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Early and Middle Pleistocene environments, landforms and sediments in Scotland

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Running head abbreviation: Early Middle Pleistocene Scotland

ABSTRACT: This paper reviews the changing environments, developing landforms and terrestrial stratigraphy during the Early and Middle Pleistocene stages in Scotland. Cold stages after 2.7 Ma brought mountain ice caps and lowland permafrost, but larger ice sheets were short-lived. The late Early and Middle Pleistocene sedimentary record found offshore indicates more than 10 advances of ice sheets from Scotland into the North Sea but only 4-5 advances have been identified from the terrestrial stratigraphy. Two primary modes of glaciation, mountain ice cap and full ice sheet modes, can be recognised. Different zones of glacial erosion in Scotland reflect this bimodal glaciation and the spatially and temporally variable dynamics at glacier beds. Depths of glacial erosion vary from almost zero in Buchan to hundreds of metres in glens in the western Highlands and in basins both onshore and offshore. The presence of tors and blockfields indicates repeated development of patches of cold-based, non-erosive glacier ice on summits and plateaux. In lowlands, chemical weathering continued to operate during interglacials, but gruss-type saprolites are mainly of Pliocene to Early Pleistocene age. The Middle Pleistocene terrestrial stratigraphic record in Scotland, whilst fragmentary and poorly dated, provides important and accessible evidence of changing glacial, periglacial and interglacial environments over at least three stadial–interstadial–interglacial cycles. The distributions of blockfields and tors and the erratic contents of glacial sediments indicate that the configuration, thermal regime and pattern of ice flow during MIS 6 were broadly comparable to those of the last ice sheet. Improved control over the ages of Early and Middle Pleistocene sediments, soils and saprolites and on long-term rates of weathering and erosion, combined with information on palaeoenvironments, ice extent and sea level, will in future allow development and testing of new models of Pleistocene tectonics, isostasy, sea-level change and ice sheet dynamics in Scotland.

KEY WORDS: Early Pleistocene, erosion, landform, Middle Pleistocene, Scotland, stratigraphy, weathering

The onset of extensive glaciation in the latest Pliocene in the Northern Hemisphere marked a fundamental change in the suite of geomorphic processes acting on land surfaces. On the segment of the North Atlantic passive margin in Scotland, landscapes had evolved during the Mesozoic and earlier Cenozoic through the interplay of tectonics, rock properties and surface processes operating under warm to temperate humid climates. Denudation involved prolonged and pervasive chemical weathering acting on a diverse rock substrate (Godard, 1965; Hall, 1991), with formation of thick saprolites (Hall, 1986). The removal of weathering products was by solution and slope processes, with fluvial transport of the detritus of weathering towards sediment sinks on the North Atlantic shelf (Stoker *et al.*, 2010) and in the North Sea basin (Japsen, 1997; Hall & Bishop, 2002).

During the Pleistocene (ca. 2.6–0.01 Ma), renewal of the saprolite layer slowed due to episodic glacier ice cover, lower average temperatures in ice-free intervals, the development of permafrost and increasing exposure of quick-drying rock surfaces. Chemical weathering rates remained high, however, as frost weathering and glacial comminution generated small rock fragments of high surface area that were then exposed to soil water (Raymo & Ruddiman, 1992). Periglacial slope processes were likely highly effective in mountain areas in moving existing and newly produced regolith towards river channels (Bartsch *et al.*, 2009), as in Scotland during the Lateglacial and Holocene periods (Ballantyne & Harris, 1994). Episodic ice sheet development was locally preservative in its impact on landscapes, where cold-based, non-erosive ice covers effectively sealed off the landsurface from weathering and erosion for long periods (Sugden, 1968; Hall & Sugden, 1987). Elsewhere, glacial erosion had a transformative effect on scenery, stripping away old weathering mantles (Clark & Pollard, 1998) and quarrying and abrading newly exposed fresh rock surfaces in the lowlands (Krabbendam & Bradwell, 2011). In the mountains, channelling of ice flow along existing and new valleys led to efficient vertical glacial erosion and the deep incision of valleys and cirques (Sugden, 1968; Hall & Kleman, 2014).

