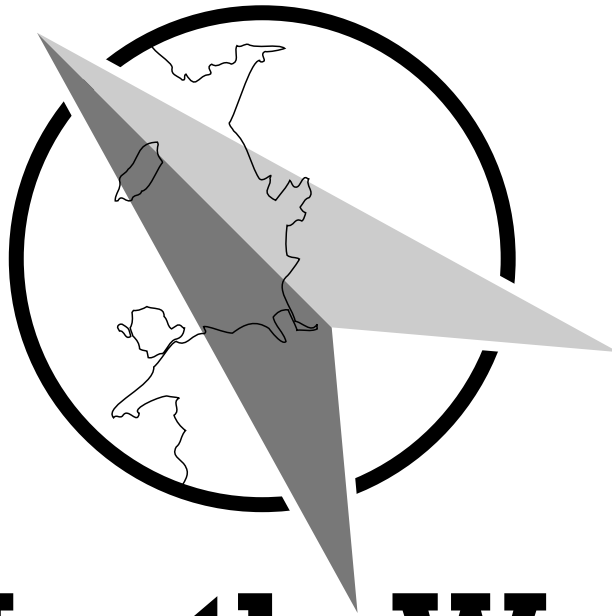


ISSN 1476-1580



North West Geography

Volume 1, Number 2, 2001

Esker Formation and the Nature of Deglaciation: the Ballymahon Esker, Central Ireland

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Abstract

The Ballymahon esker, central Ireland, is one of a series of eskers formed shortly after a drumlinising event towards the end of the last glaciation. It lies within a belt of composed of segments, each of which comprises a narrow, sharp-crested ridge composed of coarse-grained sediments leading down-ice to a flat-topped terminus. The segments are interpreted as subglacial tunnel/channel to ice-marginal 'beads', deposited sequentially as the ice margin retreated. Tunnel/channel deposits underlie the esker remnants, indicating that short-lived drainage routeways existed to either side of the main routeway during ice margin retreat. The evidence indicates that deglaciation in this area was characterised by stagnation-zone retreat, rather than mass *in situ* downwasting of the ice.

Keywords:

esker, hummocky moraine, stagnation zone retreat, Ireland

Introduction

Eskers are found throughout the Irish Midlands. Their formation as meltwater deposits laid down within, or at the exit from, an icewalled channel was first proposed by Sollas in 1896, and has been widely accepted since the work of Flint during the early 1930s (Flint 1930). Eskers have long been associated with the stagnant and slow-moving margins of receding ice sheets, and are often found in association with hummocky moraine (Price 1966; Banerjee and McDonald 1975). However, research on esker morphology and sedimentology indicates that esker characteristics vary considerably, depending on the type of ice margin and the nature of the ice recession.

Deposition can occur within subglacial and englacial conduits, within subaerial ice-walled channels, at the mouth of such channels or conduits, or within reentrants along the ice margin (Price 1966, 1969; Banerjee and McDonald 1975; Christiansen 1987; Brennand 1994; Warren and Ashley 1994; Huddart *et al.* 1999). The nature of the depositional site can vary temporally (Huddart and Bennett 1997): conduit roofs may collapse, englacial tunnels may be lowered to a subglacial position, and ice margins can migrate.

This temporal evolution has caused Brennand (2000) to suggest that two basic esker types can be recognised, indicating quite different ice sheet characteristics. Synchronous eskers are formed over several years in relation to a single ice-marginal position, usually within long tunnels which must extend a considerable way up-

glacier. They are associated with conditions which prevent the inflow of ice into the tunnel. These conditions include formation within an ice sheet where ice is stagnant and cannot fill the tunnel space; formation when melting continues throughout the winter period, preventing tunnel closure; or formation where the presence of a large body of water at the ice margin keeps hydrostatic pressure high and prevents the influx of ice (Brennand 2000).

Time-transgressive eskers are formed in relation to a number of different ice margins and consist of a number of ice tunnel/channel to ice-marginal deposits arranged sequentially, each deposit having formed within and at the mouth of a short tunnel or channel. Where the tunnel section is particularly short, and recession of the ice margin is sufficient to separate each deposit, the segments are termed 'beads' (Synge, 1950; Warren and Ashley 1994). This pulsed deposition is thought to indicate that widespread stagnation or melting did not occur. Deglaciation was characterised by the existence of a narrow stagnation zone at the edge of ice sheet during retreat instead (Koteff and Pessl 1981; Hebrand and Amark 1989; Warren and Ashley 1994).

Differentiating between the two types of esker can therefore reveal the nature of the subglacial drainage system and the ice margin during deglaciation. In particular, if the existence of a large proglacial lake can be discounted, eskers can indicate whether deglaciation occurred by widespread *in situ* stagnation, indicating widespread collapse of the ice sheet involving a reduction/

cessation of ice accumulation, which is likely to be associated with major climatic amelioration; or by stagnation zone retreat, which is associated with active ice up-glacier and therefore continued ice accumulation, and more gradual climate change.

Hummocky moraine can also provide considerable information about the condition of the ice sheet during formation. Traditionally, hummocky moraine is interpreted as an ice-stagnation deposit, formed by the resedimentation of supraglacial debris into hollows on an uneven ice surface during vertical melting of the ice sheet (Boulton 1972). This can occur either by widespread *in situ* stagnation, or by the recession of an ice marginal stagnation zone. Recent studies suggest that hummocky moraine may also form subglacially, either by erosion of pre-existing sediments by subglacial flooding, indicating subglacial ponding of water (Munro and Shaw 1997), or by differential gravitational loading by ice of wet, plastic till, indicating that the ice was likely to have been actively moving on a deformable bed layer (Eyles *et al.*, 1999). Finally, hummocky moraine can form due to thrusting of ice and sediment at the glacier snout and in the proximal pro-glacial zone (Bennett *et al.* 1998, Hambrey *et al.* 1997, Huddart and Hambrey 1996). Thrusting results in the formation of 'controlled' hummocky moraine, consisting of parallel, ice-transverse or arcuate ridges.

