Geomorphology and Quaternary glacial legacy

by David J A Evans

The last 2.6 million years of Earth history (the Quaternery Period) is characterised by large volumes of global ice relative to previous geological periods and is the culmination of a long-term cooling trend that began some 55 million ago. The extent of ice has varied in an oscillatory fashion so that the Quaternary Period is characterised by two dominant climate extremes called glacials and interglacials. However, the climate is never stable, oscillating instead dynamically from one extreme state to the other and necessitating the use of the terms stadial and interstadial to refer to phases of relative cold and warmth during glacial stages.

Many physiographic details of the North Pennines relate specifically to the lithological and structural control of the underlying bedrock, whose denudation and incision has resulted in conspicuous stepped hillslope profiles and tableland type topographic features. Additionally, the area contains some remarkable relict channels and underfit valleys (those now hosting streams too small to have been capable of cutting them), which are developed respectively on valley sides and across lower lying, undulatory to hummocky topography; such valleys are either of a glacial meltwater origin or relate to more complex and longer timescale combined fluvial and glacial origin (Evans 2017). The longer timescale drainage features date to fluvial processes that may have operated long before the onset of the Ice Age or the Quaternary Period.

Glaciation is manifest in the landscapes of Teesdale and the North Pennines in the form of erosional features cut directly by the ice or by its meltwater and more obviously in the form of glacigenic drift. Drift is a term used to describe surface materials that are clearly related to former ice action and includes glacifluvial sands and gravels (meltwater deposits) and tills (poorly sorted sediments plastered on the landscape by glacier ice). Early geologists referred to tills as ‘boulder clays’, a term that unfortunately still persists despite being entirely inappropriate due to the fact that tills are hardly ever composed only of boulders and clay.

Bedrock controls on physiography and Quaternary deposits

The physiography of the northern Pennines, and Teesdale in particular, is dictated by the fabric of the bedrock geology, which gives rise to an eastward-dipping dissected plateau, upon which it is thought that early eastward-draining river networks were developed (Mills & Hull 1976). The strong geomorphological inheritance of the underlying bedrock structure and lithology is exemplified by the sub-horizontal valley-side benches and flat-topped mountain summits (or mesas and buttes), which reflect the predominantly flat-lying to shallow dipping strata of the Carboniferous sandstones, millstone grits, limestones and coal measures.

The tableland or mesa and butte topographic features at the highest elevations along the North Pennine upland chain have developed into extensive mountain summit blockfields, interpreted as the products of in situ frost-shattering. The blockfield on Cross Fell (Mitchell & Huddart 2002) and adjacent hilltops has been central to long standing debates on the former existence of nunataks above the British-Irish Ice Sheet (Dwerryhouse 1902; Raistrick 1931). Small areas of blockfield also exist on the summits of Little Fell, Mickle Fell, Long Crag and Bink Moss to the south of the River Tees and Middleton Common, Monk'sMoor and Eggleston Common to the north. The alternative interpretation of these blockfields (Trotter 1929) was that they had survived beneath a cover of thin and passive glacier ice. More recently, Trotter's idea has been substantiated and the vertical transition from upper drift limits to blockfield is interpreted as marking a thermal boundary in formerly extensive ice sheets; this involves the occurrence of warm ice in valleys where it is thickest and cold ice on surrounding summits where it is thinnest and dynamically sluggish or even inert.

Quaternary deposits that overlie this predominantly stepped bedrock topography thicken in valley bottoms in a range of glacial landforms but thin rapidly upslope above the middle Tees valley and its tributaries to form clear drift limit; above this limit the Quaternary deposits form an often patchy veneer through which bedrock structure is clearly visible (Evans 2017). Mapped over the region as 'boulder clay' with valley floor pockets of 'glacial sand and gravel' (Mills & Hull 1976), this Quaternary cover thins also towards the valley heads of upper Teesdale, Lunedale, Baldersdale and Deepdale, in the direction of the NW–SE trending ridge of the North Pennines mountain chain. This mountain chain (600-890 m) is punctuated by passes to the north and south of the Mickle Fell/Little Fell summit ridge, the latter forming one of several cols that feed into the drainage basins of Lunedale, Baldersdale and Deepdale; the glacially streamlined, relatively lower elevation topography of this terrain is collectively named the Stainmore Gap, after the pass (Stainmore Common/Cotherstone Moor) that crosses the North Pennines between the higher summit massifs of the Durham and Yorkshire dales.

Glacierisation of the North Pennines

Contrary to many media-based, popularised views of the ice age, ice sheets do not march southwards from the Arctic to engulf mid-latitude regions like Northern England when colder conditions prevail. Instead it is the upland surfaces, like the Pennines themselves, which spawn glaciers and ice caps, simply because they are at relatively high altitude, where colder environmental conditions will cause the accumulation of snow first.

The operation of a North Pennines independent ice dispersal centre during glaciations was first proposed by Dakyns et al. (1891), Dwerryhouse (1902) and Raistrick (1931). They envisaged that the ice built up in the easterly-facing valley heads that lie below the Cross Fell-Mickle Fell summit ridge, resulting in northerly and easterly flowing valley glaciers in the Tyne, Wear and Tees catchments.

Regional ice flowing from Scotland then flowed around this partially ice-covered upland, creating major ice streams in the Tyne Gap and Vale of Eden/Stanmore Gap. This pattern of ice flow is one that persists in modern reconstructions (Figure 1) but some significant details have been refined, as detailed below.