Recent work in Scotland has been focussed on the study of Late Pleistocene (128-12 ka) environments, landforms and sediments (Ballantyne & Small, 2018; Merrit *et al.*, 2018; Smith *et al.*, 2018). Events in the Early (2.588-0.774 Ma) and Middle (774-128 ka) Pleistocene have received much less attention despite the far longer time periods involved. Yet these critical intervals bridge the deep time of the Palaeogene and Neogene and the near-present of the last glacial cycle. This paper aims to provide the first synoptic review of changing environments, developing landforms and terrestrial stratigraphy during the Early and Middle Pleistocene in Scotland. The tectonic and climatic framework for relief development, erosion and sedimentation is explored using evidence from climate proxies, the offshore sedimentary record and ice sheet models. The variable impact of glacial erosion across Scotland is examined using its landscapes and landforms and linked to former glacier basal thermal regimes. Non-glacial processes were also important in shaping the landsurface, especially during the Early Pleistocene, through the action of chemical weathering, pedogenesis, frost-riving and solifluction operating over rock substrates of diverse lithology and structure. Sediments of Early to Middle Pleistocene ages are not widely preserved on land in Scotland but those which exist represent an important archive of environmental changes before the last glacial cycle and the extent, flow paths and dynamics of Middle Pleistocene ice sheets.

1. Pleistocene tectonic and climate history

Episodic Cenozoic uplift of Scotland commenced in the middle Palaeocene and continued into the Neogene (Le Coeur, 1999; Praeg *et al.*, 2005; Gregersen & Johannessen, 2007; Stoker *et al.*, 2010). The latest phase of uplift commenced at ~4 Ma, prior to the onset of extensive glaciation, and may have extended into the Pleistocene (Stoker *et al.*, 2010). In the English Peak District uplift has been estimated at 300 m since 12 Ma (Pound & Riding, 2015) or ~3 Ma (Westaway, 2009). Evidence from caves of valley incision and from raised beaches suggests uplift of the Alston Block in northern England at rates of 0.2 mm/yr over the last 0.8 Ma (Westaway, 2016). Subsidence continued in the North Sea basin through the Plio-Pleistocene (Cameron *et al.*, 1987; Westaway, 2016), with the top surface of Pliocene lignite-bearing deltaic sediments found in borehole 81/19 in the outer Moray Firth) now lying at a depth of 180 m (Andrews *et al.*, 1990). Pleistocene uplift of the land area of Scotland was probably limited as an extensive peripheral planation surface of likely Pliocene age is now found at 80-120 m a.s.l. in Lewis, NW Scotland, Caithness and Buchan (Godard, 1965). Remnants of deep gruss weathering indicate prolonged subaerial exposure and a position above sea level during weathering. Marine deposits and platforms are absent from elevations >45 m in Scotland (Smith *et al.*, 2018), although flint gravels in eastern Buchan at up to 140 m a.s.l. have been interpreted as beach deposits (Bridgland *et al.*, 1997). In The Minch and the Sea of the Hebrides, the peripheral planation surface is dislocated, with up to 150 m of displacement along the Minch and Camasunary-Skerryvore Faults and uplift of up to 200 m for the Rum horst (Le Coeur, 1988), but with submergence of platforms W of the Outer Hebrides. Neotectonic activity, including Lateglacial reactivation of existing faults in response to postglacial isostatic rebound is now widely documented around the Inner Hebrides (Firth & Stewart, 2000; Smith *et al.*, 2009; Stoker & Bradwell, 2009).

Global climate cooled through the Cenozoic Era. The first ice sheets appeared in Greenland at 38 Ma (Eldrett *et al.*, 2007), but it was not until ~2.7 Ma that large ice sheets developed at mid-latitudes in the Northern Hemisphere (Bailey *et al.*, 2013). In the Early Pleistocene, global climate forcing was driven by 41 ka orbital cycles, but during the Middle Pleistocene Transition (MPT) at 1.2–0.7 Ma (Head & Gibbard, 2005) there was a shift towards forcing driven by 100 ka cyclicity (Clark *et al.*, 2006). As James Croll (1875) foresaw nearly 150 years ago, a global consequence was to produce longer and more intense cold periods, which changed both the timing and extent of glaciation (Lee *et al.*, 2015).