In this context, the intention of this paper is to reconstruct the conditions of formation of the late Devensian (22-14,000 years b.p.) Ballymahon esker, and the surrounding hummocky moraine, using morphology, sedimentology and the relationship with surrounding landforms, with a view to establishing the condition of the last ice sheet during deglaciation.

The Irish eskers and hummocky moraine

Eskers throughout the Irish Midlands are thought to have formed after the last Glacial Maximum, at c. 22,000 years b.p., during the recession of the British and Irish Ice Sheet (B.I.I.S.). The eskers lie to the south of the major northern Midlands drumlin field (Figure 1a). Two orientations of eskers can be recognised: a major system is aligned east-west across the central Midlands and is related to an ice margin to the east (Figure 1; Warren and Ashley 1994); a number of smaller eskers to the north, including the Ballymahon esker, are aligned roughly northwest-southeast, and are thought to have formed after the east-west system ((Figure 1; Synge 1950; McCabe *et al.* 1998; Delaney 2001 (in press)). These eskers continue into the drumlin field at their northern ends. As the esker paths tend to follow the low areas between the drumlins, they are believed to postdate drumlin formation (Delaney 2001 (in press); Figure 2).

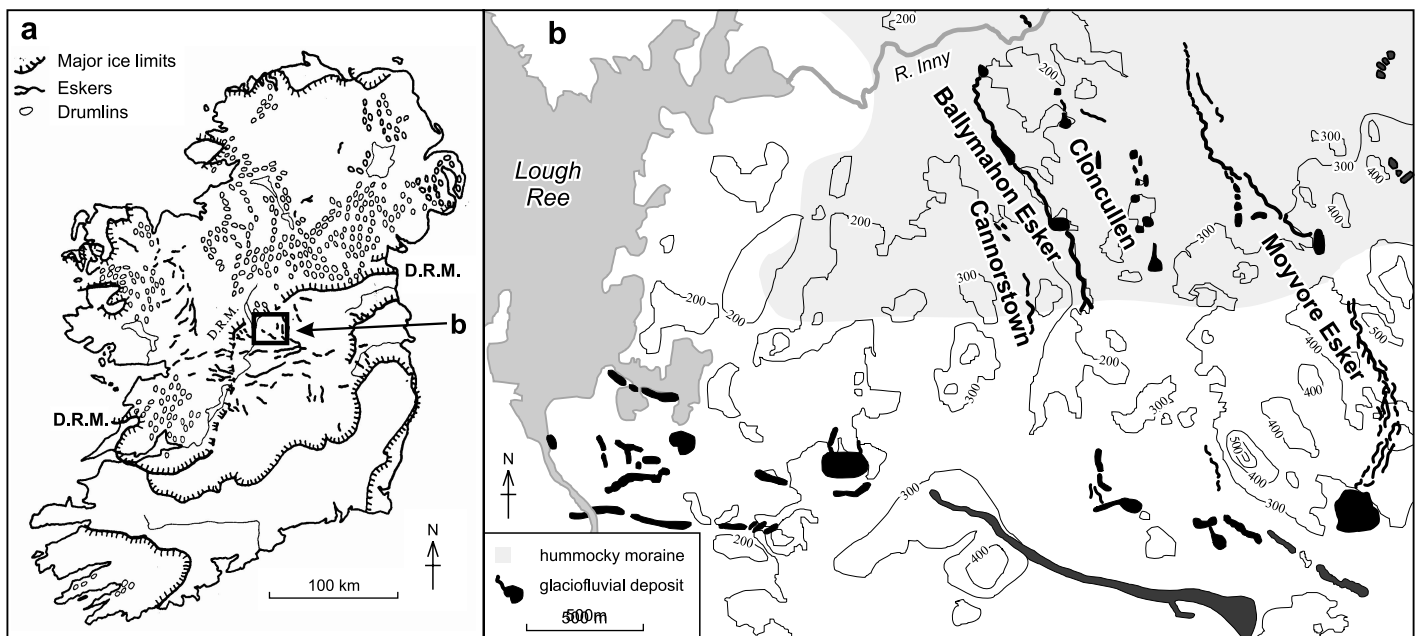


Figure 1: a. Quaternary glacial landforms in Ireland. The position of eskers, drumlins and ice-marginal features mentioned in the text are shown, including the Drumlin Readvance Moraine (D.R.M.) Redrawn by P. Coxon, after McCabe (1987). b. Eskers east of Lough Ree. The position of the Ballymahon esker and associated esker remnants, and the southern margin of hummocky moraine are shown.

The hummocky moraine discussed in this paper forms a belt some 10km wide extending east-northeast across the Midlands from Lough Ree (Figure 1b). The hummocky moraine has been mapped as kame topography, and has been interpreted as forming part of the Drumlin Readvance Moraine (DRM), an ice-marginal feature associated with a readvances towards the end of the last glaciation (Synge 1979; Warren 1992; McCabe 1996). However, the position of the DRM, if it exists, has never been clearly established (Warren 1992), and the hummocky moraine has not been examined in detail.

