaggeration. Lithofacies codes: fissile diamict (Dmf), massive, clast-supported gravels (Gcm). Based upon Crown Intellectual Property and reproduced with the permission of Land & Property Services under delegated authority from the Keeper of Public Records, © Crown copyright and database right (2026) MOU577.X.



(caption on next page)

Fig. 8. a) the Carey Valley in northeast Co. Antrim showing key glaciolacustrine deltas (i-iii) that have previously undergone investigation by McCabe and Eyles (1988) and Benetti et al. (2021) amongst others (illumination from the northeast, 5× vertical exaggeration); b) ice-distal braided outwash deposits at Watertop Farm; c) ice-proximal hyperconcentrated flow deposits (RB-1.1) and glaciofluvial deposits (RB-1.3) at Runkerry Beach (trowel is 31 cm tall); d) clast form results from key glaciofluvial and glaciolacustrine sediments. Results from WF-1-2 include schist clasts (light blue dots on ternary diagram), WF-1-2b represents basalt clasts only. Lithofacies codes: poorly sorted gravels (Gmm), clast-supported gravels (Gcm), massive sand (Sm), planar bedded gravels (Gp), matrix-supported gravels (Gm). Based upon Crown Intellectual Property and reproduced with the permission of Land & Property Services under delegated authority from the Keeper of Public Records, © Crown copyright and database right (2026) MOU577.X. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Discussion

New geomorphological and sedimentological evidence provides a crucial foundation for achieving our core aim of understanding the dynamics of a smaller, rapidly reorganising BIIS as it transitions to a terrestrial-based ice mass. Here, we bring together process-form relationships from the study area to discuss new insights into palaeo-ice sheet dynamics during this poorly constrained phase of deglaciation. Below, each set of landform assemblages is discussed in a relative chronological framework of ‘flow stages’ based on morphostratigraphic principles. The relative timing of flow stages is discussed in morphostratigraphic order (see Table 2). Chronological data are employed to propose potential absolute timings and highlight discrepancies with the geomorphological record, emphasising avenues for future research.

Irish Grid reference coordinates are given for key locales mentioned in the text that are not labelled in Fig. 1 or Fig. 2 and can be found on gridded 1:25,000 and 1:50,000 scale maps available from the SpatialNI Map Viewer (<https://osni-spatialni.hub.arcgis.com/apps/61a4d209f6854ab2b79437fad24a6e9d/explore>).

5.1. Palaeo-ice sheet dynamics and flow stages

5.1.1. Flow Stage A: lowland ice dome

Subglacial landform assemblages between the Antrim Hills and Sperrin Mountains (Figs. 2, 4c, 7a, d, e) are attributed to a time-transgressive recession of a wide ice lobe margin pertaining to the ‘Lough Neagh Ice Dome’ (fs50 of Greenwood and Clark, 2009a). Ice-marginal and glaciofluvial assemblages reveal deglaciation in the Lower Bann valley was punctuated by episodic transitions between stable, grounded, polythermal margins and unstable glacial lake-terminating margins. Pro-glacial lakes potentially reaching 20–45 m depth between Kilrea and the Armoy Moraine may have promoted calving and instability, as observed in other palaeo-ice sheets undergoing similar styles of lowland ice centre fragmentation (Atkinson et al., 2016; Hickin et al., 2015; Utting and Atkinson, 2019). Ice-marginal and glaciofluvial assemblages on the Antrim Plateau suggest ice was more grounded at slightly higher elevations, potentially thinning and stagnating towards its margins as a separate lobe. The ice centre then shifted southeast over Co. Down, draining via a thick, high-velocity outlet producing thrust ridges east of Lough Neagh (Figs. 3b, 4d, 5a), strongly linking ice divide migration to major ice centre collapse after a phase of thinning and margin instability.

A single ^{36}Cl exposure age near Rasharkin of 17.5 ± 2.6 ka BP (Bowen et al., 2002) and a minimum deglacial age from Sluggan Bog near Randalstown of 14.3 ± 0.3 cal. ka BP (Lowe et al., 2004; Walker et al., 2012) present much of the period between the Last Glacial Maximum and Late Glacial as a potential timeframe for Flow Stage A. Ice sheet flow northwest down the Lower Bann valley at this time (Fig. 9) is best explained by a large ice straddle stretching from western Ireland to the Lough Neagh basin and across the North Channel into Scotland, comparable with the 18 ka time slice reconstructions from DATED-1 (Hughes et al., 2016) and BRITICE-CHRONO (Clark et al., 2022).

5.1.2. Flow Stage B: ephemeral ice stream

Landform assemblages in the Lower Bann valley between Kilrea and Ballymoney (Figs. 2, 4a) indicate a shrinking lowland ice dome was temporarily drained by a small ice stream as its margin retreated

southward. A ‘bedrock-bump’ sticky spot (Stokes et al., 2007) at Mullan Head (C 99461 16614) lies adjacent to streamlined (‘evolved’) ribbed moraines (Vérité et al., 2023), characteristic of an ice stream shear margin (Vérité et al., 2021), downstream of strongly parallel and increasingly elongated drumlins typical of an ice stream trunk (Stokes and Clark, 2001, 1999). Glaciofluvial and subglacial assemblages reveal topographic focussing and distributed meltwater routing at the ice-bed interface were strong controls on ice stream initiation (Jennings, 2006; Vérité et al., 2021; Winsborrow et al., 2010). This small (20 km long, 5–10 km wide) ice stream is directly comparable in size to palaeo-ice streams that temporarily drained small ice sheet fringe catchments during deglaciation (Benediktsson et al., 2022; Knight et al., 1999; McCabe et al., 1999). Its characteristics are particularly reminiscent of ‘ephemeral ice streams’ proposed for Laurentide Ice Sheet settings (Margold et al., 2018, 2015; Stokes et al., 2009). The Lower Bann ice streaming event appears to have been a product of rapidly shifting ice sheet geometry, regional topographic and intrinsic dynamic factors, and perhaps more widespread ice sheet instability during its demise (e.g. Kleman and Applegate, 2014).

As landforms associated with Flow Stage B are nested within the landform signature of Flow Stage A (Fig. 9), a similar broad timeframe of c. 17.5–14.3 ka BP is adopted for this stage.

5.1.3. Flow Stage C: oscillatory readvancing ice margin

Assemblages of the Armoy Moraine in this (Fig. 7a) and previous studies reveal multiple stacked layers of till and reworked proglacial sediments with high-angle (15–60°) faults and nappes (Knight, 2004; Shaw and Carter, 1980), channel-breached recessional moraines, and hummocky regions suggesting restricted stagnation of debris-rich polythermal ice (Evans, 2009) or meltwater rerouting during a thermal transition (Delaney et al., 2023). These characteristics have previously been attributed to unstable oscillatory ice margins with strong ice-bed coupling at the terminus after high-velocity flow conditions facilitated by distributed meltwater drainage (Benediktsson et al., 2010, 2009; Evans and Rea, 2013; Lønne, 2016; Lovell et al., 2018), and so is characterised as an oscillatory readvancing ice margin here. This readvance (Flow Stage C1, fs46 of Greenwood and Clark, 2009a) most plausibly originated from Scotland (supported by the provenance of erratics within the Armoy Moraine), overriding lineations associated with Flow Stage A and B. Furthermore, glaciolacustrine landforms overlying Flow Stage B lineations up to ~50 m OD, suggesting an interlobate lake could have formed contemporaneously with this readvance and Lough Neagh Ice Dome wastage (Flow Stage A), postdating ephemeral ice streaming (Flow Stage B).

Assemblages along the north coast (Figs. 5, 6, 7c) reveal hitherto unexplored dynamics of this lobe. Multiple standstills were topographically constrained during active ice margin retreat (Flow Stage C2) characterised by high ice-bed interface stresses resulting in till matrix dewatering, ice-bed coupling, and thrusting. The lobe terminated in standing water, forming hyperconcentrated flows and other high-energy, subaqueous deposits (Figs. 5c, 8c). Shallow marine conditions here are plausible (Clark et al., 2022; McCabe et al., 1994; Shennan et al., 2018), though the deposits themselves do not contain conclusive evidence of marine conditions (Dardis, 1990b).

Flow Stage C represents a readvance of the Malin Sea Ice Stream characterised by the drawdown of ice over soft marine sediments from a Scottish source. This readvance was potentially contemporaneous with a

Table 2

Summary of each Flow Stage identified in northeast Ireland and their timing.

Flow stage (FS)	Landsystem	Landform-sediment associations	Timing
FS-A	Lowland Ice Dome	Topographically influenced drumlins and drumlinised ribbed moraines; broad hummocky moraine ridges; valley-confined glaciolacustrine deposits and outwash deposits	Relative: FS-A does not appear to modify older landforms; FS-B 'smears' FS-A bedforms in the Lower Bann valley only
FS-B	Ephemeral Ice Stream	Strongly parallel drumlins, megaflutes, and MSGs overlying elongated ribbed moraines	Absolute: Possibly c. 17.5 ± 2.5 ka BP (Bowen et al., 2002); 14.3 ± 0.2 ka BP (Walker et al., 2012) minimum age
FS-C	Oscillatory Readvancing Ice Stream Margin	Parallel drumlins and MSGs terminating at a complex ridge; topographically constrained moraine loops and minor transverse ridges in some valleys behind complex ridge; deformed traction till overlain by subaqueous deposits	Relative: Truncates FS-A and FS-B between the north Antrim coast and the Armoy Moraine; must post-date them
			Absolute: OSL ages from the Armoy Moraine considered outliers (Benetti et al., 2021); seemingly predates FS-A and FS-B at c. 22-24 ka BP (Benetti et al., 2021)
FS-D	Glaciolacustrine and Plateau Icefield	Glaciolacustrine deltas <125 m OD down-valley of, ice-distal outwash and small moraines ~160-180 m OD; wide, low-relief valley head(s) relatively barren of glacial landforms	Relative: Must be contemporaneous with FS-C to damn lakes ~125 m OD in the Carey Valley
			Absolute: Glaciolacustrine delta and glaciofluvial sedimentation c. 22-24 ka BP (Benetti et al., 2021)
FS-E	Alpine Icefield	Small, valley-confined terminal moraines down-valley of wide upland source area with glacially scoured mountain flanks	Relative: Potentially overlaps with any stage; feasibly attached to Antrim Plateau ice (FS-A)
			Absolute: No direct constraints
FS-F	Lowland Reorganising Ice Sheet	Valley-confined drumlins, ribbed moraines, and megaflutes terminated by latero-frontal moraines or minor transverse ridges; NE-SW bedforms crosscutting and smearing older bedforms oriented SE-NW	Relative: Crosscuts and 'smears' FS-A on the east coast; could be contemporaneous with FS-C (e.g. McCabe and Williams, 2012; Finlayson et al., 2014) and FS-E should ice have thinned to <240 m OD in some Antrim Glens
			Absolute: No direct constraints; must pre-date marine transgression in Belfast Lough c. 15.7 ka BP (Plets et al., 2019) and Rough Island c. 14.9-15.5 ka BP (McCabe et al., 1998)
Ice-free conditions	–	–	Marine transgression and interstadial lake sedimentation c. 14.3-15.7 ka BP (McCabe et al., 1998; Lowe et al., 2004; Walker et al., 2012; Plets et al., 2019)

receding ice margin of the Lough Neagh Ice Dome, forming an interlobate lake between a well-nourished Scottish outlet and an unstable Irish lobe (Fig. 9a). A newly identified quasi-stable, oscillatory period then followed, with the ice margin becoming more influenced by topography, subglacial hydrology, and proglacial lake dynamics once becoming mostly grounded above sea level.