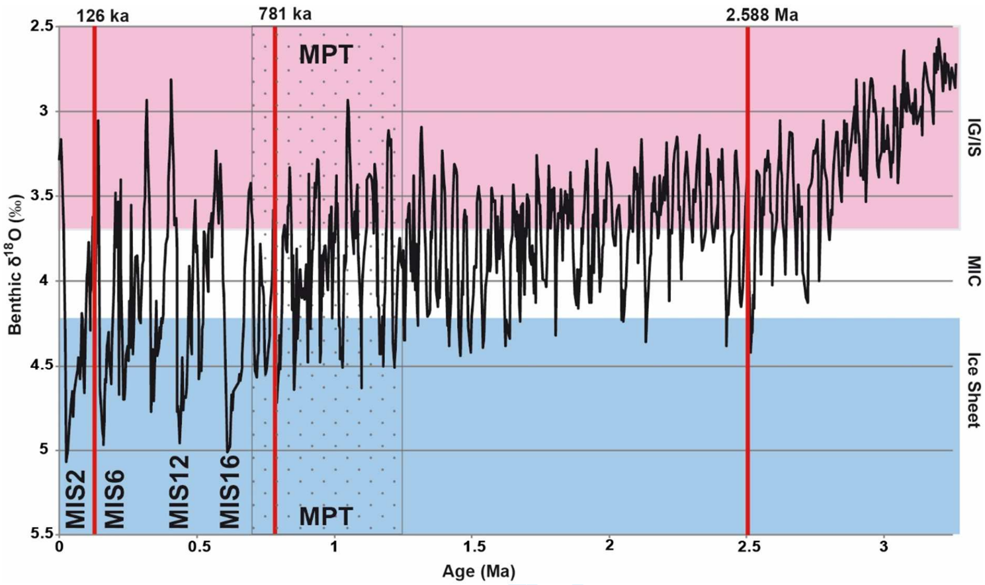

Figure 1 The δ^{18}O record for benthic foraminifera from marine core DSDP 607 (Ruddiman *et al.*, 1989) interpreted as a proxy for glacier extent in Scotland. The cut-off value of >3.7‰ δ^{18}O indicates when conditions were equivalent to the Younger Dryas event (Small & Fabel, 2016) when mountain ice caps, valley and corrie glaciers formed in Scotland (Clapperton 1997). The cut off value of >4.2‰ δ^{18}O is that at 37.5 ka in DSDP 607, a time when the last ice sheet started to build up in Scotland (Hubbard *et al*. 2009). IG - interglacial; IS - interstadial; MIC - mountain ice cap; MPT - Mid-Pleistocene Transition. Marine isotope stages (MIS) marked are equivalent to the following British and NW European stages: MIS 16 (676-621 ka; Happisburgh-Donian), MIS 12 (478-424 Ma; Anglian-Elsterian), MIS 6 (186-130 ka) (Wolstonian-Saalian) and 2 (29-14 ka; Late Devensian-Late Weichselian).

The δ^{18}0 record for North Atlantic marine sediments constrains the first-order timing and intensity of environmental change in Scotland through the Pleistocene. This approach follows earlier work in Scotland (Clapperton, 1997) and northern Fennoscandia (Kleman *et al.*, 2008; Hall *et al.*, 2013a). We take δ^{18}0 values for known Late Pleistocene glacial events in Scotland and assume that similar events occurred in the past when δ^{18}0 values were similar (**Figure *1***). This comparison is simplistic because the global ocean temperature fluctuations recorded by benthic foraminifera can provide only a general picture of ice sheet extent and volume at the regional scale (Clark *et al.*, 2009). Nonetheless, this method suggests that the build-up of ice caps in Scotland started at ~2.72 Ma, with ice sheets covering most of Scotland for brief periods (mainly <10 ka) from 2.5 Ma onwards. The Early Pleistocene period was otherwise dominated by two climate types (**Figure *1***): (i) an interglacial or interstadial type, when warm or cool temperate conditions prevailed and glaciers were absent; and (ii) a stadial type, when ice caps developed at higher elevations and periglacial conditions, with periods of permafrost (Vandenberghe, 2001), prevailed for long periods at lower, peripheral locations. The Early Pleistocene vegetation records of East Anglia indicate warmer interglacial conditions than at present in England, with establishment of temperate mixed coniferous/deciduous forest that included *Tsuga* (hemlock)and *Pterocarya* (wingnut) (West, 1962). Comparison with MIS 5 temperature gradients in NW Europe (Sejrup & Larsen, 1991) suggests the widespread growth at low elevations in Scotland of deciduous woodland in warm stages of the Early Pleistocene.