Position and morphology of the Ballymahon esker

The Ballymahon esker lies to the east of Lough Ree, towards the western edge of the hummocky moraine. The 12km esker was initially mapped using Ordnance Survey 1:25,000 air photos and the morphology was then truthed by field survey. The esker commences at Ballymahon and runs southeastwards and gently uphill, along the edge of the Dungolman river valley (Figure 2). It forms a relatively continuous ridge, with a few short breaks, but the height of the ridge is irregular. Three basic morphologies were recognised within the ridge: narrow steep-sided, sharp crested ridges, which occasionally become higher and wider, without losing their morphology; wider, flat-topped, steep sided segments, which punctuate the narrower ridge segments at intervals; and fan-shaped areas, which occur at the southern end of the esker only (Figure 2). Breaks in the ridge were located both within the sharp-crested sections, and at the downstream end of fan-shaped and flat-topped areas.

Morphology of the hummocky moraine

Field mapping of the hummocky moraine on either side of the Ballymahon esker revealed that it was formed of a number of different mound morphologies. The area is dominated by low, rounded hummocks less than 5m high, but without distinct depressions, which in places grades into undulatory topography with no distinct mounds. Within these hummocks, remnants of sinuous ridges aligned parallel to the Ballymahon esker were visible on air photos and in the field, and are classified as esker remnants. Two main locations were recognised. At Cannorstown, to the west of the esker, a series of narrow, elongate ridges with rounded crests and rising 2-4m above the surrounding land, are found in association with pronounced, rounded hummocks (Figure 3). The ridges and mounds lie in low ground to either side of drumlins (Figure 3). To the east of the Ballymahon esker, the

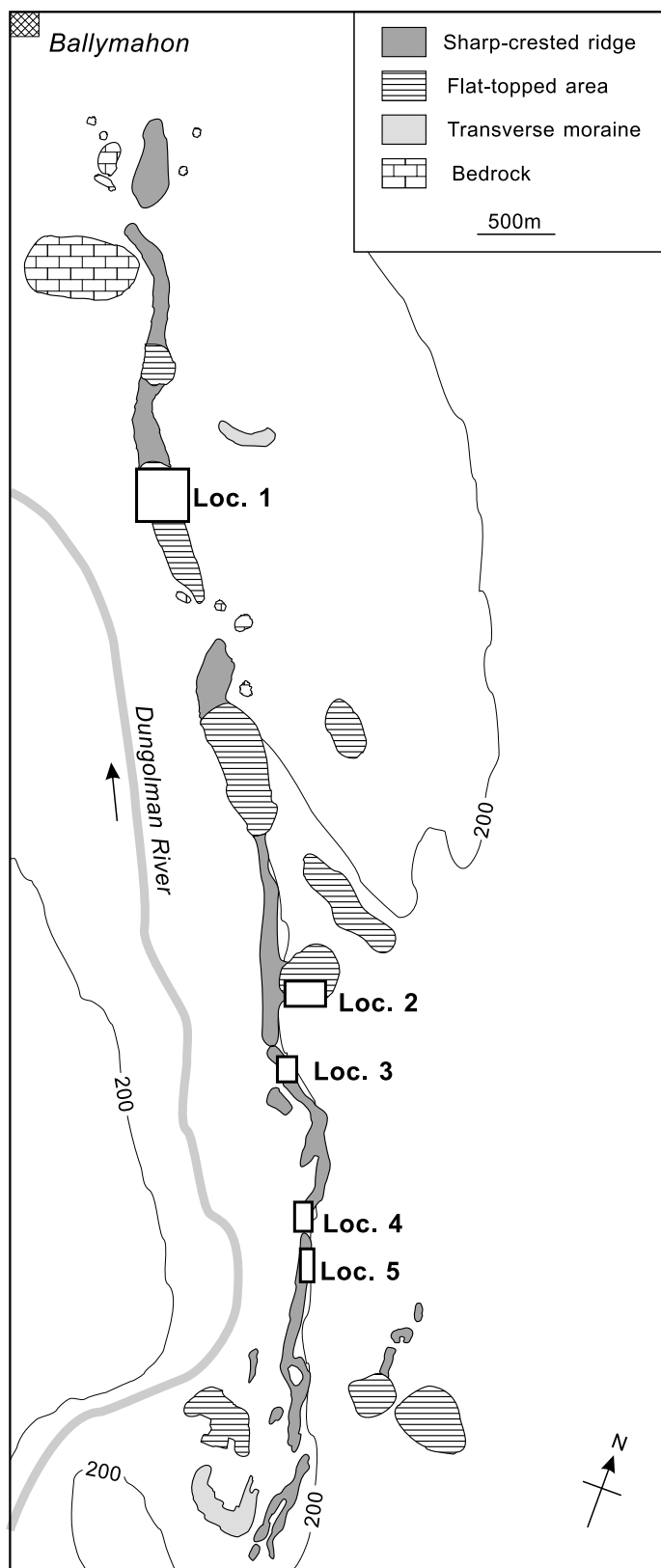


Figure 2: Morphology of the Ballymahon Esker. The position of locations and features mentioned in the text are shown.