Bayesian age modelling of the Malin Sea Ice Stream yields a constraint of 20.6 ± 0.6 ka BP for this flow stage (Benetti et al., 2021). However, this date relies on relatively imprecise OSL ages (Fig. 1c) that cannot directly be associated with this Flow Stage, and our morphostratigraphic reconstruction (Table 2, Fig. 9) suggests Flow Stage C (c. 20 ka BP) cannot be older than Flow Stage A or B (c. 18-14 ka BP). Opposing ice masses during this stage are feasible but poorly reproduced in model reconstructions c. 20-18 ka BP (Clark et al., 2022; Ely et al., 2024). This highlights potential complexities in the interactions and drivers of readvancing Scottish ice and decaying Irish ice and the need for additional absolute chronological controls.

5.1.4. Flow Stage D: ice-dammed glacial lake and semi-independent plateau icefield interactions

A suite of landform-sediment assemblages in northeast Antrim allude to the potential co-existence of ice-dammed glacial lakes and a semi-independent plateau icefield during Flow Stage D. Glaciolacustrine delta elevation, dip, and palaeo-current data (Benetti et al., 2021; McCabe and Eyles, 1988) in Glenmakeeran (D 16442 38455) and the Carey Valley (Dwerryhouse, 1923; Warren, 1990) reveal a series of glacial lakes reaching up to ~125 m OD existed in northeast Antrim as ice in the Malin Sea peeled away from the coast. Damming lakes at these elevations in the Carey Valley would have required ice from the Malin Sea to have extended across the north Antrim coast, reaching the limits of Flow Stage C, thus making Flow Stage D coeval with Flow Stage C.

Landform-sediment assemblages in the high reaches of the Carey Valley (Fig. 8a, b) suggest that as this separation progressed, active ice originating from the head of the valley formed subglacial traction till, moraines, and ice-proximal to ice-distal glaciofluvial terraces.

We propose this is somewhat consistent with a plateau icefield (Bickerdike et al., 2018; Finlayson et al., 2011; Rea and Evans, 2013), whereby relatively thin, perhaps cold-based ice sat at the head of the Carey Valley and Glenmakeeran (Fig. 9a). It seems necessary that for active retreat to have persisted here, this icefield must have been attached to ice in the North Channel (Hill and Prior, 1968; Stephens et al., 1975). It is also plausible that this plateau icefield still fed ice-dammed lakes as it transitioned to a remnant ice mass (e.g. Johnsen and Brennand, 2006). Consequently, an ice dam in the Malin Sea may have still existed (i.e. Flow Stage C), suggesting the decay of a plateau icefield attached to ice in the North Channel was a result of ice thinning in the North Channel, rather than solely climatic or topographic factors (e.g. Boston and Lukas, 2019).

5.1.5. Flow Stage E: Alpine icefield and niche glacier evolution

Sediment-landform assemblages in Glendun (D 18315 30387) and Glenaan (D 19665 28,189) comprise small morainic ridges (Figs. 2, 3c), occasionally made up of contorted material (Prior, 1970) and subglacial tills dominated by local geologies (Creighton, 1974). Angular local schistose boulders are strewn across the landscape. The heads of these valleys show minor degrees of glacial modification (Fig. 3c) feasibly due to the presence of mostly cold-based ice covering the Antrim Hills. Down-valley, subtle roches moutonnées indicate outlets indicate warm-based erosion under thin ice was underway. This evidence suggests short, topographically restricted outlet lobes descended from the Trostan-Slievenanee-Slieveanorra region (Fig. 9a) and experienced an active retreat. Lowland coastal chalky till generation (Prior, 1970),

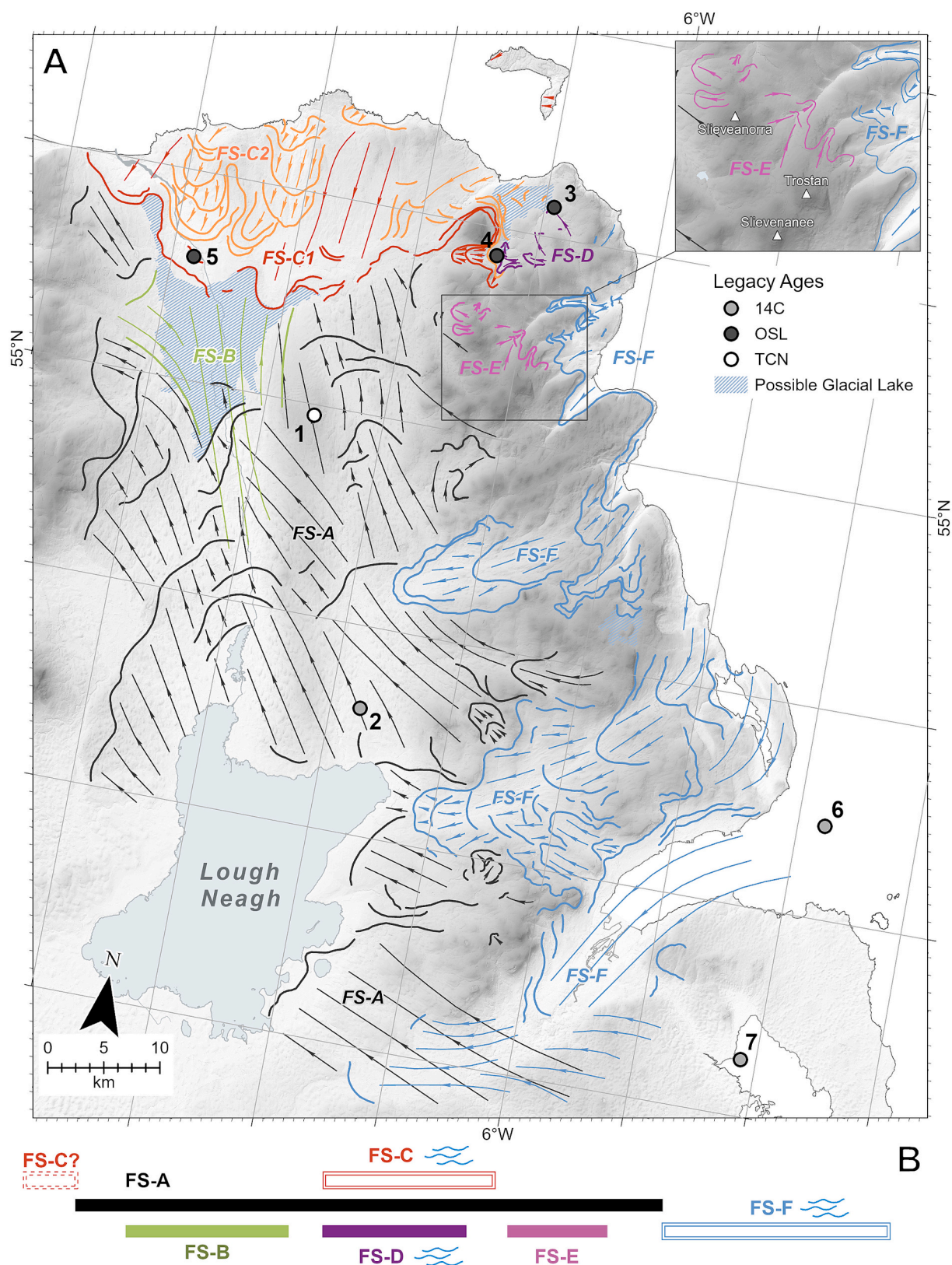


Fig. 9. a) new proposed flow stages, flowlines, and ice margins of the study area in northeast Ireland, and; b) their relative timing from oldest (left) to youngest (right). Overlapping flowlines are only drawn where cross-cutting is evident. Legacy ages (14C = radiocarbon, OSL = optically stimulated luminescence, TCN = terrestrial cosmogenic nuclide) associated with each flow stage are mentioned in the text: 1. Rasharkin (location assumed based on descriptions by [Bowen et al., 2002](#)); 2. Sluggan Bog; 3. Drumadoon; 4. Glenshesk; 5. Castleroe; 6. Belfast Lough. Solid fill rectangles in (b) represent Irish ice and hollow double-walled rectangles represent Scottish ice. Wave symbols in (b) indicate Flow Stages during which glacial lakes may have formed, shown in (a).

moraines pointing up-valley, and an esker in Glendun all likely formed by ice in the North Channel following the retreat of upland outlet lobes. These results are broadly consistent with a small, high elevation Alpine icefield (Bickerdike et al., 2018) which was detached from ice in the North Channel but could have been attached to thick ice on the Antrim Plateau (Fig. 9).

Glacially modified valley heads and subdued terminal moraine assemblages down-valley of some of these heads (Fig. 3c) could be associated with a transition to niche glacier (Bickerdike et al., 2018) development. If niche glaciers existed here, it was likely as a cold-based icefield source region decayed, briefly leaving behind very small, sheltered warm-based glaciers, comparable to other peripheral regions of the BIIS (Barth et al., 2016; Boyes and Pearce, 2024; Harrison et al., 2015).

Rather than harbouring a thick ice divide during deglaciation (Finlayson et al., 2014; Gandy et al., 2019), the Antrim Hills instead harboured a smaller ($\sim 40 \text{ km}^2$) icefield as ice thinned on the Antrim Plateau and in the North Channel. This icefield is analogous to the small ice masses persisting on the fringes of contemporary ice sheets (Davies and Glasser, 2012; Gillespie et al., 2023; Martin et al., 2022; Saito et al., 2016) and (palaeo-)icefields (Boston et al., 2015; Boston and Lukas, 2019; Chandler et al., 2019; Davies et al., 2024), and would have been particularly sensitive to climatic shifts and changes in internal dynamical processes.