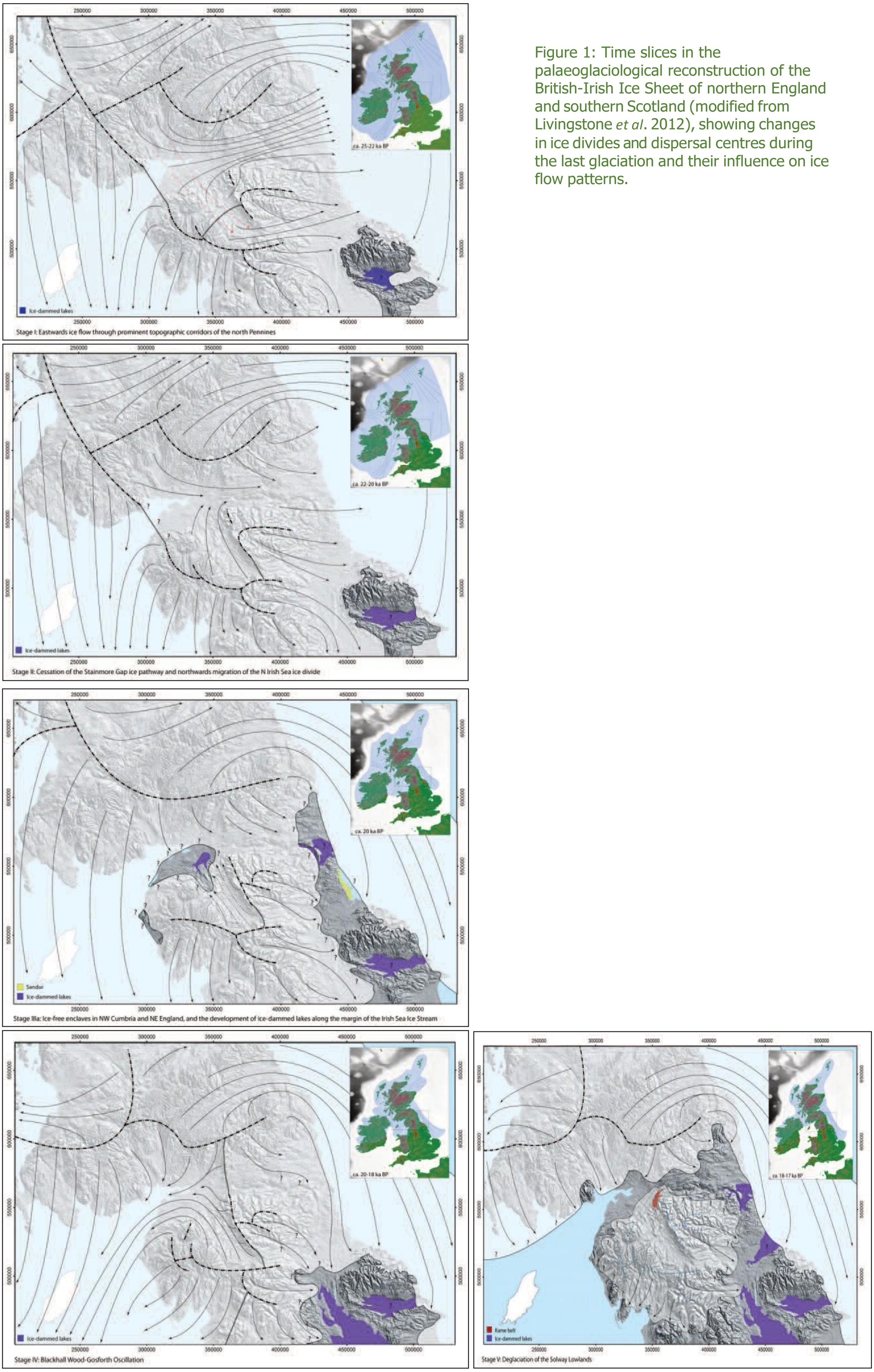


Figure 1: Time slices in the palaeoglaciological reconstruction of the British-Irish Ice Sheet of northern England and southern Scotland (modified from Livingstone *et al*. 2012), showing changes in ice divides and dispersal centres during the last glaciation and their influence on ice flow patterns.

The notion that palaeonunataks lay above these various fast-flowing ice masses was based on the assumption that the summit blockfields, such as Cross Fell, required long periods of freeze-thaw weathering to develop and hence must have lain above the ice during glaciation. We now understand that not only can blockfield form quickly (ie. in postglacial time) but it can also survive beneath the cold-based inert ice that would have been typical of such upland settings during glaciation; indeed, glacierisation started on these uplands. So it is now conventional, as introduced above, to interpret the transition between upper drift limits and blockfield as thermal boundaries in ice sheets.

So instead of lying above the ice sheets, the Pennine uplands were one of the spawning grounds for them. This was first appreciated climatologically in the 1950s' research of Gordon Manley, who used the North Pennines to identify important relationships between snowfall accumulation and physiography, noting the tendency for plateaux in particular to be the seeding grounds of ice caps and hence to play a critical role in the early stages of glacierisation during cold stages of the Quaternary Period. This plateau-icefield style of initial glacierisation creates a particular landform imprint, but one that is often overrun and hence heavily modified by more extensive ice sheet growth as a glaciation progresses.

In terms of geomorphological change in terrains like the North Pennines, the highest plateaux are likely to have been occupied by ice for the longest cumulative period of time throughout the Quaternary Period, because most of that Period of million years has been characterised by an Earth surface with an intermediate style of glacier coverage; so the planet has for most of the Ice Age been in a state of glacierisation that lies somewhere between full glacial maxima (extensive ice sheets) and interglacial minima (like the present day). This concept is termed 'average' glacial conditions, and these are the most effective in terms of longer-term landscape change because they dominate for most of the time.