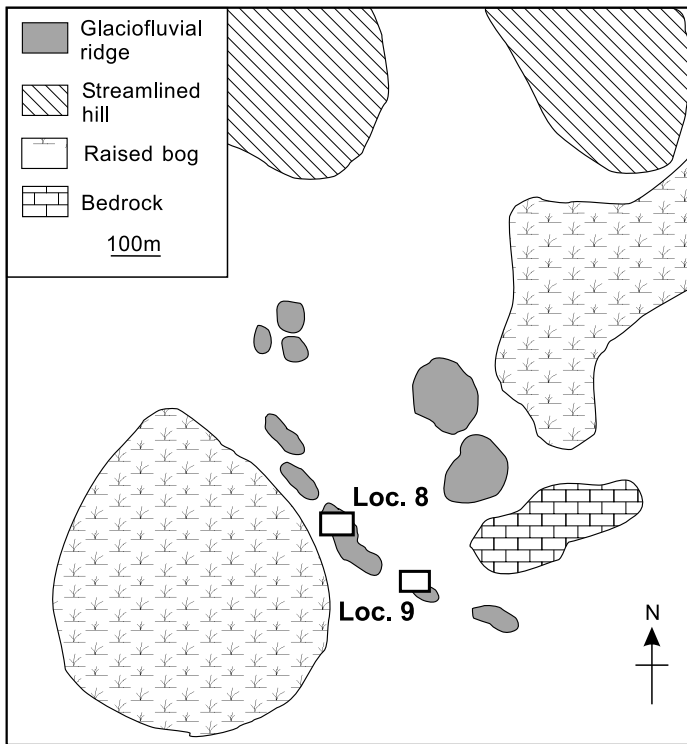


Figure 3: Morphology of the Cannorstown esker remnant. The position of locations and features mentioned in the text are shown.

Cloncullen remnant consists of a series of ridges and accompanying fan-shaped or flat-topped kames. These are continuous to the north of the Ballymahon esker, and form a short esker ridge, which follows the low ground between drumlins (Figure 4). Further south, the ridge and flat-topped segments are disjunct, but are arranged linearly, separated by distances of 100-1000m (Figure 4). Finally, small transverse ridges (height less than 15m; length less than 100m) aligned at right angles to ice flow direction were found in the hummocky moraine, both adjacent to the Ballymahon esker, and within the Cloncullen remnant (Figures 2, 4).

Sedimentology

A number of exposures in small borrow pits were located within sharp-crested and flat-topped areas in both the Ballymahon esker and the esker remnants, and in a flow-transverse ridge to the east of the esker (Figures 2, 3, 4). Unfortunately, no exposure occurred within fan-shaped areas. Following Miall (1978), sediments were grouped into lithofacies associations (L.F.As). Clast orientation measurements are plotted on stereoplots, and eigenvectors

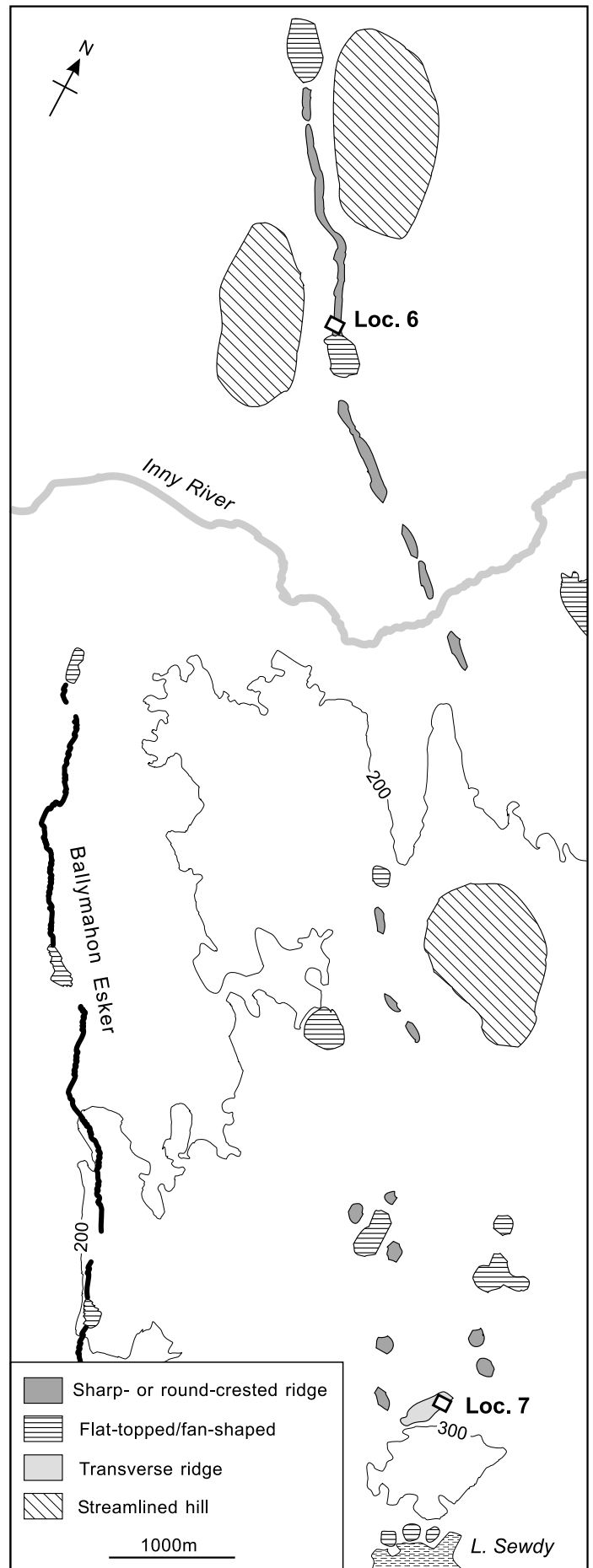


Figure 4: Morphology of the Cloncullen esker remnant. The position of locations and features mentioned in the text are shown.

and eigenvalues calculated using Wintek 2.0 (Peterek and Krumm, 2000). A clear association was found between ridge morphology and the nature of the underlying sediments. Consequently, sediment descriptions are grouped by ridge morphology.