The MPT is not readily apparent in the DSDP 607 record (Fig. 1) but the intensity and duration of the cooling events after 0.7 Ma is striking, implying up to 10 subsequent phases of ice sheet development in the British Isles. Last (MIS 3-2) ice sheet models indicate a maximum ice surface elevation of 1.5-2 km (Kuchar *et al.*, 2012). Ice sheets of equivalent or greater thickness probably developed in the culminations of the MIS 16, 12 and 8 to 6 cold stages (**Figure *1***). Although the dating and extent of some Middle Pleistocene glaciations in eastern England remain controversial (White *et al.*, 2017), glacial deposits in East Anglia (Lee *et al.*, 2015) and in the North Sea (Bendixen *et al.*, 2017) have been correlated with each of these cold stages. Flow of ice from Scotland is recorded by indicator heavy minerals and erratic clasts in Middle Pleistocene tills in East Anglia (Lee *et al.*, 2012).

At the onset of Northern Hemisphere glaciation, mountains ~1 km-high existed in those parts of Scotland that hold high summits today. Hence it is likely that the first extensive glaciation of northern Fennoscandia at 2.7 Ma (Flesche Kleiven *et al.*, 2002) was accompanied by the growth of mountain glaciers in Scotland. Ice-rafted Carboniferous debris records multiple phases of glaciation in Ireland between 2.6 and 1.7 Ma (Thierens *et al.*, 2011). Iceberg scours are reported from the floor of the northern North Sea through the Early and Middle Pleistocene (Dowdeswell & Ottesen, 2013), requiring marine termination of the Fennoscandian Ice Sheet (FIS) on several occasions. Thick glacimarine sediments accumulated in the northern North Sea, sourced mainly from Fennoscandia, between 2 and 1.2 Ma, but there is no firm evidence for advance of the Fennoscandian or British ice sheets into the central part of the basin in this period (Reinardy *et al.*, 2017) and fluvial sedimentation continued E of Shetland (Ottesen *et al.*, 2014). Subsequent glaciation by an early Shetland ice cap is recorded by N-S oriented mega-scale glacial lineations (MSGLs) seen in seismic surveys close to the Fladen Ground and dated to 1.1-1.0 Ma (Buckley, 2017).

In the west central North Sea, the Early Pleistocene Aberdeen Ground Formation is truncated by an extensive erosional unconformity, the Upper Regional Unconformity (URU), formed at ~ 1.2 Ma (Reinardy *et al.*, 2017), that is widely regarded as predominantly of glacial origin (Larsen *et al.*, 2000; Bradwell *et al.*, 2008b; Graham *et al.*, 2010; Graham *et al.*, 2011). Increasing sediment influx from the west above the URU indicates the growing importance through the MPT of glaciers in Scotland as sediment conveyors to the North Sea. Several sets of MSGLs attributed to subglacial streamlining of sediment have been reported from the Middle to Late Pleistocene sequence, for example, in the Witch Ground Basin between 58˚ and 59˚N (Graham *et al.*, 2007; Graham *et al.*, 2010; Stewart *et al.*, 2013). In addition, seven generations of tunnel valleys, thought to have been formed mainly by subglacial meltwater flow, have also been observed above the URU in the central North Sea (Stewart & Lonergan, 2011). These glacial landforms provide strong evidence supporting inferences from the isotope record (**Figure *1***) for multiple advances of grounded ice sheets from Scotland into the North Sea basin since 0.774 Ma.

Patterns of ice flow derived from the transport of glacial erratics by the last ice sheet have long indicated coalescence from discrete ice centres (**Figure *2***) (Geikie, 1901). Major centres for ice build-up included the high mountains of Galloway, the western Grampians, the NW Highlands and the Cairngorms, with minor ice domes over the Skye Cuillin and Mull (Sissons, 1967). Other large, locally warm-based ice masses, including low-elevation cirque glaciers (Barr *et al.*, 2017), formed over the mainly low ground of the Outer Hebrides (von Weymarn, 1979), Orkney (Ballantyne *et al.*, 2007) and Shetland (Flinn, 1978b), indicating high snow accumulation rates along the North Atlantic seaboard. These growth points are also evident in models of the last British-Irish Ice Sheet (BIIS) (Boulton & Hagdorn, 2006; Hubbard *et al.*, 2009). Topographic lows developed on Palaeozoic and Mesozoic sedimentary basins exerted a strong influence over the location and orientation of major ice streams draining the last BIIS in the Sea of the Hebrides, The Minch, the Moray Firth and the Forth. That these topographic and climatic controls also influenced the dynamics of earlier ice sheets is indicated by the geometry and provenance of sediment stacks along the edge of the North Atlantic shelf (Stoker, 1997) and in the North Sea basin (Stoker & Bent, 1985). The topographic low centred on the Fladen Ground (**Figure *2***) received ice lobes from the eastern BIIS and the western edge of the FIS (Sejrup *et al.*, 1987). The Norwegian Channel ice stream became a recurrent feature after 1.1 Ma (Sejrup *et al.*, 2003), directing ice flow towards the N and perhaps thereafter reducing the westward extent of Scandinavian ice in the central North Sea (Batchelor *et al.*, 2017). During glacial maxima in the Middle Pleistocene, the BIIS and FIS were probably confluent across a shifting, broad zone in the North Sea (Bendixen *et al.*, 2017) (**Figure *2***).