In order to understand the range of possible plateau icefield glacial configurations on the North Pennines, Evans and Jamieson (2017) used a numerical glacier model driven by the palaeoclimate data from the Greenland ice core record. This record covers the period that includes the Younger Dryas Stadial of 12,900–11,700 years ago, when mountain glaciers re-occupied the British Isles after having largely disappeared at the end of the last glaciation.

This phase of glacierisation is significant because it is regarded globally as the likely average glacial condition for the Quaternary Period. The evidence for two small glaciers of possible Younger Dryas age have been identified in Upper Teesdale (see below), but one, Tarn Rigg (445 m), is contentious and the other, High Cup Plain (580 m), is likely an underestimate of plateau ice cover.

The altitudes of both sites can however be used to drive the numerical model, because they can be used as upper and lower estimates of the glacier equilibrium line altitude (ELA = the altitude at which a glacier can exist, because it marks the altitude at which inputs of snow and ice equal outputs due to melting).

The model output for the 580 m ELA simulation (Figure 2A) reveals that the Younger Dryas palaeo-temperatures are sufficient to build a small but reasonably stable plateau icefield in the North Pennines and the ice reaches the location of the proposed High Cup Plain glacier. The model also shows the locations likely to be characterised by the build-up of drift (moraines) due to the duration of ice-marginal stability (Figure 2B). The 445 m ELA experiment (Figures 2C & 2D) creates far more extensive ice, with the Teesdale ice reaching beyond Barnard Castle at its maximum and hence an ice cover that is too large to align with field evidence for potential Younger Dryas glacier ice. It does, however, show that under a more extreme glacial climate the regional ice cover develops initially from plateau dispersal centres.

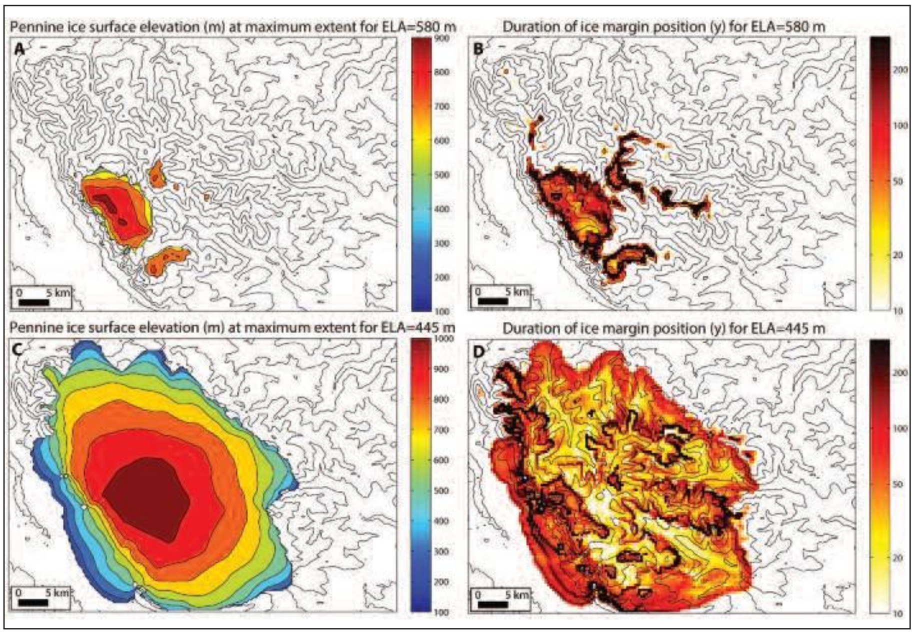


Figure 2: Maximum Younger Dryas ice extent (left) and the duration of ice margin stabilisation (right) for two model scenarios including the likely ELA of 580 m (top) and a lower ELA of 445 m (bottom). From Evans and Jamieson (2017).

This plateau icefield style of glacierisation was subsumed only during full ice sheet conditions by easterly-draining ice streams of an ice sheet that extended as far south as North Norfolk in the east and the Isles of Scilly in the west.

Once coalescent, all the ice masses that were expanding from their various upland dispersal centres (eg. North Pennines, Lake District, Southern Uplands, Scottish Highlands) submerged the landscape and evolved in glacierisation style from topographically- confined flow to unconfined full ice sheet flow. The latter was characterised by significant ice flow reversals over the North Pennines in particular (Figure 1).

We now understand ice sheets to be extremely dynamic systems in which flow directions, particularly those related to ice streams, switch in response to changes in ice sheet thickness and dispersal centre locations. In the North Pennines the extent of the regional ice (derived from Scotland) and the persistence of plateau-centred local ice throughout glaciation was identified by the mapping of erratics (Johnson & Dunham 1963; Vincent 1969; Taylor et al. 1971; Francis 1974; Lunn 1995a, b, 2004).

This showed that only the higher plateau of Cross Fell and Cold Fell contained no westerly-derived regional erratics and hence it generated independent ice that flowed radially but most strongly eastwards down Teesdale (Figure 3). This easterly flow was a result of the Pennine ice being forced to flow with the stronger Scottish-derived regional ice during the ice sheet maximum phase while at the same time still excluding it from the highest Pennine plateau.