Lithofacies Association 1: Sharp-crested ridge sediments

Exposures in sharp-crested ridges occur at four locations within the Ballymahon esker (Locations 3, 4, 5; Figure 2), at one exposure in the Cloncullen remnant (Location 6; Figure 4) and at two exposures within the Cannorstown remnant (Locations 8, 9; Figure 3). Sediments are uniformly coarse-grained, and are dominated by two lithofacies types. Beds of internally massive cobble and pebble gravel are generally clast-supported, but with a range of matrix types (Plate 1). The most poorly sorted have a polymodal texture, with a matrix ranging from clay size to pebbles too coarse to have infiltrated pores after deposition of the framework clasts; clast a-axes are aligned parallel to the ridge and dip downstream (Figure 5a and c). As sorting improves, the pebble and clay content decreases, and the matrix becomes a muddy sand. In these beds, a-axes are close to horizontal and transverse to flow direction (Figure 5d), and in some cases, b-axes are imbricated upstream (Figure 5b). The fabrics indicate that transport was parallel to the ridge.

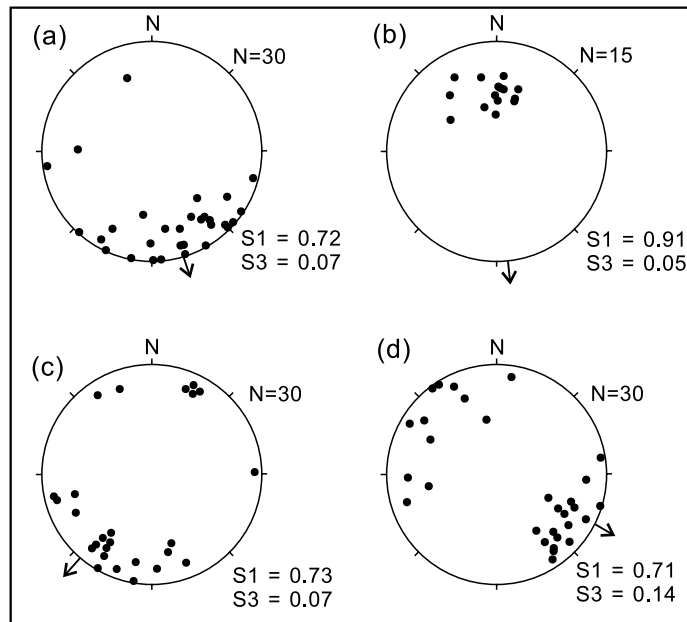


Figure 5: Orientation of clasts in massive boulder and cobble gravels. (a) Location 5, Ballymahon esker: a-axis parallel orientation in polymodally sorted cobble gravel. (b) Location 8, Cannorstown remnant: b-axis imbrication in bimodal cobble gravel. (c) Location 4, Ballymahon esker: a-axis parallel orientation in polymodally sorted boulder gravel. (d) Location 4, Ballymahon esker: a-axis transverse orientation in poorly sorted cobble gravel.



Plate 1: Massive boulder and cobble gravel with a poorly sorted matrix, Location 4, Ballymahon esker. Three beds are exposed here, separated by discontinuous lenses of sand (immediately behind figure in centre of picture).

These massive sediments generally overlie horizontally bedded cobble and pebble gravel which contain occasional sand laminae. Where sand laminae are absent, horizontal bedding can be distinguished either by lags of coarser clasts, or by discontinuous horizons of openwork clasts (Plate 2). Occasionally dip increases downstream, and the beds become shallow cross-bedded.

Large scale cross beds of cobble gravel were observed at two sites. At Location 5 in the Ballymahon esker, beds 2-5m thick are arranged in alternate sets and dip roughly downstream, but inwards towards the centre of the ridge. At Location 4, crossbeds up to 10m thick dip upstream parallel to the ridge axis. These beds are irregular, and the matrix is poorly sorted.



Plate 2: Horizontally bedded cobble and pebble gravel, Location 4, Ballymahon esker. Sediments are poorly sorted, with a muddy sand matrix. Bedding is formed by discontinuous openwork horizons and lags of larger clasts, one of which is located immediately behind the spade handle.

Interpretation: The very coarse-grained nature of the sediments indicates deposition from high-energy flows. This, combined with ridge morphology and clast orientation, indicates that these are fluvial deposits, formed within ice-walled channels or tunnels. Sediments indicate deposition under a range of flow types. While massive, clast-supported, polymodal gravels with a-axis parallel fabrics are formed by deposition from hyperconcentrated flood flows with sediment concentrations of 40% or more (Smith 1986, Costa 1988), those sediments with a finer matrix are associated with high energy, normal (fluidal) stream flow. Variation in clast size in horizontally- and cross-bedded sediments indicates that flow energy fluctuated considerably (Smith 1974). Downstream-dipping crossbeds are interpreted as aggrading alternate bars, commonly associated with low-sinuosity, narrow, deep channels (Billi *et al.* 1987). Upstream dipping crossbeds have been observed in eskers elsewhere and are interpreted as antidune-type beds formed under a migrating hydraulic jump (Johansson 1975; Lundquist 1979; Brennand 1994). Such beds form at a point of sudden flow deceleration, such as a tunnel exit into standing water, or upstream from a tunnel blockage; Russell (pers. comm.) has observed similar bedding has also been observed within subaerial jokullhlaup deposits at Skeiðarárjökull, Iceland.