We suggest this icefield persisted during deglaciation prior to the Late Glacial ($>15 \text{ ka BP}$), rather than the Younger Dryas Stadial (c. 12.8–11.7 ka BP). This is because its size ($\sim 40 \text{ km}^2$) and the elevational range of outlet termini ($\sim 230\text{--}250 \text{ m OD}$) are substantially larger than and lower elevation to, respectively, Younger Dryas glaciers found elsewhere in Ireland, reaching $3\text{--}5 \text{ km}^2$ in total area with equilibrium line altitudes of $\sim 550\text{--}600 \text{ m OD}$ (Barr et al., 2017; Knight et al., 2025). The potential for this icefield to have been attached to ice on the Antrim Plateau suggests Flow Stage E occurred broadly contemporaneously with Flow Stage A (Fig. 9b) c. 18–14 ka BP as a minimum-bounding age. However, these hypotheses on the timing of Flow Stage E cannot be confirmed without direct ages.

5.1.6. Flow Stage F: reorganising ice sheet outlet

Flow Stage F represents a drastic reorganisation of lowland outlet lobes dispersing at first from a grounded region over Co. Down and later from a marine-influenced centre in the North Channel. This stage is attributed to the previously described ‘East Antrim Coastal Readvance’ (Finlayson et al., 2014; McCabe and Williams, 2012).

Topographically constrained subglacial bedforms and ice-marginal landforms in the Braid River valley, Glenarm, and Six Mile Water valley (Figs. 2, 6b) reveal warm-based glaciers flowing westward deposited a distinct basalt- and chalk-dominated till (Creighton, 1974) with erratics from northeast Antrim (Hill and Prior, 1968). Glacial lakes may have formed as the ice margin receded (Charlesworth, 1938; Derryhouse, 1923; McCabe and Williams, 2012). Ice margin retreat from glacial lakes in south Antrim (e.g. Lough Neagh) was notably less stable than the retreat of grounded margins. Flow Stage F lineations appear to completely override and replace Flow Stage A lineations in the Braid valley and Six Mile Water valley (Figs. 2, 9). However, east of Lough Neagh around the Belfast Hills and Lagan valley, the transition between these flow stages appears more ‘smeared’.

Ice sheet thinning and flow reorientation during Flow Stage F in the Lagan valley and Belfast Lough is evidenced by progressively lower lateral moraines between Whiteabbey (J 35216 82,485) and Carrickfergus (Fig. 2), as well as valley-confined latero-frontal moraine complexes formed by lobes directed south-westward (e.g. Fig. 6b). Moraine complexes and ice-marginal meltwater channels in these valleys indicate the ice surface never exceeded $\sim 300 \text{ m OD}$ and surface slope towards the ice margin was shallow ($<10^\circ$). Thus, some of the highest summits in the south Antrim Hills and Belfast Hills such as Divis (478 m OD, J 28104 75475), Slemish (437 m OD, D 22191 05353), Big Collin (353 m J 23245

96653), and Carn Hill (312 m OD, J 34662 89108) remained ice-free. This contrasts with McCabe and Williams (2012) and Finlayson et al. (2014) who depict a thicker outlet from Scotland almost entirely overtopping these summits.

This stage represents the fracturing of a thick ice divide over Co. Down and Galloway (southwest Scotland) and the establishment of a new outlet in the North Channel (Finlayson et al., 2014). Lobes in the Braid valley and Antrim Glens appear to have been thicker, grounded, and more stable with consistent flow orientations compared to those further south in the Lagan and Six Mile Water valleys. However, low ice surface elevations and surface slopes imply ice reaching east Antrim from the Firth of Clyde may have been overextending.

Flow Stage F lineations override those of Flow Stage A (Fig. 9a), solidifying that this stage occurred after the decay of the Lough Neagh Ice Dome. By extension, this also makes Flow Stage F older than Flow Stage B and E as both could have occurred as the ice margin withdrew during Flow Stage A (Fig. 9b). Furthermore, thinning Flow Stage F ice means it would not have overtopped the Antrim Hills and fed glacial lakes in the Carey Valley, making it older than Flow Stage D (Fig. 9). Given the disparities in landsystem signature and ice surface elevation between the north and east coasts, it is plausible that Flow Stage F was not coeval with Flow Stage C (cf. Finlayson et al., 2014; McCabe and Williams, 2012).

Minimum deglacial ages for Belfast Lough of $15.7 \pm 0.3 \text{ cal. ka BP}$ (Plets et al., 2019) and the Firth of Clyde of $14.5 \pm 0.2 \text{ cal. ka BP}$ (Peacock et al., 2012) suggest the youngest Flow Stage in the region feasibly occurred between the Killard Point Readvance c. 16.5–16.3 ka BP (McCabe et al., 2007, 2005, 1998; McCabe and Williams, 2012) and the Late Glacial c. 15 ka BP. At this time of deglaciation, the Irish Ice Sheet was likely reducing to an upland source centred over Donegal (Wilson et al., 2019) whilst the margins of Scottish outlets oscillated at lower elevations.

6. Conclusions

Geomorphological and sedimentological investigations in northeast Ireland were employed to study palaeo-ice sheet dynamics in unparalleled detail between the Last Glacial Maximum and the Late Glacial (c. 20–15 ka BP). The largest compendium of glacial landforms mapped in northeast Ireland was produced from a novel 0.4 m resolution photogrammetry DSM with a level of continuous and widespread coverage not seen for areas elsewhere under the BIIS. A morphostratigraphic reconstruction of palaeo-ice sheet dynamics was then established.

We identify six ‘Flow Stages’ in northeast Ireland revealing a complex style of deglaciation: a) lowland Lough Neagh Ice Dome wastage c. 18 ka BP which was briefly accompanied by; b) ephemeral ice stream initiation; c) Malin Sea Ice Stream readvance on the north Antrim coast, whose absolute age (c. 21 ka BP) is discordant with our morphostratigraphic reconstruction (contemporary with or post-dates the Lough Neagh Ice Dome); d) ice-dammed glacial lake development in northeast Antrim coeval with this readvance, followed by; e) icefield development in the Antrim Hills at some point between c. 18–15 ka BP, and finally; f) topographically restricted Scottish outlet grounding in east Antrim after c. 18 ka BP and before c. 14.3–15.7 ka BP.

A major ice dispersal centre over northeast Ireland, connected to southwest Scotland, experienced an unstable wastage influenced by ice sheet thinning, topography, hydrology, and glacial lake dynamics after c. 18 ka BP. Ephemeral ice stream initiation reveals rapid shifts in ice sheet dynamics during terrestrial-based decay. Ice divide migration and fragmentation drove the catastrophic collapse of this terrestrial-based ice centre before c. 14.3–15.7 ka BP.

The Malin Sea Ice Stream impinged on the north Antrim coast potentially as early as c. 20.6 ka BP (Benetti et al., 2021). However, our morphostratigraphic reconstruction suggests this readvance must have been contemporaneous with or younger than the decay of the Lough Neagh ice centre (c. 18 ka BP), highlighting limitations in the existing

suite of dates from this region of the BIIS. Ice originated from a well-nourished Scottish source whilst the northeast Irish Ice Sheet continued to lose mass. The ice stream margin experienced an active, oscillatory retreat once grounding and becoming more stable above sea level.

Icefield development in the Antrim Hills highlights previously unrecognised interactions between small upland centres and major adjacent ice sheet outlets during the unzipping of the BIIS. Due to its potential size and elevational range, it may have been attached to an adjacent terrestrial-based outlet of the Lough Neagh centre at some point c. 18–15 ka BP. Once becoming isolated, it would have been sensitive to climate shifts and the surrounding topography.

CRediT authorship contribution statement

Alexander M. Clark: Writing – review & editing, Writing – original draft, Visualization, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Bethan J. Davies:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Sam Roberson:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **Simon P.E. Blockley:** Supervision, Project administration, Funding acquisition, Conceptualization. **Adrian P. Palmer:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Magret Damaschke:** Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

AMC is supported by the London NERC Doctoral Training Partnership studentship (grant NE/S007229/1). This work was in part funded by the British Geological Survey University Funding Initiative (BUFI) PhD studentship (S476). Additional fieldwork was funded by the Quaternary Research Association (QRA) New Research Workers' Award. The photogrammetry digital surface model was provided to the Geological Survey of Northern Ireland under the Northern Ireland Mapping Agreement (NIMA) by the Ordnance Survey of Northern Ireland, a branch of Land & Property Services and the Department of Finance. We would like to thank the Northern Ireland Environment Agency and private landowners for allowing access to and giving permission to sample in Areas of Special Scientific Interest (ASSI).

Data availability

The data that support the findings of this study are openly available in Mendeley Data. (<https://data.mendeley.com/datasets/xk6svzwwdp/1>)

References

- Aber, J.S., Croot, D.G., Fenton, M.M., 1989. Large composite-ridges. In: Aber, J.S., Croot, D.G., Fenton, M.M. (Eds.), *Glaciotectionic Landforms and Structures*. Springer, Netherlands, Dordrecht, pp. 29–46. https://doi.org/10.1007/978-94-015-6841-8_3.
- Anderson, H., Walsh, J., Cooper, M., 2016. Faults, intrusions and flood basalts: the Cenozoic structure of the north of Ireland. In: Young, M.E. (Ed.), *Unearthed: Impacts of the Tellus Surveys of the North of Ireland*. Royal Irish Academy, Dublin, pp. 179–189.
- Atkins, C., Dickinson, W., 2007. Landscape modification by meltwater channels at margins of cold-based glaciers, Dry Valleys, Antarctica. *Boreas* 36, 47–55. <https://doi.org/10.1080/03009480600827306>.
- Atkinson, N., Pawley, S., Utting, D.J., 2016. Flow-pattern evolution of the Laurentide and Cordilleran ice sheets across west-central Alberta, Canada: implications for ice sheet