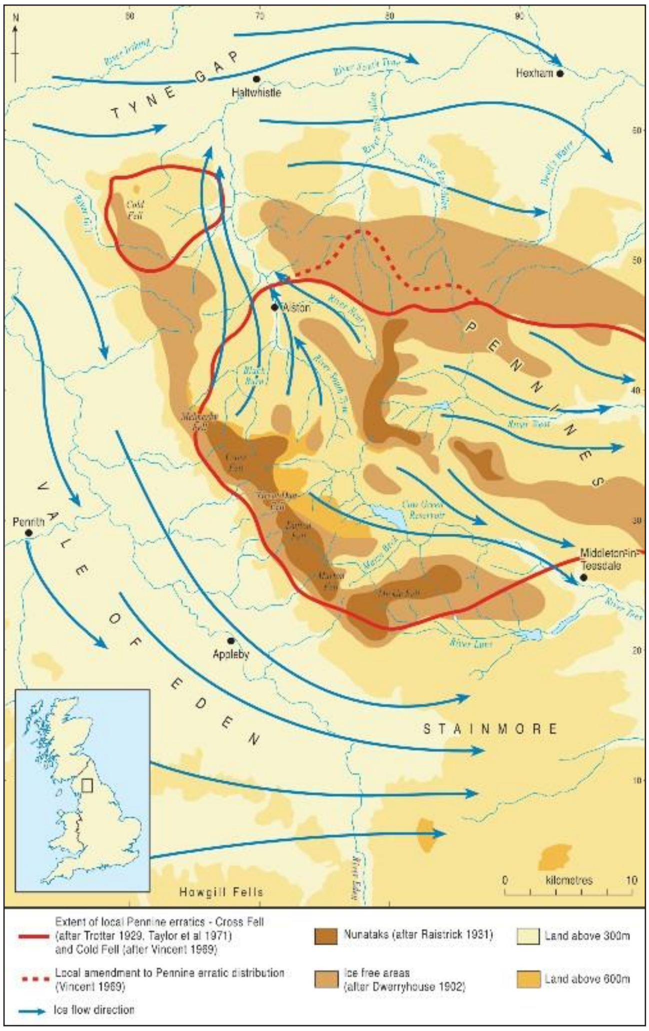


Figure 3: Map of Upper Teesdale and adjacent areas showing the former ice flow directions depicted by Dwerryhouse (1902) at a relatively early stage of ice flow up the Vale of Eden from Scotland. Note the radial flow of the Pennine-centred ice from the Cross Fell plateau and the deflection of easterly flowing Tyne Gap and Stainmore Gap ice streams around this ice. Also shown are the proposed nunataks of the north Pennines from Dwerryhouse (1902) and Raistrick (1931), features now interpreted as the levels of thermal regime changes in the overlying ice sheet. Red lines demarcate the limit of regional, western-derived erratics and thereby outline areas characterised by Pennine erratics only (after Trotter 1929; Vincent 1969; Taylor *et al*. 1971).

Glacial geomorphology of Teesdale

In addition to the distribution of erratics, the most significant landform evidence for former ice sheet flow patterns comes from streamlined drift mounds, often composed entirely of till and called drumlins and flutings. Although the exact origins of these features are debated, it is accepted that they record the streamlining of deformable and erodible materials by a glacier as it flows over its bed. Where little deformable material (sediment) is available, the ice can produce similarly streamlined forms by dragging debris over the bedrock and eroding it to produce features called whalebacks or rock drumlins.

As the long axes of these streamlined forms are aligned with former glacier flow, it is easy to reconstruct the ice flow dynamics. Additionally, changes in ice flow direction over time can result in the overprinting of streamlined forms and we have such evidence recorded in the patterns of alignment and overprinting in the drumlins and flutings of Teesdale and adjacent areas.

The drumlins and flutings display some relatively high elongation ratios (up to 13.75) and a relief of up to 20 m. A restricted number of valley floor exposures reveal multiple till sequences up to 10 m thick, but elsewhere many streamlined features merely constitute discrete lineations that are likely controlled by underlying bedrock structure, especially on the northern slopes of upper Teesdale and on the higher terrain of the Stainmore Gap. Drumlinoid drift tails have also been developed on the interfluves of the tributaries to the upper River Tees where older recessional lateral moraines (see below) likely have been glacially overridden. Abnormally large drumlinised mounds (15 - 20m relief) but with low elongation ratios (2.25 - 3.0) occur on the floor of upper Teesdale, at Holwick. These streamlined landforms show that regional ice sheet flow was dominated by the easterly flowing Tyne Gap and Stainmore Gap ice streams. The limit of the Teesdale ice, or more specifically its suture zone with the Stainmore ice stream, was first identified by Dwerryhouse (1902) using the distribution of regional erratics. Teesdale ice was deflected significantly northwards downstream of Middleton-in-Teesdale to flow into the drainage of the Gaunless Valley, as determined by the distribution of Shap granites delivered by the Stainmore ice stream.

In the upper Teesdale catchment, Mitchell (2007) used the cross-cutting relationships of the drumlins in the Moor House/Cow Green area to show that changes in ice flow direction took place also in the Pennine- centred ice, likely when it was a smaller plateau-based ice mass.

Figure 5: Teesdale drumlins: a) west of Cow Green Reservoir; b) Forest-in-Teesdale; c) Seats Hill, Holwick; and d) multiple tills in a drumlin at Stack Holme, Lunedale: © D J A Evans

An early southerly ice flow appears to have been driven by an west-east aligned ice divide but this was replaced by an easterly to southeasterly ice flow when the ice divide migrated westwards. Drumlins like this, which are indicative of significant subglacial sedimentation and deformation (thick drift), are unusual in upland settings such as the upper Tees catchment. So why is there so much drift in upper Teesdale?