Lithofacies Association 2: Flat-topped ridge sediments

Exposure in a flat-topped ridge occurs at two locations in the Ballymahon esker (Locations 1 and 2). The sediment sequence is similar, but is best seen at Location 1 (Figure 6). The sediments here can be divided into three units. The lowest unit is exposed in section A only (Figure 6) and consists of cobble and boulder gravels with a sandy matrix arranged in alternating bimodal and openwork couplets, similar to sharp-crested ridge sediments exposed elsewhere, but exhibiting much post-depositional distortion. These gravels form a central core, and are buried by the overlying sediments. The next unit consists of beds of horizontal or gently inclined (dips less than 8°) medium to fine sands, silts and clays, with occasional lenses of massive pebble gravel or diamicton. Sand beds are rhythmically bedded, and are climbing-ripple cross-laminated and normally graded, with increasing silt laminations upwards. Clay laminations become increasingly frequent upwards. Paleoflow directions are southeastwards, parallel to the esker. Lenses of bimodal pebble and cobble gravel (0.05-0.7m thick) are also normally graded and internally massive, tabular in long section and up to 85m in length, but lenticular in cross-section, often with a convex upper

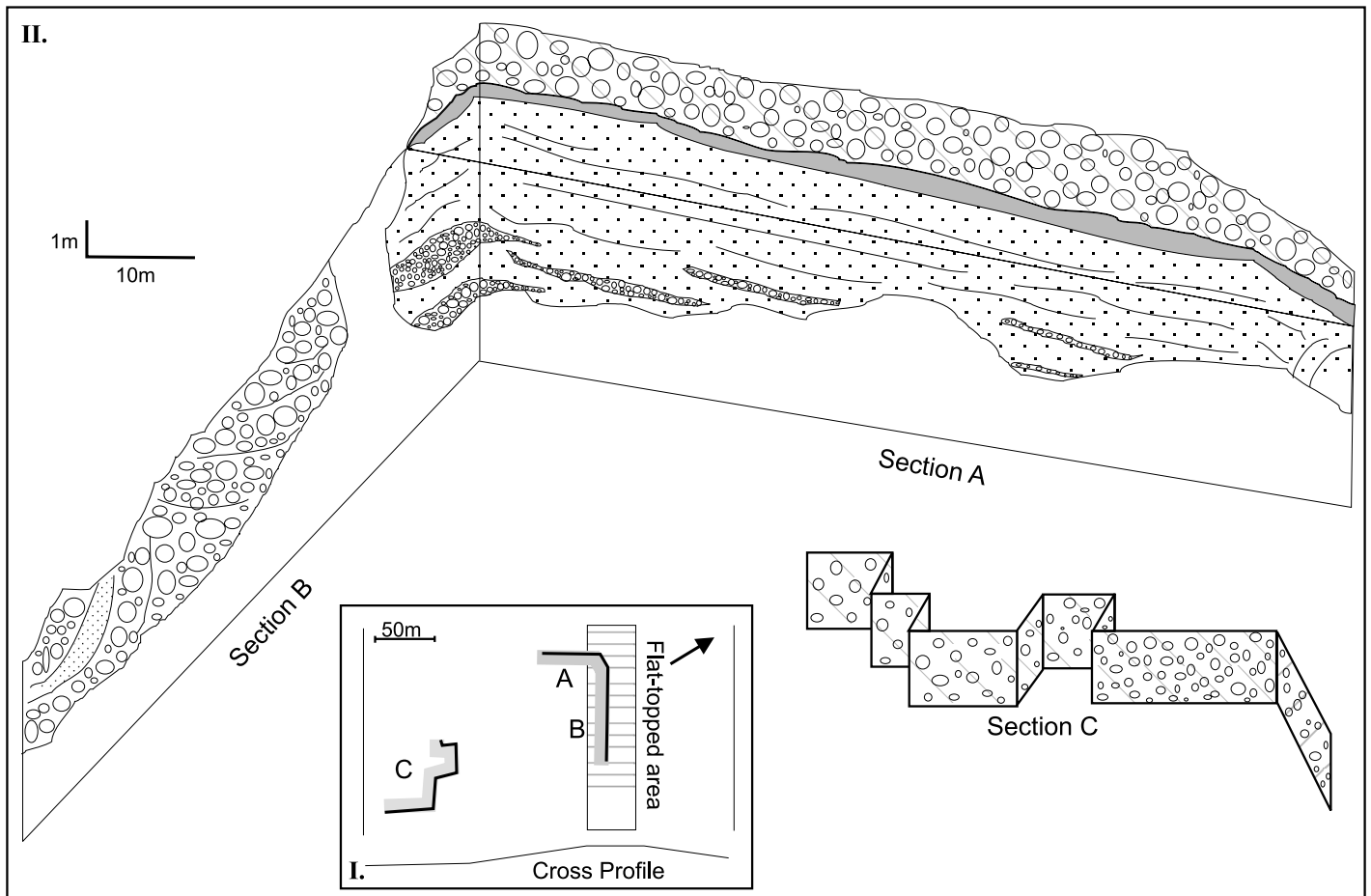


Figure 6: Sketch of Location 1, Ballymahon esker. A. Position of locations in relation to esker ridge. Main diagram: sketch of sections. Section A contains poorly sorted and distorted cobble and boulder gravels, overlain by laminated sands, silts and clays with occasional diamicton and gravel lenses, which extend into Section B. The upper part of Section B and Section C are composed entirely of cross-bedded cobble gravels.

boundary. Thin stringers of diamicton (less than 0.3m) were also observed in the exposure parallel to the esker ridge, consisting of a matrix of sandy mud with occasional rounded pebbles and cobbles, similar in size to surrounding sediments.

These fine grained sediments are overlain by a third sedimentary unit, consisting of sets of planar to tangential cross-beds of normally graded, well-stratified, pebble and cobble gravel. These occur both at the highest point of the esker ridge, and at lower levels to either side, where they interdigitate with the finer grained deposits (Section C, Figure 6). Cross-bed progradation was parallel to the esker. The lowest, core unit of cobble and boulder gravel was not observed at Location 2. However, the upper two units were exposed at the site.