- growth, retreat and dynamics during the last glacial cycle. *J. Quat. Sci.* 31, 753–768. <https://doi.org/10.1002/jqs.2901>.
- Ballantyne, C.K., McCarroll, D., Stone, J.O., 2007. The Donegal ice dome, northwest Ireland: dimensions and chronology. *J. Quat. Sci.* 22, 773–783. <https://doi.org/10.1002/jqs.1116>.
- Barr, I.D., Roberson, S., Flood, R., Dortch, J., 2017. Younger Dryas glaciers and climate in the Mourne Mountains, Northern Ireland. *J. Quat. Sci.* 32, 104–115. <https://doi.org/10.1002/jqs.2927>.
- Barr, I.D., Ely, J.C., Spagnolo, M., Evans, I.S., Tomkins, M.D., 2019. The dynamics of mountain erosion: cirque growth slows as landscapes age. *Earth Surf. Process. Landf.* 44, 2628–2637. <https://doi.org/10.1002/esp.4688>.
- Barth, A.M., Clark, P.U., Clark, J., McCabe, A.M., Caffee, M., 2016. Last Glacial Maximum cirque glaciation in Ireland and implications for reconstructions of the Irish Ice Sheet. *Quat. Sci. Rev.* 141, 85–93. <https://doi.org/10.1016/j.quascirev.2016.04.006>.
- Benediktsson, Í.Ö., Ingólfsson, Ó., Schomacker, A., Kjær, K.H., 2009. Formation of submarginal and proglacial end moraines: implications of ice-flow mechanism during the 1963–64 surge of Brúarjökull, Iceland. *Boreas* 38, 440–457. <https://doi.org/10.1111/j.1502-3885.2008.00077.x>.
- Benediktsson, Í.Ö., Schomacker, A., Lokrantz, H., Ingólfsson, Ó., 2010. The 1890 surge end moraine at Eyjabakkajökull, Iceland: a re-assessment of a classic glaciotectionic locality. *Quat. Sci. Rev.* 29, 484–506. <https://doi.org/10.1016/j.quascirev.2009.10.004>.
- Benediktsson, Í.Ö., Aradóttir, N., Ingólfsson, Ó., Brynjólfsson, S., 2022. Cross-cutting palaeo-ice streams in NE-Iceland reveal shifting Iceland Ice Sheet dynamics. *Geomorphology* 396. <https://doi.org/10.1016/j.geomorph.2021.108009>.
- Benetti, S., Chiverrell, R.C., Ó Cofaigh, C., Burke, M., Medialdea, A., Small, D., Ballantyne, C., Bateman, M.D., Callard, S.L., Wilson, P., Fabel, D., Clark, C.D., Arosio, R., Bradley, S., Dunlop, P., Ely, J.C., Gales, J., Livingstone, S.J., Moreton, S.G., Purcell, C., Saher, M., Schiele, K., Van Landeghem, K., Weilbach, K., 2021. Exploring controls of the early and stepped deglaciation on the western margin of the British Irish Ice Sheet. *J. Quat. Sci.* 36, 833–870. <https://doi.org/10.1002/jqs.3315>.
- Benn, D.I., 1992. The genesis and significance of “hummocky moraine”: evidence from the Isle of Skye, Scotland. *Quat. Sci. Rev.* 11, 781–799. [https://doi.org/10.1016/0277-3791\(92\)90083-K](https://doi.org/10.1016/0277-3791(92)90083-K).
- Benn, D.I., Ballantyne, C.K., 1993. The description and representation of particle shape. *Earth Surf. Process. Landf.* 18, 665–672. <https://doi.org/10.1002/esp.3290180709>.
- Benn, D.I., Ballantyne, C.K., 1994. Reconstructing the transport history of glacialine sediments: a new approach based on the co-variance of clast form indices. *Sediment. Geol.* 91, 215–227.
- Benn, D.I., Lukas, S., 2021. Clast shape. In: Evans, D.J.A., Benn, D.I. (Eds.), *A Practical Guide to the Study of Glacial Sediments*. Quaternary Research Association, Ruddington, pp. 107–124.
- Bennett, M.R., 2001. The morphology, structural evolution and significance of push moraines. *Earth Sci. Rev.* 53, 197–236.
- Bennett, M.R., Hambrey, M.J., Huddart, D., 1997. Modification of clast shape in high-Arctic glacial environments. *J. Sediment. Res.* 67, 550–559.
- Bickerdike, H.L., Ó Cofaigh, C., Evans, D.J.A., Stokes, C.R., 2018. Glacial landsystems, retreat dynamics and controls on Loch Lomond Stadial (Younger Dryas) glaciation in Britain. *Boreas* 47, 202–224. <https://doi.org/10.1111/bor.12259>.
- Boston, C.M., Lukas, S., 2019. Topographic controls on plateau icefield recession: insights from the Younger Dryas Monadhliath Icefield, Scotland. *J. Quat. Sci.* 34, 433–451. <https://doi.org/10.1002/jqs.3111>.
- Boston, C.M., Lukas, S., Carr, S.J., 2015. A Younger Dryas plateau icefield in the Monadhliath, Scotland, and implications for regional palaeoclimate. *Quat. Sci. Rev.* 108, 139–162. <https://doi.org/10.1016/j.quascirev.2014.11.020>.
- Boulton, G.S., 1976. The origin of glacially fluted surfaces-observations and theory. *J. Glaciol.* 17, 287–309. <https://doi.org/10.3189/s0022143000013605>.
- Boulton, G.S., Van Der Meer, J.J.M., Beets, D.J., Hart, J.K., Ruegg, G.H.J., 1999. The sedimentary and structural evolution of a recent push moraine complex: Holmströmbreen, Spitsbergen. *Quat. Sci. Rev.* 18, 339–371.
- Bowen, D.Q., Phillips, F.M., McCabe, A.M., Knutz, P.C., Sykes, G.A., 2002. New data for the Last Glacial Maximum in Great Britain and Ireland. *Quat. Sci.* 21, 89–101.
- Boyes, B.M., Pearce, D.M., 2024. Evidence of palaeo-cirque glaciers in the Ewes Valley, southern Scotland. *Scott. Geogr. J.* <https://doi.org/10.1080/14702541.2024.2341936>.
- Bradwell, T., Stoker, M., Krabbendam, M., 2008. Megagrooves and streamlined bedrock in NW Scotland: the role of ice streams in landscape evolution. *Geomorphology* 97, 135–156. <https://doi.org/10.1016/j.geomorph.2007.02.040>.
- Bradwell, T., Fabel, D., Clark, C.D., Chiverrell, R.C., Small, D., Smedley, R.K., Saher, M.H., Moreton, S.G., Dove, D., Callard, S.L., Duller, G.A.T., Medialdea, A., Bateman, M.D., Burke, M.J., McDonald, N., Gilgannon, S., Morgan, S., Roberts, D.H., Ó Cofaigh, C., 2021. Pattern, style and timing of British-Irish Ice Sheet advance and retreat over the last 45 000 years: evidence from NW Scotland and the adjacent continental shelf. *J. Quat. Sci.* 36, 871–933. <https://doi.org/10.1002/jqs.3296>.
- Brennand, T.A., 2000. Deglacial meltwater drainage and glaciodynamics: inferences from Laurentide eskers, Canada. *Geomorphology* 32, 263–293.
- Bromley, G., Bunce, C., Hall, B., Putnam, A., McDermott, F., 2026. Deglaciation of the Burren glacio-karst, western Ireland, during Termination 1: implications for North Atlantic climate and karstification. *J. Quat. Sci.* <https://doi.org/10.1002/jqs.70068>.
- Callard, S.L., Ó Cofaigh, C., Benetti, S., Chiverrell, R.C., Van Landeghem, K.J.J., Saher, M.H., Gales, J.A., Small, D., Clark, C.D., Livingstone, S.J., Fabel, D., Moreton, S.G., 2018. Extent and retreat history of the Barra Fan Ice Stream offshore western