To answer this we return to our concept of 'average' glacial conditions. The summit ice of plateau icefields, because it is both thin and a centre of dispersal, and hence of low flow velocity, is predominantly geomorphologically inert or protective. As a result the maximum erosional and depositional capacity of such systems is concentrated in surrounding, lower elevation valley heads where strain heating is induced by increased flow velocities. This gives rise to a concentration of depositional landforms not on the plateaux but on the lower surrounding terrain. Based upon our numerical modelling (Figure 2) we can assume quite confidently that for most of the last glacial cycle the short occupancy time of mountain icefields was capable of producing only subtle erosional and depositional imprints and that the most substantial depositional products of repeat glaciations should lie in this intermediate zone at the plateau base.

Using our knowledge of debris transport pathways through glaciers, we can predict that over time an ice mass will advect material towards its margin. Hence, each ice margin will be marked by a marginal-thickening wedge of subglacial sediment, the volume of which is dictated by the residence time of the ice (Figure 2). It is highly likely that the large volume of glacigenic debris represented by the Cow Green drumlins marks the location of plateau icefield marginal moraines constructed during average glacial conditions and then subsumed by thick erosive ice during phases of more extensive, regional ice flow activity.

Other, non-streamlined, drift mounds in Teesdale are more difficult to interpret in terms of former glacial processes. Some contain substantial glacitectonic bedrock rafts (Figure 5a), as demonstrated by reports on a rare extensive exposure temporarily made available at an opencast coal mine near Tow Law (Mills 1976).

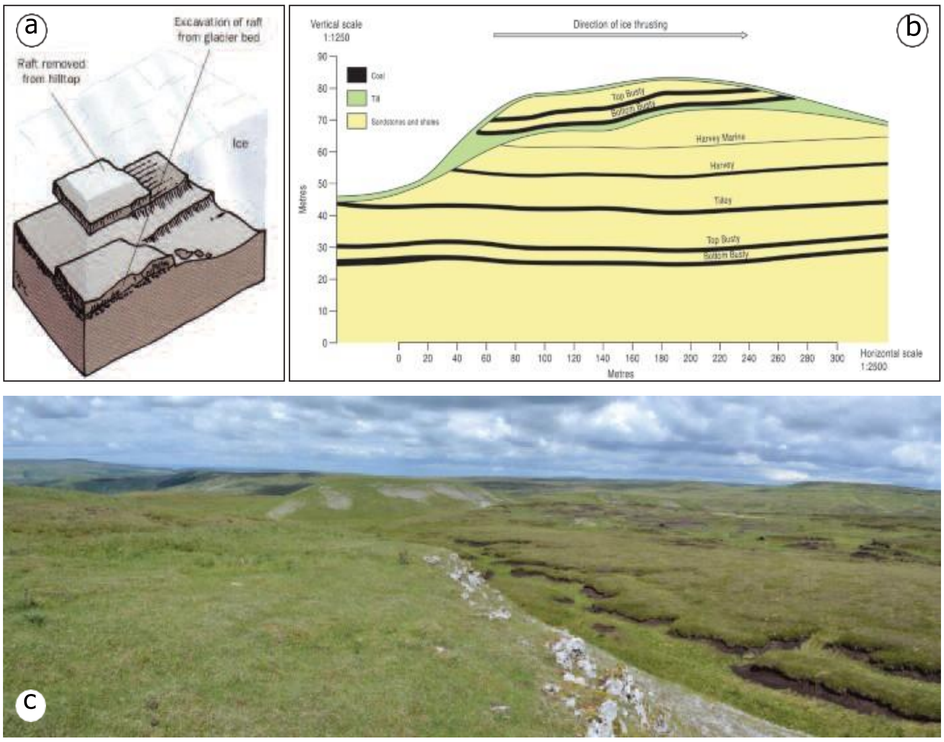


Figure 5: Glacitectonic thrust masses of bedrock: a) idealized sketch of the formation of a glacitectonised raft (modified from Evans & Benn 2010); b) the Sunniside and Broom Hill interfluve glacitectonic rafts, near Tow Law, County Durham, showing repetition of strata after Mills (1974) and Moore (1994); c) view within and across the Bullman Hills from the southwest, showing the flat-topped nature of the mounds and the surface outcrops of the Great Limestone that comprises the core of the landform assemblage: Photography © D J A Evans

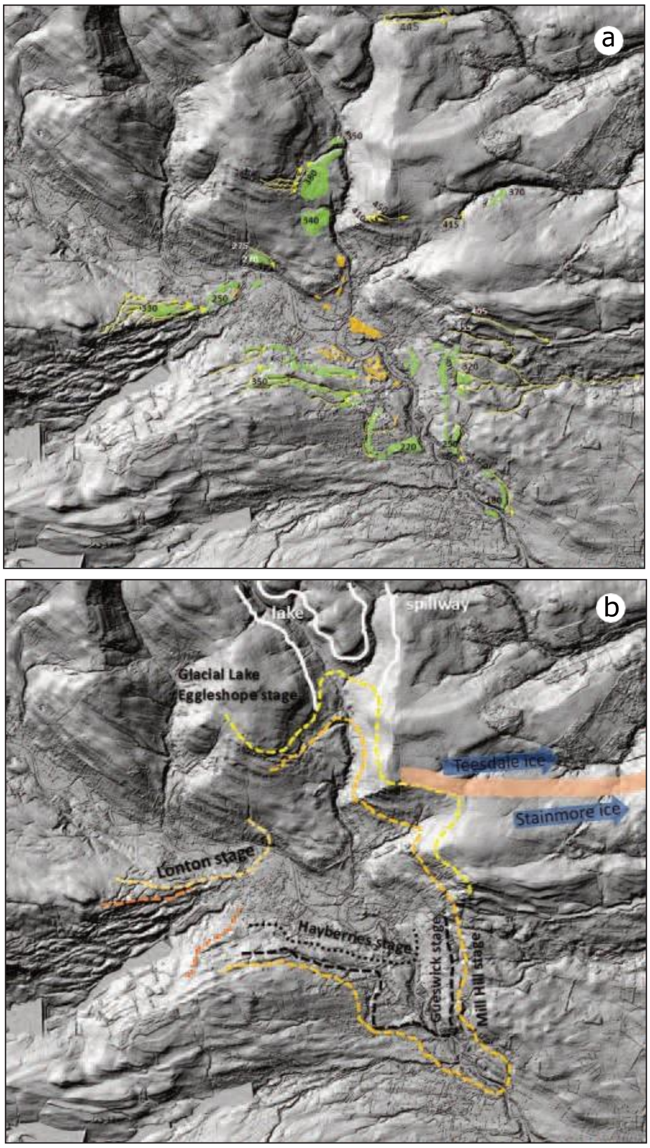
Although outside Teesdale, this exposure through hillocks (Figure 5b) clearly illustrates the importance of bedrock dislocation and glacitectonic raft development in the Carboniferous strata of the region. In the Upper Teesdale catchment, further impressive examples are the Bullman Hills and Lambgreen Hills (Lunn 1995a, b) which are huge blocks of Great Limestone displaced from the Cross Fell summit and carried northwards by ice dispersing radially on the Cross Fell plateau (Figure 5c).