Interpretation: The coarse-grained core sediments are interpreted as an ice-walled channel or conduit deposit. Bed distortion indicates that they were formed supraglacially or englacially and subsequently lowered. The overlying laminated silts and clays are characteristic of suspension deposition in standing water, while associated graded and ripple-laminated sands are interpreted as underflow deposits, graded beds in particular being characteristic of turbidity current underflows (Ashley 1975; Leckie and McCann 1982). These sediments indicate ponding of water within, or at the edge of, the ice sheet. Lenses of sorted, normally graded gravel are also interpreted as turbidity current deposits, of resedimented material, while diamicton lenses are interpreted as debris flows (Eyles *et al.* 1987).

The overlying gravel cross beds are interpreted as delta foresets, formed by fluctuating flows, which have prograded into the lake basin over the underlying bottomsets. The sequence is typical of a glacio-deltaic system (Lundquist 1979; Smith *et al.* 1982). Initially, deposition appears to have occurred within the confines of ice walls, as sediments are located at the top of the ridge. However, as deposition continued, the walls must have receded, allowing further foresets and bottomsets to be laid down on the western side of the ridge.

Lithofacies Association 3: Transverse ridge sediments

One exposure only was found in a transverse ridge at Location 7 in the Cloncullen remnant. The ridge is steep-sided (slopes 22-25°) and symmetrical in cross-section. The 5m thick exposure is parallel to the long-axis of the ridge and is illustrated in Figure 7. The 1m thick basal unit consists of a bimodal boulder gravel with sand matrix, overlain by interbedded horizontally laminated and climbing-ripple cross-laminated sands, indicating transport southwards, and containing lenses of clayey diamicton and dropstones. The upper contact of this unit is erosional and partly sheared. It is overlain by a clay-rich diamicton, which becomes increasingly silty upwards; clasts exhibit a strong a-axis fabric, showing a dominant dip towards 315° (at right angles to the ridge crestline; Figure 7).

Interpretation: The lower sediments exposed here are clearly water laid; however, the geometry of the deposit is unclear, so the environment of deposition cannot be distinguished. However, the sheared contact, and the well-developed fabric indicate that the overlying diamicton is an active ice deposit. The dimensions of the ridge, coupled with the evidence for active ice, indicates that it formed in one of three ways: as an ice marginal or pro-glacial thrust moraine (Bennett *et al.* 1998, Hambrey *et al.* 1997, Huddart and Hambrey 1996); as a subglacial 'crevasse-fill' or 'crevasse-squeeze' ridge (Sharp 1985); or as an ice-marginal ice-push moraine (Benn 1992). Of the three possibilities, interpretation as an ice-push moraine is preferred, as the ridge geometry differs from that expected in a thrust moraine, and dips of clasts are lower than expected in a crevasse squeeze ridge. Ice-push moraines are common in highland hummocky moraine (Benn 1992).

Discussion

The morpho-sedimentological approach indicates that the Ballymahon esker and the esker remnants to either side

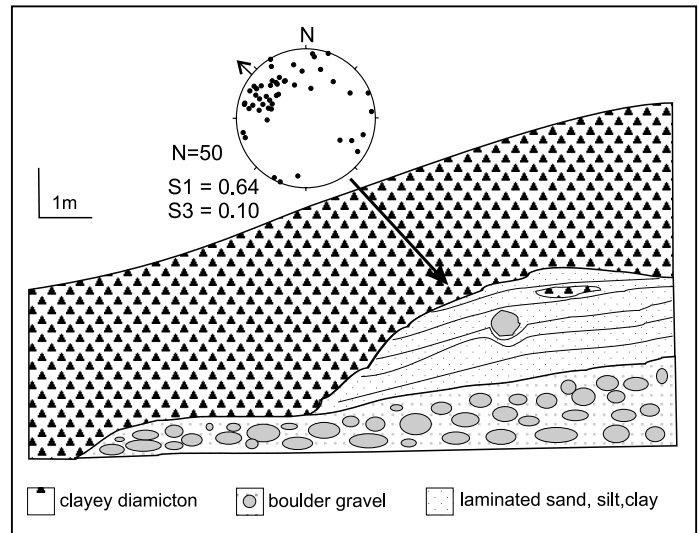


Figure 7: Sketch of sediments exposed in transverse ridge at Location 7, Cloncullen remnant. A basal horizontally bedded boulder gravel is overlain by laminated sands and silts, and then by a clay-rich diamicton. Clast a-axes show a dominant dip northwestward, transverse to the ridge long-axis orientation.

are formed from a combination of point discharge deposits and ice-walled channel or tunnel deposits. Exposures indicate that sharp-crested and round-crested ridges were deposited within the confines of ice walls. Flat-topped segments were formed in standing water. Although no exposure was found in fan-shaped segments, their morphology indicates that these are also point-discharge deposits, although it is unclear whether they are subaerial or subaqueous fans. Finally, ice-transverse ridges are interpreted as ice-marginal push moraines.

Channel/tunnel deposits

These deposits are similar to those found in free-surface gravel-bed rivers, although many form only under conditions of extreme flooding. However, the sediments observed could also form easily within a tunnel. While backset bedding has previously been interpreted as a tunnel deposit, formed under full-pipe flow (Johannson 1975, Lundquist 1979), there is no reason why they cannot be formed under free surface flow (Brennan 1994), and such bedforms have been observed in supraglacial channels associated with extreme floods (Russell, pers. comm.). In this case, the morphology of the ridges indicates that they were formed within the confines of the ice sheet.