- Scotland and northern Ireland during the last glaciation. *Quat. Sci. Rev.* 201, 280–302. <https://doi.org/10.1016/j.quascirev.2018.10.002>.
- Chandler, B.M.P., Lovell, H., Boston, C.M., Lukas, S., Barr, I.D., Benediktsson, Í.Ö., Benn, D.I., Clark, C.D., Darvill, C.M., Evans, D.J.A., Ewertowski, M.W., Loibl, D., Margold, M., Otto, J.C., Roberts, D.H., Stokes, C.R., Storror, R.D., Stroeven, A.P., 2018. Glacial geomorphological mapping: a review of approaches and frameworks for best practice. *Earth Sci. Rev.* 185, 806–846. <https://doi.org/10.1016/j.earscirev.2018.07.015>.
- Chandler, B.M.P., Boston, C.M., Lukas, S., 2019. A spatially-restricted Younger Dryas plateau icefield in the Gaick, Scotland: reconstruction and palaeoclimatic implications. *Quat. Sci. Rev.* 211, 107–135. <https://doi.org/10.1016/j.quascirev.2019.03.019>.
- Chandler, B.M.P., Chandler, S.J.P., Evans, D.J.A., Ewertowski, M.W., Lovell, H., Roberts, D.H., Schaefer, M., Tomczyk, A.M., 2020. Sub-annual moraine formation at an active temperate Icelandic glacier. *Earth Surf. Process. Landf.* 45, 1622–1643. <https://doi.org/10.1002/esp.4835>.
- Charlesworth, J.K., 1938. Some observations on the glaciation of North-East Ireland. *Proc. Roy. Irish Acad.*, B 45, 255–295.
- Chiverrell, R.C., Thrasher, I.M., Thomas, G.S.P., Lang, A., Scourse, J.D., van Landeghem, K.J.J., McCarroll, D., Clark, C.D., Ó Cofaigh, C., Evans, D.J.A., Ballantyne, C.K., 2013. Bayesian modelling the retreat of the Irish Sea Ice Stream. *J. Quat. Sci.* 28, 200–209. <https://doi.org/10.1002/jqs.2616>.
- Chiverrell, R.C., Smedley, R.K., Small, D., Ballantyne, C.K., Burke, M.J., Callard, S.L., Clark, C.D., Duller, G.A.T., Evans, D.J.A., Fabel, D., van Landeghem, K., Livingstone, S., Ó Cofaigh, C., Thomas, G.S.P., Roberts, D.H., Saher, M., Scourse, J.D., Wilson, P., 2018. Ice margin oscillations during deglaciation of the northern Irish Sea Basin. *J. Quat. Sci.* 33, 739–762. <https://doi.org/10.1002/jqs.3057>.
- Clark, C.D., 1993. Mega-scale glacial lineations and cross-cutting ice-flow landforms. *Earth Surf. Process. Landf.* 18, 1–29. <https://doi.org/10.1002/esp.3290180102>.
- Clark, C.D., Meehan, R.T., 2001. Subglacial bedform geomorphology of the Irish Ice Sheet reveals major configuration changes during growth and decay. *J. Quat. Sci.* 16, 483–496. <https://doi.org/10.1002/jqs.627>.
- Clark, C.D., Stokes, C.R., 2013. Palaeo-ice stream landform. In: Evans, D.J.A. (Ed.), *Glacial Landforms*. Routledge, London, pp. 204–227.
- Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Spagnolo, M., Ng, F.S.L., 2009a. Size and shape characteristics of drumlins, derived from a large sample, and associated scaling laws. *Quat. Sci. Rev.* 28, 677–692. <https://doi.org/10.1016/j.quascirev.2008.08.035>.
- Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009b. The Last Glacial maximum. *Science* 325, 710–714.
- Clark, C.D., Ely, J.C., Hindmarsh, R.C.A., Bradley, S., Ignézi, A., Fabel, D., Ó Cofaigh, C., Chiverrell, R.C., Scourse, J., Benetti, S., Bradwell, T., Evans, D.J.A., Roberts, D.H., Burke, M., Callard, S.L., Medialdea, A., Saher, M., Small, D., Smedley, R.K., Gasson, E., Gregoire, L., Gandy, N., Hughes, A.L.C., Ballantyne, C., Bateman, M.D., Bigg, G.R., Doole, J., Dove, D., Duller, G.A.T., Jenkins, G.T.H., Livingstone, S.L., McCarron, S., Moreton, S., Pollard, D., Praeg, D., Sejrup, H.P., Van Landeghem, K.J., Wilson, P., 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>.
- Cooper, M.R., Johnston, T.P., 2005. Central highlands (Grampian) terrane - metamorphic basement. In: Mitchell, W.I. (Ed.), *The Geology of Northern Ireland: Our Natural Foundation*. Geological Survey of Northern Ireland, Belfast, pp. 9–24.
- Cooper, M.R., Mitchell, W.I., 2005. Midland valley terrane. In: Mitchell, W.I. (Ed.), *The Geology of Northern Ireland: Our Natural Foundation*. Geological Survey of Northern Ireland, Belfast, pp. 25–40.
- Cooper, M.R., Tapster, S., Condon, D.J., 2026. Feeling the pulse? Paleogene chronostratigraphy of Northern Ireland and the north of Ireland temporally coupled to the North Atlantic Igneous Province. *Geology* 54, 539–544. <https://doi.org/10.1130/G54157.1>.
- Creighton, J.R., 1974. *A study of the Late Pleistocene geomorphology of North-Central Ulster*. Belfast.
- Dardis, G.F., 1990a. Vow. In: Wilson, P. (Ed.), *Field Guide No. 13: North Antrim and Londonderry*. Irish Association for Quaternary Studies, Dublin, pp. 85–88.
- Dardis, G.F., 1990b. Runkerry. In: Wilson, P. (Ed.), *Field Guide No. 13: North Antrim and Londonderry*. Irish Association for Quaternary Studies, Dublin, pp. 52–54.
- Davies, B.J., Glasser, N.F., 2012. Accelerating shrinkage of Patagonian glaciers from the Little Ice Age (~AD 1870) to 2011. *J. Glaciol.* 58, 1063–1084. <https://doi.org/10.3189/2012JoG12J026>.
- Davies, B., McNabb, R., Bendle, J., Carrivick, J., Ely, J., Holt, T., Markle, B., McNeil, C., Nicholson, L., Pelto, M., 2024. Accelerating glacier volume loss on Juneau Icefield driven by hypsometry and melt-accelerating feedbacks. *Nat. Commun.* 15. <https://doi.org/10.1038/s41467-024-49269-y>.
- Delaney, C.A., McCarron, S., Davis, S., 2018. Irish Ice Sheet dynamics during deglaciation of the central Irish Midlands: evidence of ice streaming and surging from airborne LiDAR. *Geomorphology* 306, 235–253. <https://doi.org/10.1016/j.geomorph.2018.01.011>.
- Delaney, C.A., Adamson, K., Lynch, L.D., Davis, S., McCarron, S., 2023. Reconstructing terrestrial ice sheet retreat dynamics from hummocky topography using multiscale evidence: an example from central Ireland. *Quat. Sci. Rev.* 308. <https://doi.org/10.1016/j.quascirev.2023.108041>.
- Delaney, C.A., Adamson, K.R., Lane, T.P., Hughes, P.D., Gheorghiu, D., Fabel, D., 2026. Reconstruction and 36Cl based geochronology of the deglaciation of central Ireland. *Quat. Sci. Rev.* 378. <https://doi.org/10.1016/j.quascirev.2026.109846>.
- Delmas, M., Gunnell, Y., Calvet, M., 2014. Environmental controls on alpine cirque size. *Geomorphology* 206, 318–329. <https://doi.org/10.1016/j.geomorph.2013.09.037>.
- Dunlop, P., Clark, C.D., 2006. The morphological characteristics of ribbed moraine. *Quat. Sci. Rev.* 25, 1668–1691. <https://doi.org/10.1016/j.quascirev.2006.01.002>.
- Dwerryhouse, 1923. *The Glaciation of north-eastern Ireland*. *Quart. J. Geol. Soc. Lond.* 79.
- Ely, J.C., Clark, C.D., Spagnolo, M., Hughes, A.L.C., Stokes, C.R., 2018. Using the size and position of drumlins to understand how they grow, interact and evolve. In: Presented at the Earth Surface Processes and Landforms. John Wiley and Sons Ltd, pp. 1073–1087. <https://doi.org/10.1002/esp.4241>.
- Ely, J.C., Clark, C.D., Hindmarsh, R.C.A., Hughes, A.L.C., Greenwood, S.L., Bradley, S.L., Gasson, E., Gregoire, L., Gandy, N., Stokes, C.R., Small, D., 2021. Recent progress on combining geomorphological and geochronological data with ice sheet modelling, demonstrated using the last British-Irish Ice Sheet. *J. Quat. Sci.* 36, 946–960. <https://doi.org/10.1002/jqs.3098>.
- Ely, J.C., Stevens, D., Clark, C.D., Butcher, F.E.G., 2023. Numerical modelling of subglacial ribs, drumlins, herringbones, and mega-scale glacial lineations reveals their developmental trajectories and transitions. *Earth Surf. Process. Landf.* 48, 956–978. <https://doi.org/10.1002/esp.5529>.
- Ely, J.C., Clark, C.D., Bradley, S.L., Gregoire, L., Gandy, N., Gasson, E., Veness, R.L.J., Archer, R., 2024. Behavioural tendencies of the last British-Irish Ice Sheet revealed by data-model comparison. *J. Quat. Sci.* 39, 839–871. <https://doi.org/10.1002/jqs.3628>.
- Evans, D.J.A., 2000. Quaternary geology and geomorphology of the Dinosaur Provincial Park area and surrounding plains, Alberta, Canada: the identification of former glacial lobes, drainage diversions and meltwater food tracks. *Quat. Sci. Rev.* 19, 931–958.
- Evans, I.S., 2006. Allometric development of glacial cirque form: geological, relief and regional effects on the cirques of Wales. *Geomorphology* 80, 245–266. <https://doi.org/10.1016/j.geomorph.2006.02.013>.
- Evans, D.J.A., 2009. Controlled moraines: origins, characteristics and palaeoglaciological implications. *Quat. Sci. Rev.* 28, 183–208. <https://doi.org/10.1016/j.quascirev.2008.10.024>.
- Evans, D.J.A., Campbell, I.A., 1992. Evans and Campbell 1992 article. *Quat. Sci. Rev.* 11.
- Evans, D.J.A., Hansom, J.D., 1996. The edinburgh castle crag-and-tail. *Scott. Geogr. Mag.* 112, 129–131. <https://doi.org/10.1080/14702549608554461>.
- Evans, D.J.A., Rea, B.R., 2013. Surging glacier landform. In: Evans, D.J.A. (Ed.), *Glacial Landforms*. Routledge, London, pp. 259–288.
- Evans, D.J.A., Lemmen, D.S., Rea, B.R., 1999. Glacial landforms of the southwest Laurentide Ice Sheet: modern Icelandic analogues. *J. Quat. Sci.* 14, 673–691. [https://doi.org/10.1002/\(SICI\)1099-1417\(199912\)14:7%3C673::AID-JQS467%3E3.0.CO;2](https://doi.org/10.1002/(SICI)1099-1417(199912)14:7%3C673::AID-JQS467%3E3.0.CO;2).
- Evans, D.J.A., Clark, C.D., Mitchell, W.A., 2005. The last British Ice Sheet: a review of the evidence utilised in the compilation of the Glacial Map of Britain. *Earth Sci. Rev.* 70, 253–312. <https://doi.org/10.1016/j.earscirev.2005.01.001>.
- Evans, D.J.A., Clark, C.D., Rea, B.R., 2008. Landform and sediment imprints of fast glacier flow in the southwest Laurentide Ice Sheet. *J. Quat. Sci.* 23, 249–272. <https://doi.org/10.1002/jqs.1141>.
- Evans, D.J.A., Young, N.J.P., Ó Cofaigh, C., 2014. Glacial geomorphology of terrestrial-terminating fast flow lobes/ice stream margins in the southwest Laurentide Ice Sheet. *Geomorphology* 204, 86–113. <https://doi.org/10.1016/j.geomorph.2013.07.031>.
- Everest, J., Bradwell, T., Gollidge, N., 2005. Subglacial landforms of the tweed palaeo-ice stream. *Scott. Geogr. J.* 121, 163–173. <https://doi.org/10.1080/00369220518737229>.
- Eyles, N., 2012. Rock drumlins and megaflutes of the Niagara Escarpment, Ontario, Canada: a hard bed landform assemblage cut by the Saginaw-Huron Ice Stream. *Quat. Sci. Rev.* 55, 34–49. <https://doi.org/10.1016/j.quascirev.2012.09.001>.
- Finlayson, A., Gollidge, N., Bradwell, T., Fabel, D., 2011. Evolution of a Lateglacial mountain icecap in northern Scotland. *Boreas* 40, 536–554. <https://doi.org/10.1111/j.1502-3885.2010.00202.x>.
- 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. *Quat. Sci. Rev.* 83, 28–45. <https://doi.org/10.1016/j.quascirev.2013.10.009>.
- Foreman, A.C., Bromley, G.R.M., Hall, B.L., Jackson, M.S., 2022. A 10Be-dated record of glacial retreat in Connemara, Ireland, following the Last Glacial Maximum and implications for regional climate. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 592. <https://doi.org/10.1016/j.palaeo.2022.110901>.
- Foreman, A.C., Bromley, G.R.M., Hall, B.L., Rodríguez, P.C., 2025. Thinning and retreat of the temperate Connemara ice centre, Ireland, during Heinrich Stadial 1 constrained with cosmogenic 10Be dating. *Geomorphology* 475. <https://doi.org/10.1016/j.geomorph.2025.109661>.
- Fowler, A.C., 2000. An instability mechanism for drumlin formation. In: Maltman, A.J., Hubbard, B., Hambrey, M.J. (Eds.), *Deformation of Glacial Materials*. The Geological Society, Bath, pp. 307–320.
- Fyfe, G.J., 1990. The effect of water depth on ice-proximal glaciolacustrine sedimentation: Salpausselkä I, southern Finland. *Boreas* 19, 147–164. <https://doi.org/10.1111/j.1502-3885.1990.tb00576.x>.
- Gandy, N., Gregoire, L.J., Ely, J.C., Cornford, S.L., Clark, C.D., Hodgson, D.M., 2019. Exploring the ingredients required to successfully model the placement, generation, and evolution of ice streams in the British-Irish Ice Sheet. *Quat. Sci. Rev.* 223. <https://doi.org/10.1016/j.quascirev.2019.105915>.
- Geldard, J.A.S., Bradwell, T., Benn, D.I., 2024. Megaflutes in the Menteith hills, central Scotland. *Scott. Geogr. J.* <https://doi.org/10.1080/14702541.2024.2432317>.