Some drift mounds appear to be overridden moraines because their plan form resembles that of latero-frontal moraines in narrow valley settings but their surfaces are faintly fluted or streamlined. An excellent example occurs on the floor of Harwood Beck near Low End (Figure 6a), which likely demarcates the limits of plateau-based ice during average glacial conditions, later streamlined by easterly flowing regional ice streams.

Figure 6: Latero-frontal moraines; a) large drift ridges of Harwood Beck viewed from the west. Valley side ridges descend diagonally down slope towards valley floor ridges. The largest valley floor ridge is that in the middle distance, which crosses the valley near Low End. This feature appears to have been overridden by glacier ice during the last glaciation; b) inset sequence of linear ridges (lateral moraines) below Widdy Bank in upper Teesdale, documenting the recession of topographically confined ice into the Cow Green area: © D J A Evans

Examples of unaltered latero-frontal moraines or arcuate, valley floor drift assemblages are recognisable throughout Teesdale. The most obvious latero-frontal moraines occur near Cronkley Scar, where they demarcate the margins of a valley-confined glacier lobe at the later stages of deglaciation (Figure 6b). A further substantial assemblage of drift mounds forms an arcuate loop across the main Teesdale valley between the villages of Romaldkirk and Cotherstone, the largest of which is a wide cross-valley ridge, named locally the Gueswick Hills and mapped as morainic drift by Mills and Hull (1976).

The Gueswick Hills can be traced onto the west and east slopes of Teesdale as discontinuous linear ridges (Figure 7); those on the east slopes below High Shipley ascend diagonally upslope to a more extensive assemblage of mounds in the area around Folly Head and Windy Hill and those on the west bank form an arc that extends up stream to join patchy drift mounds around Romaldkirk. Immediately to the northwest of the Gueswick Moraine, a number of discrete, non-streamlined drift mounds are similarly interpreted as glacier marginal deposits.



Fgure 7: The glacial features and interpreted glacial stages in mid-Teesdale: a) glacial landforms mapped on the NEXTMap DEM showing selected altitudinal values in metres. Green areas are glacigenic drift mounds interpreted as moraines, orange areas are glacifluvial mounds interpreted either as eskers or kames, and yellow arrows represent selected meltwater channels associated with the moraines; b) reconstructions of the sequentially younger stages of ice-marginal positions relating to the topographic confinement of glacier ice in Teesdale. The maximum northerly position of the full glacial ice stream suture zone is marked by the northern extent of regional erratics (thick orange line and blue arrows). The spillway and likely upper level of Glacial Lake Eggleshope is also marked (DEM courtesy of NERC via the Earth Observation Data Centre).

Although exposures are rare, the occurrence of these mounds on valley sides and interfluves and across valley floors strongly suggests that they are glacigenic. The largest of these mound types are in Eggleston Burn and includes a dissected cross valley ridge and an expanse of hummocks and ridges on the interfluve with the main Teesdale valley above Froggerthwaite, the latter interpreted as ‘ablation moraine’ by Mills and Hull (1976). Their orientation, as well as their association with lateral meltwater channels on the adjacent higher slopes, suggests that these mounds (collectively hereby termed the Froggerthwaite Moraine; Figure 7) were deposited at the margin of topographically confined ice in Teesdale when it back-filled Eggleston Burn during overall ice sheet recession.

Finally, an area of substantial drift mounds occurs around the area of Lonton and Laithkirk, at the junction of Lunedale and Teesdale. These features are closely associated with densely spaced and deeply incised lateral meltwater channels that demarcate the receding margins and former coalescence zone of Teesdale and Lunedale ice lobes (see below). Each of these landform assemblages marks a separate stage in the recession of ice in Teesdale, some of which are re-advances (Figure 7b; Evans 2017).

Glacifluvial landforms and deposits are well represented in the North Pennines and comprise meltwater channels and eskers and kames. A number of elongate ridges and associated mounds and benches can be confidently ascribed to glacifluvial depositional processes because they are composed of sands and gravels (cf. Mills and Hull 1976). Other features in which there are no sedimentary exposures have also been interpreted as glacifluvial in origin based upon their morphology and general context or relationships with other landforms.