Point discharge deposits

Deposits underlying flat-topped sections of the esker are interpreted as Gilbert deltas, deposited at an efflux point into standing water. However, deposition in an ice-contact, pro-glacial lake position cannot be automatically assumed, as the steep sides of the ridge at these points indicate that deposition was partly confined within ice walls, and lacustrine deposits within eskers have been inferred to form subglacially within cavities (Lewis 1949; Mickelson 1987; Gorrell and Shaw 1991; Brennand 1994). Nevertheless, three pieces of evidence suggest that these deposits are ice-marginal rather than subglacial in origin. Firstly the position of these flat-topped areas along the central part of the ridge indicates that these segments are unlikely to have been deposited within a cavity to one side of a conduit, as suggested by Gorrell and Shaw (1991). Secondly, the position of the deltaic sediments overlying channel/conduit deposits at Location 1 indicates that deposition is not likely to have occurred within ponded water at a low point on the glacier bed, as suggested by Mickelson (1987), as such sediments would be succeeded by channel/conduit deposits, rather than overlying them. Thirdly, the arrangement of foresets at this location suggests that the ice walls here must have retreated over time, allowing the level of the ponded water to drop, the inflowing current to be diverted to one side of the ridge, and deposition of foresets to occur at a lower level here. These deposits are therefore interpreted as having formed within reentrants along the ice margin, at a stream discharge point where water was temporarily ponded by a combination of ice and bedrock. Fan-shaped deposits are also interpreted as pro-glacial ice-contact features, as there is no evidence of confinement within ice walls in their morphology.

Nature of the ice marginal zone

The identification of ice marginal deposits at two sites, and the presence of three other flat-topped or fan-shaped areas along the esker indicates that the Ballymahon esker was formed time-transgressively, and the ice margin was located in at least five different positions during esker formation. This indicates that the ice-marginal zone is likely to have been characterised by stagnation zone retreat, rather than *in situ* downwasting, and that the hummocky moraine was also formed time-transgressively. There is also some minor evidence of active ice, resulting in the formation of ice-push moraines. These, however, are rare.

The development of tunnel/channel deposits indicates that this ice-marginal zone was characterised by water drainage along sub-parallel lines perpendicular to

the ice margin, and with occasional reentrants along the edge of the ice sheet. However, the position of drainage within the glacier is unclear, as all tunnel/channel deposits could have formed in either a tunnel or a subaerial channel. The one possibility that can be discounted is formation on the glacier bed within a subaerial channel, as this is incompatible with the uphill path of the esker. There is some evidence of deposition on ice at Location 1, indicating an englacial or supraglacial channel here; however, this the only place where evidence of post-depositional disturbance was found, either in the Ballymahon esker or the esker remnants. It is likely, therefore, that most of the sharp-crested ridges were formed subglacially within conduits. In any case, the sediments indicate that these conduits are likely to have been filled very rapidly during a sediment-laden flood event, rather than by a gradual accumulation of sediment over time. This has important implications for the operation of the drainage network in the ice-marginal zone, as conduits must have become blocked periodically, resulting in diversion of flow into other conduits, or upwards into the englacial and supraglacial zones.

While the eskers and esker remnants, and the existence of a further esker to the east (Figure 1), indicate the existence of sub-parallel drainage routeways, it is unknown whether these were operational at the same time, as some of the former conduits may have formed and/or enlarged after the blocking of the main conduits. The continuity of the Ballymahon esker, and the stacking of ice-marginal deposits on conduit/channel deposits at Location 1 indicates that water discharged continuously along this routeway for several seasons at least, and that this was the dominant drainage routeway in this area. This indicates the importance of the subglacial bed topography in controlling drainage, as the esker is confined to the Dungolman valley.

Interpretation of the esker remnants is less clear, as it is possible that these are the remains of more continuous eskers which were destroyed after exposure, a common occurrence in modern glacial environments (Lewis 1949; Price 1966). In the case of the Cannorstown remnant, field mapping indicates that glaciofluvial deposits are absent to the north and south, so the likeliest explanation is that these deposits represent a short-lived drainage routeway, possibly over a single season. However, the linear arrangement of the individual ridges of the Cloncullen remnant indicate that drainage continued along this routeway for some time. In this case, the gaps between the ridges may have been caused by post-depositional erosion after exposure of the ridge, or they may represent areas of

non-deposition, when water was diverted elsewhere. The likeliest explanation, which is supported by the evidence that the Ballymahon drainage route must have infilled with sediment rapidly, is that the Cloncullen routeway operated as an overflow channel when the main Ballymahon routeway was blocked, resulting in periodic deposition of sediment in short sections of tunnel. This also explains the continuity of the Cloncullen remnant north of the Ballymahon esker, as this continuous section would have formed after the final diversion of water into the eastern routeway.

Conclusions

Investigation of both eskers and hummocky moraine in this area indicates that the ice-marginal drainage network was considerably more complicated than indicated by the eskers alone, and highlights the importance of combining detailed morphological mapping with sedimentological work within hummocky moraine belts (Benn 1992). The recognition of the time-transgressive nature of these deposits, and the identification of a stagnant ice zone, is important, as it places

constrictions on the interpretation of the nature of deglaciation of the British ice sheet here, and points to a gradual recession rather than a widespread collapse of the ice sheet. However, reconstruction of the ice marginal zone is severely limited: the position of the drainage network is unknown, the length of the channels or conduits is unknown, and the width of the stagnant ice zone cannot be calculated. Finally, while it is clear that these deposits are time-transgressive, the amount of time taken to form them is unknown, and in the absence of an accurate dating method, it is unlikely that these issues will be resolved in the near future.

Acknowledgements

Fieldwork for this paper was supported by the Manchester Geographical Society, and by a Geological Survey of Ireland research assistantship. I am grateful to the Cassells family, Cloncullen and Eamon and Kathleen Delaney for field assistance, and Dr. John Graham for many helpful discussions.

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