- Gillespie, M.K., Yde, J.C., Andresen, M.S., Citterio, M., Gillespie, M.A.K., 2023. Ice geometry and thermal regime of Lyngmarksbræen Ice Cap, West Greenland. *J. Glaciol.* <https://doi.org/10.1017/jog.2023.89>.
- Glasser, N.F., Harrison, S., Jansson, K.N., 2009. Topographic controls on glacier sediment-landform associations around the temperate North Patagonian Icefield. *Quat. Sci. Rev.* 28, 2817–2832. <https://doi.org/10.1016/j.quascirev.2009.07.011>.
- Gordon, J.E., Brian Whalley, W., Gellatly, A.F., Vere, D.M., 1992. The formation of glacial flutes: assessment of models with evidence from Lyngsdalen, North Norway. *Quat. Sci. Rev.* 11, 709–731. [https://doi.org/10.1016/0277-3791\(92\)90079-N](https://doi.org/10.1016/0277-3791(92)90079-N).
- Greenwood, S.L., Clark, C.D., 2008. Subglacial bedforms of the Irish ice sheet. *J. Maps* 4, 332–357. <https://doi.org/10.4113/jom.2008.1030>.
- Greenwood, S.L., Clark, C.D., 2009a. Reconstructing the last Irish Ice Sheet 1: changing flow geometries and ice flow dynamics deciphered from the glacial landform record. *Quat. Sci. Rev.* 28, 3085–3100. <https://doi.org/10.1016/j.quascirev.2009.09.008>.
- Greenwood, S.L., Clark, C.D., 2009b. Reconstructing the last Irish Ice Sheet 2: a geomorphologically-driven model of ice sheet growth, retreat and dynamics. *Quat. Sci. Rev.* 28, 3101–3123. <https://doi.org/10.1016/j.quascirev.2009.09.014>.
- Greenwood, S.L., Clason, C.C., Nyberg, J., Jakobsson, M., Holmlund, P., 2017. The Bothnian Sea ice stream: early Holocene retreat dynamics of the south-central Fennoscandian Ice Sheet. *Boreas* 46, 346–362. <https://doi.org/10.1111/bor.12217>.
- Greenwood, S.L., Avery, R.S., Gyllencreutz, R., Regnéll, C., Tylmann, K., 2024. Footprint of the Baltic Ice Stream: geomorphic evidence for shifting ice stream pathways. *Boreas* 53, 4–26. <https://doi.org/10.1111/bor.12634>.
- Hall, A.M., Riding, J.B., 2016. The last glaciation in Caithness, Scotland: revised till stratigraphy and ice-flow paths indicate multiple ice flow phases. *Scott. J. Geol.* 52, 77–89. <https://doi.org/10.1144/sjg2016-001>.
- Hall, A.M., Ebert, K., Hättestrand, C., 2013. Pre-glacial landform inheritance in a glaciated shield landscape. *Geogr. Ann. Ser. B* 95, 33–49. <https://doi.org/10.1111/j.1468-0459.2012.00477.x>.
- Hambrey, M.J., Glasser, N.F., 2012. Discriminating glacier thermal and dynamic regimes in the sedimentary record. *Sediment. Geol.* 251–252, 1–33. <https://doi.org/10.1016/j.sedgeo.2012.01.008>.
- Hambrey, M.J., Huddart, D., 1995. Englacial and proglacial glaciotectonic processes at the snout of a thermally complex glacier in Svalbard. *J. Quat. Sci.* 10, 313–326. <https://doi.org/10.1002/jqs.3390100402>.
- Hambrey, M.J., Huddart, D., Bennett, M.R., Glasser, N.F., 1997. Genesis of ‘hummocky moraines’ by thrusting in glacier ice: evidence from Svalbard and Britain. *JGS* 154, 623–632. <https://doi.org/10.1144/gsjgs.154.4.0623>.
- Harrison, S., Knight, J., Rowan, A.V., 2015. The southernmost Quaternary niche glacier system in Great Britain. *J. Quat. Sci.* 30, 325–334. <https://doi.org/10.1002/jqs.2772>.
- Hart, J.K., 1990. Proglacial glaciotectonic deformation and the origin of the Cromer Ridge push moraine complex, North Norfolk, England. *Boreas* 19, 165–180. <https://doi.org/10.1111/j.1502-3885.1990.tb00577.x>.
- Hart, J.K., Boulton, G.S., 1991. The interrelation of glaciotectonic and glaciodepositional processes within the glacial environment. *Quat. Sci. Rev.* 10, 335–350.
- Hättestrand, C., Kleman, J., 1999. Ribbed moraine formation. *Quat. Sci. Rev.* 18, 43–61.
- Haynes, V.M., 1968. The influence of glacial erosion and rock structure on corries in Scotland. *Geogr. Ann. Ser. A, Phys. Geogr.* 50.
- Hewitt, J.L., Creyts, T.T., 2019. A model for the formation of Eskers. *Geophys. Res. Lett.* 46, 6673–6680. <https://doi.org/10.1029/2019GL082304>.
- Hickin, A.S., Lian, O.B., Levson, V.M., Cui, Y., 2015. Pattern and chronology of glacial Lake Peace shorelines and implications for isostasy and ice-sheet configuration in northeastern British Columbia, Canada. *Boreas* 44, 288–304. <https://doi.org/10.1111/bor.12110>.
- Hiemstra, J.F., Matthews, J.A., Evans, D.J.A., Owen, G., 2015. Sediment fingerprinting and the mode of formation of singular and composite annual moraine ridges at two glacier margins, Jotunheimen, southern Norway. *Holocene* 25, 1772–1785. <https://doi.org/10.1177/0959683615591359>.
- Hill, A.R., 1973. The distribution of drumlins in county down. *Ann. Assoc. Am. Geogr.* 63, 226–240.
- Hill, A.R., Prior, D.B., 1968. Directions of ice movement in north-east Ireland. *Proc. Roy. Irish Acad.*, B 66, 71–84.
- Hoek, W.Z., 2008. The last glacial-interglacial transition. *Episodes* 31, 226–229.
- Hooke, R.L., 1991. Positive feedbacks associated with erosion of glacial cirques and overdeepenings. *Geol. Soc. Am. Bull.* 103, 1104–1108.
- Hooke, R.L.B., Jennings, C.E., 2006. On the formation of the tunnel valleys of the southern Laurentide ice sheet. *Quat. Sci. Rev.* 25, 1364–1372. <https://doi.org/10.1016/j.quascirev.2006.01.018>.
- Huddart, D., Hambrey, M.J., 1996. Sedimentary and tectonic development of a high-arctic, thrust-moraine complex: Comfortlessreen, Svalbard. *Boreas* 25, 227–243. <https://doi.org/10.1111/j.1502-3885.1996.tb00639.x>.
- Hughes, A.L.C., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J., Svendsen, J.I., 2016. The last Eurasian ice sheets - a chronological database and time-slice reconstruction, DATED-1. *Boreas* 45, 1–45. <https://doi.org/10.1111/bor.12142>.
- Iverson, N.R., 1991. Potential effects of subglacial water-pressure fluctuations on quarrying. *J. Glaciol.* 37, 27–36. <https://doi.org/10.1017/S0022143000042763>.
- Jennings, C.E., 2006. Terrestrial ice streams-a view from the lobe. *Geomorphology* 75, 100–124. <https://doi.org/10.1016/j.geomorph.2005.05.016>.
- Johnsen, T., Brennand, T., 2006. The environment in and around ice-dammed lakes in the moderately high relief setting of the southern Canadian Cordillera. *Boreas* 35, 106–125. <https://doi.org/10.1080/03009480500359145>.
- Kilroe, J.R., 1913. Outline of geological observations in north-east Londonderry collected during the progress of revision work. In: *Proceedings of the Belfast Naturalists Field Club*. Belfast Naturalists Field Club, Belfast, pp. 634–663.
- Kirkham, J.D., Hogan, K.A., Larter, R.D., Arnold, N.S., Ely, J.C., Clark, C.D., Self, E., Games, K., Huuse, M., Stewart, M.A., Ottesen, D., Dowdeswell, J.A., 2024. Tunnel valley formation beneath deglaciating mid-latitude ice sheets: observations and modelling. *Quat. Sci. Rev.* 323. <https://doi.org/10.1016/j.quascirev.2022.107680>.
- Kleman, J., Applegate, P.J., 2014. Durations and propagation patterns of ice sheet instability events. *Quat. Sci. Rev.* 92, 32–39. <https://doi.org/10.1016/j.quascirev.2013.07.030>.
- Kleman, J., Borgström, I., Robertsson, A.-M., Lilliesköld, M., 1992. Morphology and stratigraphy from several deglaciations in the Transtrand Mountains, western Sweden. *J. Quat. Sci.* 7, 1–17. <https://doi.org/10.1002/jqs.3390070102>.
- Knight, J., 2004. Sedimentary evidence for the formation mechanism of the Armoyle moraine and Late Devensian glacial events in the north of Ireland. *Geol. J.* 39, 403–417.
- Knight, J., McCarron, S.G., McCabe, A.M., 1999. Landform modification by palaeo-ice streams in east-central Ireland. *Ann. Glaciol.* 28, 161–167. <https://doi.org/10.3189/172756499781821616>.
- Knight, L., Boston, C.M., Lovell, H., Barrows, T.T., Colhoun, E.A., Fink, D., Pepin, N.C., 2025. Restricted cirque glaciers in the Wicklow Mountains, Ireland, during the Nahanagan Stadial (Greenland Stadial-1/Younger Dryas). *J. Quat. Sci.* <https://doi.org/10.1002/jqs.3699>.
- Knudsen, C.G., Larsen, E., Sejrup, H.P., Stalsberg, K., 2006. Hummocky moraine landscape on Jæren, SW Norway-implications for glacier dynamics during the last deglaciation. *Geomorphology* 77, 153–168. <https://doi.org/10.1016/j.geomorph.2005.12.011>.
- Krabbendam, M., Bradwell, T., 2011. Lateral plucking as a mechanism for elongate erosional glacial bedforms: explaining megagrooves in Britain and Canada. *Earth Surf. Process. Landf.* 36, 1335–1349. <https://doi.org/10.1002/esp.2157>.
- Krabbendam, M., Eyles, N., Putkinen, N., Bradwell, T., Arbelaez-Moreno, L., 2016. Streamlined hard beds formed by palaeo-ice streams: a review. *Sediment. Geol.* 338, 24–50. <https://doi.org/10.1016/j.sedgeo.2015.12.007>.
- Livingstone, S.J., Storrar, R.D., Hillier, J.K., Stokes, C.R., Clark, C.D., Tarasov, L., 2015. An ice-sheet scale comparison of eskers with modelled subglacial drainage routes. *Geomorphology* 246, 104–112. <https://doi.org/10.1016/j.geomorph.2015.06.016>.
- Lønne, I., 2016. A new concept for glacial geological investigations of surges, based on High-Arctic examples (Svalbard). *Quat. Sci. Rev.* 132, 74–100. <https://doi.org/10.1016/j.quascirev.2015.11.009>.
- Lovell, H., Benn, D.I., Lukas, S., Spagnolo, M., Cook, S.J., Swift, D.A., Clark, C.D., Yde, J. C., Watts, T., 2018. Geomorphological investigation of multiphase glaciectonic composite ridge systems in Svalbard. *Geomorphology* 300, 176–188. <https://doi.org/10.1016/j.geomorph.2017.10.024>.
- Lowe, J.J., Walker, M.J.C., Scott, E.M., Harkness, D.D., Bryant, C.L., Davies, S.M., 2004. A coherent high-precision radiocarbon chronology for the Late-glacial sequence at Sluggan Bog, Co. Antrim, Northern Ireland. *J. Quat. Sci.* 19, 147–158. <https://doi.org/10.1002/jqs.814>.
- Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J.C., Yu, Z.C., 2008. Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. *Quat. Sci. Rev.* 27, 6–17. <https://doi.org/10.1016/j.quascirev.2007.09.016>.
- Lukas, S., Benn, D.I., Boston, C.M., Brook, M., Coray, S., Evans, D.J.A., Graf, A., Kellerer-Pirkbauer, A., Kirkbride, M.P., Krabbendam, M., Lovell, H., Machiedo, M., Mills, S. C., Nye, K., Reinardy, B.T.I., Ross, F.H., Signer, M., 2013. Clast shape analysis and clast transport paths in glacial environments: a critical review of methods and the role of lithology. *Earth Sci. Rev.* 121, 96–116. <https://doi.org/10.1016/j.earscirev.2013.02.005>.
- Lundqvist, J., 1989. Rogen (ribbed) moraine and possible origin identification. *Sediment. Geol.* 62, 281–292.
- Lyle, P., Thompson, S.J., 1983. The classification and chemistry of the Tertiary intermediate lavas of Northeast Ireland. *Scott. J. Geol.* 19, 17–27.
- MacGregor, K.R., Anderson, R.S., Waddington, E.D., 2009. Numerical modeling of glacial erosion and headwall processes in alpine valleys. *Geomorphology* 103, 189–204. <https://doi.org/10.1016/j.geomorph.2008.04.022>.
- Margold, M., Stokes, C.R., Clark, C.D., 2015. Ice streams in the Laurentide Ice Sheet: identification, characteristics and comparison to modern ice sheets. *Earth Sci. Rev.* 143, 117–146. <https://doi.org/10.1016/j.earscirev.2015.01.011>.
- Margold, M., Stokes, C.R., Clark, C.D., 2018. Reconciling records of ice streaming and ice margin retreat to produce a palaeogeographic reconstruction of the deglaciation of the Laurentide Ice Sheet. *Quat. Sci. Rev.* 189, 1–30. <https://doi.org/10.1016/j.quascirev.2018.03.013>.
- Martin, J., Davies, B.J., Jones, R., Thorndycraft, V., 2022. Modelled sensitivity of Monte San Lorenzo ice cap, Patagonian Andes, to past and present climate. *Front. Earth Sci.* 10. <https://doi.org/10.3389/feart.2022.831631>.
- McCabe, A.M., Eyles, N., 1988. Sedimentology of an ice-contact glaciomarine delta, Carey Valley, Northern Ireland. *Sediment. Geol.* 59, 1–14.
- 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. *Quat. Sci. Rev.* 58, 18–29. <https://doi.org/10.1016/j.quascirev.2012.10.012>.
- McCabe, A.M., Carter, R.W.G., Haynes, J.R., 1994. A shallow marine emergent sequence from the northwestern sector of the last British ice sheet, Portballintrae, Northern Ireland. *Mar. Geol.* 117, 19–34. [https://doi.org/10.1016/0025-3227\(94\)90004-3](https://doi.org/10.1016/0025-3227(94)90004-3).
- McCabe, A.M., Knight, J., McCarron, S., 1998. Evidence for Heinrich event 1 in the British Isles. *J. Quat. Sci.* 13, 549–568. [https://doi.org/10.1002/\(SICI\)1099-1417\(199810\)13:6%3C549::AID-JQS394%3E3.0.CO;2-A](https://doi.org/10.1002/(SICI)1099-1417(199810)13:6%3C549::AID-JQS394%3E3.0.CO;2-A).