The most extensive spread of glacifluvial deposits occurs in undulatory and weakly pitted benches on the margins of the River Tees valley floor located between Middleton-in-Teesdale and Romaldkirk. A number of discontinuous, elongate ridges occur on the surfaces of these benches, as well as further up valley, where they lie in isolation on the River Tees floodplain between Middleton-in-Teesdale and Bowlees. These features are interpreted as eskers, the internal sediments of which are exposed in small pits at Hayberries, near Romaldkirk (Figure 9a).

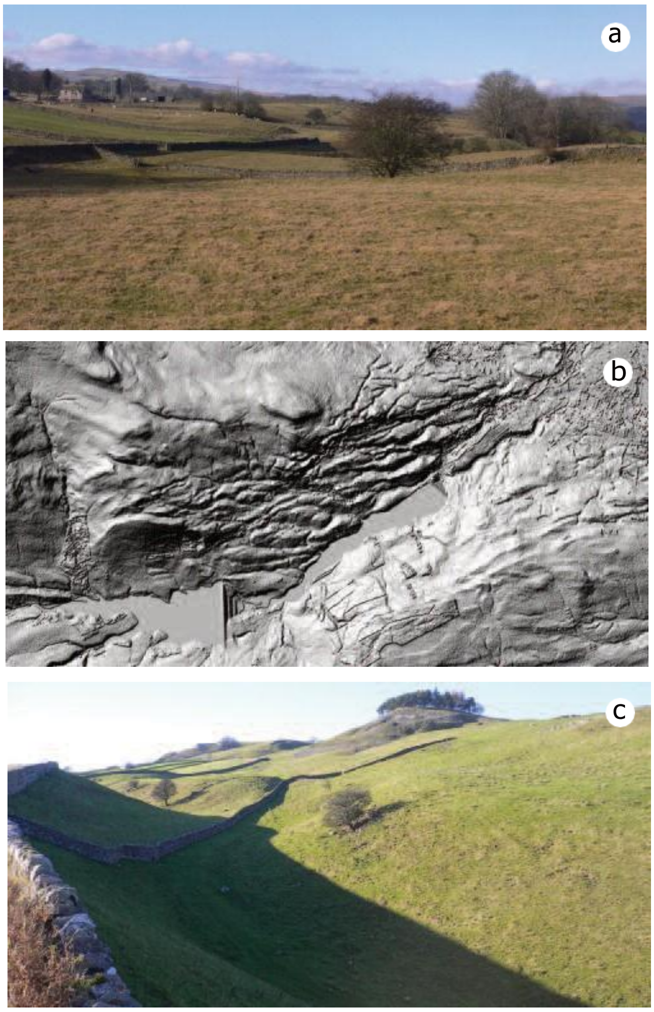


Figure 8: Examples of glacifluvial landforms of Teesdale: a) view westwards along the Mickleton-Egglestone glacifluvial terrace directly west of the Hayberries esker complex; b) NEXTMap DEM extract of the glacial landforms of lower Lunedale, showing the en echelon arrangement of lateral meltwater channels and their relationship with the Lonton Moraine and meltwater channels associated with former Teesdale ice. Also visible are streamlined mounds (drumlins) around which channels have been incised; one of the most prominent of the lateral meltwater channels on the north side of Lunedale, below Kirkcarrion: Photography by D J A Evans and DEM courtesy of NERC via the Earth Observation Data Centre.

Exposures through the glacifluvial deposits of the benches also occur near Mickleton (poorly-sorted boulder to cobble gravels) and west of Eggleston Hall (horizontally bedded gravels and sands overlying till), indicative of kame terrace origins.

Two further spreads of glacifluvial outwash exist beyond the Gueswick Hills Moraine, their apexes emerging from substantial meltwater channels. An unusual glacifluvial assemblage is the Woolly Hills, which forms a triangular-shaped assemblage of sharp- crested ridges and chaotic high relief hummocks and straddles the watershed separating the Hindon Beck (Gaunless) and Woolly Gill (Spurlswood Beck) drainage basins, clearly recording former subglacial or englacial meltwater flow that crossed normal fluvial drainage basins.

Given the close proximity of this elongate assemblage of glacifluvial landforms to the suture zone of regional (Stainmore) ice and Pennine (Teesdale) ice, as defined by the northernmost extent of regional erratics, it is likely that it represents deposition in the suture zone of the two ice flow units when meltwater was draining preferentially along the supraglacial ‘valley’ and associated englacial and subglacial drainage network created at the point of coalescence (Evans 2017).

Meltwater erosional features are particularly well developed around Teesdale. A number of possible preglacial or consequent valleys may have been re- occupied by glacial meltwater, thereby explaining their partial drift infill and locally prominent cliff margins. Clusters of spectacular dry valleys and channels of unequivocal deglacial meltwater origin occur along valley margins and hence are associated with ice- marginal or lateral meltwater drainage and sub- marginal drainage or chutes (Dyke 1993; Syverson & Mickelson 2009). A prominent series of meltwater channels cut through and descend from the Butterknowle/Copley/Wigglesworth fault scarp into Langleydale.

These meltwater channels descend diagonally from the fault scarp and record lateral meltwater incision at the margin of glacier ice downwasting from the scarp top. Early lateral meltwater incision at the margins of this ice was concentred on Arn Gill, which drains into the River Gaunless drainage basin to the north of the fault scarp summit and can be traced back to prominent channels cut into the bedrock slopes above Eggleston and Folly Head.

Once the ice margin had downwasted below the fault scarp summits of Peatmoor Crag and Cragg Top/Penny Hill, lateral meltwater began draining south-eastwards and into the Langleydale drainage basin. At later stages of ice recession, meltwater continued to be diverted into the floor of Langleydale via substantial bedrock gorges to the east of Folly Head, specifically at Pallet Crag Gill and Howe Gill, thereby initiating the later stages of incision of the drift infill.