- McCabe, A.M., Knight, J., McCarron, S.G., 1999. Ice-flow stages and glacial bedforms in north central Ireland: a record of rapid environmental change during the last glacial termination. *J. Geol. Soc. Lond.* 156, 63–72.
- McCabe, A.M., Clark, P.U., Clark, J., Dunlop, P., 2005. AMS ¹⁴C dating of deglacial events in the Irish Sea Basin and other sectors of the British-Irish ice sheet. *Quat. Sci. Rev.* 24, 1673–1690. <https://doi.org/10.1016/j.quascirev.2004.06.019>.
- McCabe, A.M., Clark, P.U., Clark, J., Dunlop, P., 2007. Radiocarbon constraints on readvances of the British-Irish Ice Sheet in the northern Irish Sea Basin during the last deglaciation. *Quat. Sci. Rev.* 26, 1204–1211. <https://doi.org/10.1016/j.quascirev.2007.01.010>.
- Meehan, R.T., 1999. Directions of ice flow during the last glaciation in counties Meath, Westmeath and Cavan. *Ir. Geogr.* 32, 26–51.
- 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. *Proc. Geol. Assoc.* 129, 583–609. <https://doi.org/10.1016/j.pgeola.2018.04.001>.
- Mitchell, W.I., 2005. Late Palaeogene (Oligocene) sedimentary basins. In: Mitchell, W.I. (Ed.), *The Geology of Northern Ireland: Our Natural Foundation*. Geological Survey of Northern Ireland, Belfast, pp. 199–204.
- Mitchell, W.I., Cooper, M., McKeever, P., McConnell, B., 2010. County Antrim Coast Road, Glens and The Giant's Causeway. In: Mitchell, I., Cooper, M., McKeever, P., McConnell, B. (Eds.), *The Classic Geology of the North of Ireland*. Geological Survey of Northern Ireland, Belfast, pp. 1–21.
- Mulder, T., Alexander, J., 2001. The physical character of subaqueous sedimentary density flow and their deposits. *Sedimentology* 48, 269–299. <https://doi.org/10.1046/j.1365-3091.2001.00360.x>.
- Norris, S.L., Margold, M., Froese, D.G., 2017. Glacial landforms of northwest saskatchewan. *J. Maps* 13, 600–607. <https://doi.org/10.1080/17445647.2017.1342212>.
- Ó Cofaigh, C., Callard, S.L., Roberts, D.H., Chiverrell, R.C., Ballantyne, C.K., Evans, D.J.A., Saher, M., Van Landeghem, K.J.J., Smedley, R., Benetti, S., Burke, M., Clark, C.D., Duller, G.A.T., Fabel, D., Livingstone, S.J., McCarron, S., Medialdea, A., Moreton, S. G., Sacchetti, F., 2021. Timing and pace of ice-sheet withdrawal across the marine-terrestrial transition west of Ireland during the last glaciation. *J. Quat. Sci.* 36, 805–832. <https://doi.org/10.1002/jqs.3295>.
- Oien, R.P., Kurjanski, B., 2026. Cirque morphology in relation to ice-sheet retreat in central West Greenland and Disko Island (Qeqertarsuaq). *Quat. Int.* 776, 110381. <https://doi.org/10.1016/j.quaint.2026.110381>.
- Ordnance Survey of Northern Ireland, 2024a. OSNI Digital Surface Model (DSM) Supply-Digital.
- Ordnance Survey of Northern Ireland, 2024b. OSNI Orthophotography What is Orthophotography?.
- Patterson, E.M., 1951. Notes on Three Tertiary Dolerites from counties down. No. 202510 *Ir. Nat. J.* 45 (45).
- Peacock, J.D., Horne, D.J., Whittaker, J.E., 2012. Late Devensian evolution of the marine offshore environment of western Scotland. *Proc. Geol. Assoc.* 123, 419–437. <https://doi.org/10.1016/j.pgeola.2012.02.005>.
- Perkins, A.J., Brennand, T.A., Burke, M.J., 2016. Towards a morphogenetic classification of eskers: implications for modelling ice sheet hydrology. *Quat. Sci. Rev.* 134, 19–38. <https://doi.org/10.1016/j.quascirev.2015.12.015>.
- Peterson, G., Johnson, M.D., 2018. Hummock corridors in the south-central sector of the Fennoscandian ice sheet, morphometry and pattern. *Earth Surf. Process. Landf.* 43, 919–929. <https://doi.org/10.1002/esp.4294>.
- Peterson, G., Johnson, M.D., Smith, C.A., 2017. Glacial geomorphology of the south Swedish uplands – focus on the spatial distribution of hummock tracts. *J. Maps* 13, 534–544. <https://doi.org/10.1080/17445647.2017.1336121>.
- Piotrowski, J.A., 1997. Subglacial hydrology in North-Western Germany during the Last Glaciation: groundwater flow, tunnel valleys and hydrological cycles. *Quat. Sci. Rev.* 16, 46–53.
- 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. *J. Quat. Sci.* 34, 285–298. <https://doi.org/10.1002/jqs.3100>.
- Preston, J., 1963. The dolerite plug at Slemish, Co. Antrim, Ireland. *Geol. J.* 3, 301–314. <https://doi.org/10.1002/gj.3350030207>.
- Prior, D.B., 1970. Ice limits in the Cushendun area of north-east Co. Antrim. In: Stephens, N., Glasscock, R.E. (Eds.), *Irish Geographical Studies in Honour of E. Estyn Evans*. The Queen's University Belfast, Belfast, pp. 59–64.
- Rapp, A., 1984. Nivation hollows and glacial cirques in Söderåsen, South Sweden. *Geogr. Ann. Ser. A, Phys. Geogr.* 66, 11–28.
- Rea, B.R., Evans, D.J.A., 2013. Plateau icefield landscapes. In: Evans, D.J.A. (Ed.), *Glacial Landscapes*. Routledge, London, pp. 407–431.
- Roberts, D.H., Ballantyne, C.K., Burke, M., Chiverrell, R.C., Evans, D.J.A., Clark, C.D., Duller, G.A.T., Ely, J., Fabel, D., Small, D., Smedley, R.K., Louise, S., Roberts, C., 2020. The deglaciation of the western sector of the Irish Ice Sheet from the inner continental shelf to its terrestrial margin. *Boreas* 49, 438–460. <https://doi.org/10.1111/bor>.
- Rose, J., 1989. Glacier stress patterns and sediment transfer associated with the formation of superimposed flutes. *Sediment. Geol.* 62, 151–176.
- Saito, J., Sugiyama, S., Tsutaki, S., Sawagaki, T., 2016. Surface elevation change on ice caps in the Qaanaaq region, northwestern Greenland. *Polar Sci.* 10, 239–248. <https://doi.org/10.1016/j.polar.2016.05.002>.
- Shaw, J., Carter, R.W.G., 1980. Late-Midlandian sedimentation and glaciotectionics of the north Antrim End. *Irish Nat. J.* 20, 67–69.
- Shennan, I., Bradley, S.L., Edwards, R., 2018. Relative sea-level changes and crustal movements in Britain and Ireland since the Last Glacial Maximum. *Quat. Sci. Rev.* 188, 143–159. <https://doi.org/10.1016/j.quascirev.2018.03.031>.
- Sissons, J.B., 1971. The geomorphology of central Edinburgh. *Scott. Geogr. Mag.* 87, 185–196. <https://doi.org/10.1080/00369227108736195>.
- Smith, M.J., Knight, J., 2011. Palaeoglaciation of the last Irish ice sheet reconstructed from striae evidence. *Quat. Sci. Rev.* 30, 147–160. <https://doi.org/10.1016/j.quascirev.2010.09.019>.
- Smith, M.J., Knight, J., Field, K.S., 2008. Glacial striae observations for Ireland compiled from historic records. *J. Maps* 4, 378–398. <https://doi.org/10.4113/jom.2008.1035>.
- Pebbles in the lower Colorado River, Texas a study in particle morphogenesis a study in particle morphogenesis1. In: Sneed, E.D., Folk, R.L. (Eds.), *J. Geol.* 66, 114–150.
- Spagnolo, M., Clark, C.D., Ely, J.C., Stokes, C.R., Anderson, J.B., Andreassen, K., Graham, A.G.C., King, E.C., 2014. Size, shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset. *Earth Surf. Process. Landf.* 39, 1432–1448. <https://doi.org/10.1002/esp.3532>.
- Spagnolo, M., Phillips, E., Piotrowski, J.A., Rea, B.R., Clark, C.D., Stokes, C.R., Carr, S.J., Ely, J.C., Ribolini, A., Wysota, W., Szuman, I., 2016. Ice stream motion facilitated by a shallow-deforming and accreting bed. *Nat. Commun.* 7. <https://doi.org/10.1038/ncomms10723>.
- Stephens, N., Creighton, J.R., Hannon, M.A., 1975. The Late-Pleistocene Period in North-Eastern Ireland: an Assessment 1975. *Ir. Geogr.* 8, 1–23.
- Stoker, B.J., Livingstone, S.J., Barr, I.D., Ruffell, A., Storrar, R.D., Roberson, S., 2021. Variations in esker morphology and internal architecture record time-transgressive deposition during ice margin retreat in Northern Ireland. *Proc. Geol. Assoc.* 132, 409–425. <https://doi.org/10.1016/j.pgeola.2021.03.002>.
- Stokes, C.R., Clark, C.D., 1999. Geomorphological criteria for identifying Pleistocene ice streams. *Ann. Glaciol.* 28, 67–74.
- Stokes, C.R., Clark, C.D., 2001. Palaeo-ice streams. *Quat. Sci. Rev.* 20, 1437–1457.
- Stokes, C.R., Clark, C.D., Lian, O.B., Tulaczyk, S., 2007. Ice stream sticky spots: a review of their identification and influence beneath contemporary and palaeo-ice streams. *Earth Sci. Rev.* 81, 217–249. <https://doi.org/10.1016/j.earscirev.2007.01.002>.
- Stokes, C.R., Clark, C.D., Storrar, R., 2009. Major changes in ice stream dynamics during deglaciation of the north-western margin of the Laurentide Ice Sheet. *Quat. Sci. Rev.* 28, 721–738. <https://doi.org/10.1016/j.quascirev.2008.07.019>.
- Stokes, C.R., Fowler, A.C., Clark, C.D., Hindmarsh, R.C.A., Spagnolo, M., 2013. The instability theory of drumlin formation and its explanation of their varied composition and internal structure. *Quat. Sci. Rev.* 62, 77–96. <https://doi.org/10.1016/j.quascirev.2012.11.011>.
- Storrar, R.D., Evans, D.J.A., Stokes, C.R., Ewertowski, M., 2015. Controls on the location, morphology and evolution of complex esker systems at decadal timescales, Breidamerkurjökull, southeast Iceland. *Earth Surf. Process. Landf.* 40, 1421–1438. <https://doi.org/10.1002/esp.3725>.
- Sugden, D.E., 1992. Evolution of large Roches Moutonnées. *Geogr. Ann. Ser. A, Phys. Geogr.* 74.
- Sutherland, J.L., Carrivick, J.L., Evans, D.J.A., Shulmeister, J., Quincey, D.J., 2019. The Tekapo Glacier, New Zealand, during the Last Glacial Maximum: an active temperate glacier influenced by intermittent surge activity. *Geomorphology* 343, 183–210. <https://doi.org/10.1016/j.geomorph.2019.07.008>.
- Synge, F.M., Stephens, N., 1966. Late-and post-glacial shorelines, and ice limits in argyll and north. *Trans. Inst. Br. Geogr.* 101–125.
- Syverson, K.M., Mickelson, D.M., 2009. Origin and significance of lateral meltwater channels formed along a temperate glacier margin, Glacier Bay, Alaska. *Boreas* 38, 132–145. <https://doi.org/10.1111/j.1502-3885.2009.00074.x>.
- Tarlari, S., Benetti, S., Callard, S.L., Ó Cofaigh, C., Dunlop, P., Georgiopoulou, A., Edwards, R., Van Landeghem, K., Saher, M., Chiverrell, R., Fabel, D., Moreton, S., Morgan, S., Clark, C.D., 2020. Final deglaciation of the malin sea through meltwater release and calving events. *Scott. J. Geol.* 56, 117–133. <https://doi.org/10.1144/sjg2019-010>.
- Thomas, G.S.P., Chiverrell, R.C., Huddart, D., 2004. Ice-marginal depositional responses to readvance episodes in the Late Devensian deglaciation of the Isle of Man. *Quat. Sci. Rev.* 23, 85–106. <https://doi.org/10.1016/j.quascirev.2003.10.012>.
- Todd, S.P., 1989. Stream-driven, high-density gravelly traction carpets: possible deposits in the Trabeg Conglomerate Formation, SW Ireland and some theoretical considerations of their origin. *Sedimentology* 36, 513–530. <https://doi.org/10.1111/j.1365-3091.1989.tb02083.x>.
- Utting, D.J., Atkinson, N., 2019. Proglacial lakes and the retreat pattern of the southwest Laurentide ice sheet across Alberta, Canada. *Quat. Sci. Rev.* 225. <https://doi.org/10.1016/j.quascirev.2019.106034>.
- Utting, D.J., Ward, B.C., Little, E.C., 2009. Genesis of hummocks in glaciofluvial corridors near the Keewatin Ice Divide, Canada. *Boreas* 38, 471–481. <https://doi.org/10.1111/j.1502-3885.2008.00074.x>.
- 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. *Quat. Sci. Rev.* 245. <https://doi.org/10.1016/j.quascirev.2020.106526>.
- Vérité, J., Ravier, É., Bourgeois, O., Pochat, S., Lelandais, T., Mourgues, R., Clark, C.D., Bessin, P., Peigné, D., Atkinson, N., 2021. Formation of ribbed bedforms below shear margins and lobes of palaeo-ice streams. *Cryosphere* 15, 2889–2916. <https://doi.org/10.5194/tc-15-2889-2021>.
- Vérité, J., Ravier, É., Bourgeois, O., Bessin, P., Pochat, S., 2023. New metrics reveal the evolutionary continuum behind the morphological diversity of subglacial bedforms. *Geomorphology* 427. <https://doi.org/10.1016/j.geomorph.2023.108627>.
- Vernon, P., 1966. Drumlins and Pleistocene ice flow over the Ards Peninsula/ Strangford Lough area, County Down, Ireland. *J. Glaciol.* 6, 401–409.
- Walker, M., Lowe, J., Blockley, S.P.E., Bryant, C., Coombes, P., Davies, S., Hardiman, M., Turney, C.S.M., Watson, J., 2012. Lateglacial and early Holocene

- palaeoenvironmental “events” in Sluggan Bog, Northern Ireland: comparisons with the Greenland NGRIP GICC05 event stratigraphy. *Quat. Sci. Rev.* 36, 124–138. <https://doi.org/10.1016/j.quascirev.2011.09.008>.
- Warren, W., 1990. Deltaic deposits in the Carey Valley, Co. Antrim, Ireland. *Sediment. Geol.* 69, 157–160.
- Wilson, P., 2004. Evidence for and reconstruction of a Nahanagan Stade Glacier at Croloughan Lough, Derryveagh Mountains, Co. Donegal. *Irish J. Earth Sci.* 22, 45–54.
- Wilson, P., Ballantyne, C.K., Benetti, S., Small, D., Fabel, D., Clark, C.D., 2019. Deglaciation chronology of the Donegal Ice Centre, north-west Ireland. *J. Quat. Sci.* 34, 16–28. <https://doi.org/10.1002/jqs.3077>.
- Winsborrow, M.C.M., Clark, C.D., Stokes, C.R., 2010. What controls the location of ice streams? *Earth Sci. Rev.* 103, 45–59. <https://doi.org/10.1016/j.earscirev.2010.07.003>.