The large volume of meltwater that was diverted into the Arn Gill/Gaunless drainage basin and then Langleydale is unusual in that glacier ice lay over significantly lower topography to the south, especially over Teesdale, and therefore meltwater had to be flowing at high levels within the ice in order for it to be delivered into the easterly draining valleys. Ice-marginal or lateral meltwater drainage would have been capable of such a flow pattern and indeed lateral meltwater channels exist on the southern slopes of Monk’s Moor and also across the Hett Dyke on the south-eastern corner of Egglestone Common (Figure 7), where they are responsible for the creation of the bedrock ridges called Knotts. The uppermost channel on Monk’s Moor descends from around 500 m to 410 m, after turning to flow up valley around the Froggerthwaite Moraine like all the inset meltwater channels on this slope (Figure 7).

On the east valley side, the uppermost channel at Knotts is at 450 m. In order to cut channels at isolated locations at such high altitudes on both sides of the Egglestone Burn, valley water flow would have to be ice-directed and hence is further evidence, in addition to the Froggerthwaite Moraine, that a lobe of Lunedale ice in Teesdale backfilled the lower half of the valley. Indeed, this pattern of drainage channel development was regarded by Mills and Hull (1976) as evidence for glacial lake spillways, whereby the upper Egglestone Burn valley was dammed by ice in Teesdale to form a lake (called Glacial Lake Eggleshope). This lake was also proposed by Dwerryhouse (1902), who identified the substantial dry gorge of Sharnberry Gill, which cuts across the eastern watershed of the valley at an altitude of 445 m, as the northern lake spillway. This spillway carried the lake waters into Euden Beck and ultimately to the River Wear drainage basin but was terminated as an outlet once the lower channels at Knotts were incised.

A flat-floored dry channel located at 415 m at the head of Spurlswood Gill indicates that spillway waters entered the Wear drainage basin via that route after Sharnberry Gill ceased to operate. This would have required ice to be occupying the Blackton Head area but it is likely that marginal meltwater was draining along the south slopes of Grey Carrs to enter the Redmire Gill channel at 405 m at around the same time, when the Mill Hill Moraine was being constructed (Figure 7). The final drainage of Glacial Lake Eggleshope was likely subglacial, beneath the thinning ice lobe occupying Teesdale, as evidenced by a small esker remnant inside the Froggerthwaite Moraine. The lack of glacilacustrine deposits suggests that it was a short-lived lake, but the size of the Froggerthwaite Moraine is consistent with a substantial stillstand and/or readvance of the Teesdale valley ice and so an alternative explanation for sparse lake sediments is that the lake drained frequently, potentially creating jökulhlaups or glacier floods that could at least partially explain the significant erosion of the gorges below Redmire Gill and Goose Tarn Beck and even have contributed to the deep incision of Arn Gill and the Gaunless valley.

A further spectacular assemblage of meltwater channels has been developed on the slopes of Lunedale (Figure 7 and 8b, c), documenting the recession of the Lunedale valley glacier once it had become topographically confined by the valley; hence the Stainmore Gap ice stream, of which the ice in Lundedale was part, had ceased to operate as a regional flow unit. The development of clusters of inset meltwater channels such as this, in locations that clearly relate to the more advanced stages of ice sheet deglaciation, has been identified not only on the nearby Pennine Escarpment by Arthurton and Wadge (1981), Greenwood et al. (2007) and Livingstone et al. (2010) but also in Strathallan, Perthshire by Evans et al. (2017), who regard this as a geomorphic signature of a significant change in meltwater drainage patterns, likely related to the temporary development of cold-based or polythermal ice conditions, the regional palaeoglaciological implications of which are still to be elucidated.

As discussed above, the most recent glacigenic imprint in the North Pennines has previously been proposed to be of Younger Dryas Stadial age (12,900- 11,700 years ago), during which small niche or proto- cirque glaciers where thought to have developed in High Cup Plain (Manley 1961) and below Cronkley Scar (Wilson & Clark 1995). Like other areas that lay at the threshold of glacierisation during the Younger Dryas, the North Pennines contain debris mounds in potential ice accumulation basins or hillside niches that have been variably interpreted as glacial (moraines), periglacial (protalus ramparts) or rock slope failures.

Mitchell (1991), reviewing earlier proposals for small glaciers based upon such features (Rowell & Turner 1952; Manley 1961), proposed that five sites in the western Pennines were of glacial origin and hence the ELA during the Younger Dryas was between 313- 612 m. Wilson and Clark's (1995) re-assessment of the debris assemblage at Tarn Rigg, below Cronkley Scar, as an end moraine rather than a lateral moraine as proposed by Dwerryhouse (1902), indicates a Younger Dryas ELA in upper Teesdale of 445 m. The High Cup Plain landforms, if they are of glacial origin and are Younger Dryas in age, indicate an ELA of 580 m.

Although the ELAs of both the proposed Tarn Rigg and High Cup Plain palaeo-glaciers lie within Mitchell's (1991) altitude range for Younger Dryas glaciation in the adjacent western Pennines, an ELA difference of 135 m between the two sites over such a short distance and within the confines of upper Teesdale is problematic in terms glacier-climate reconstructions. Indeed, the low elevation of Tarn Rigg is at odds with the easterly rise in ELAs across the western Pennines reported by Mitchell (1991). As we saw above (Figure 2), the use of such a low ELA altitude in numerical glacier modelling produces an abnormally large Younger Dryas icefield and so the glacier cover in Upper Teesdale during this period was more likely to have been a thin plateau icefield with small outlet lobes such as that on High Cup Plain.

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