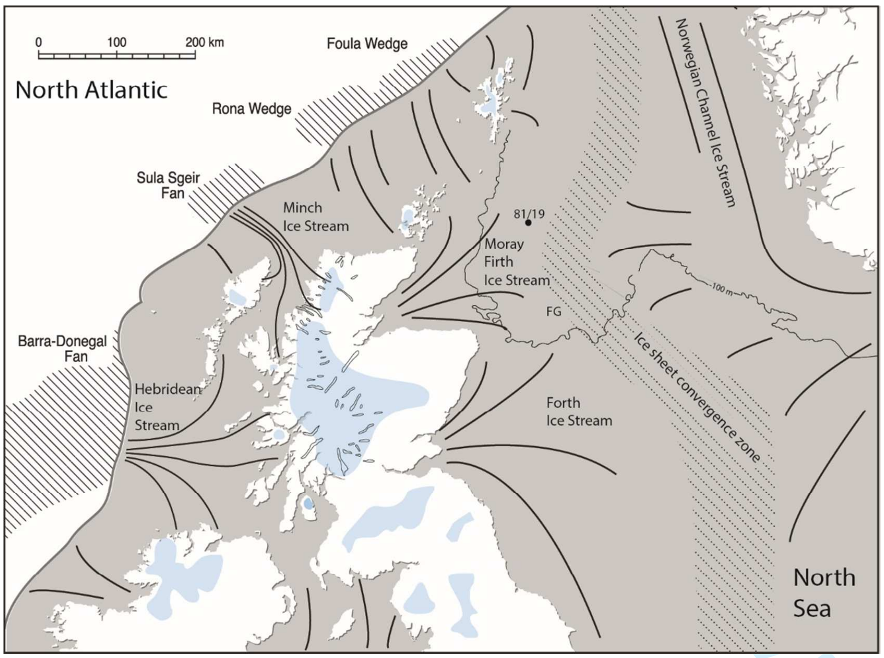

Figure 2 Main features of the Pleistocene glaciation of Scotland. Major and minor centres of ice sheet growth are shaded in blue. Note the belt of ribbon lakes in the western Highlands and the associated basins of the inner sea lochs of the west coast that define a zone of glacial over-deepening beneath former mountain ice caps. FG: Fladen Ground.

Periglacial environments in the present interglacial have remained confined to high elevations in Scotland (Ballantyne & Harris, 1994). In the cold stages of the Pleistocene, however, periglacial conditions, including permafrost extended down to sea level across large parts of NW Europe beyond glacial limits (Renssen & Vandenberghe, 2003). The cumulative duration of these phases was long, especially in the Early Pleistocene when the total duration may have approached 1 Myr (Fig. 1). Frost-churning of soils first appears in MIS 22 (0.82 Ma: Beestonian) in East Anglia and indicators of cold climates, including ice wedge casts, reappear throughout the Middle Pleistocene stratigraphy (Rose *et al.*, 1985). In Buchan, the record of permafrost, frost weathering and mass wasting extends back into the Middle Pleistocene (Connell & Hall, 1987). Largely through the work of Colin Ballantyne and his collaborators, the periglacial landforms and materials of the Late Pleistocene and Holocene have been mapped, analysed and dated in Scotland to a level of detail that is unmatched in any other similar-sized terrain in the world (Ballantyne 2018). This dataset provides the starting point for assessment of the impacts of periglacial processes in earlier periods.

2. Morphological evidence of Pleistocene glacial and non-glacial erosion

Scotland, despite its modest land area, carries remarkably varied landforms and landscapes that provide evidence of the cumulative impact of the glacial and non-glacial processes that operated on landsurfaces through the Pleistocene. At the onset of Pleistocene glaciation, a diversity of fluvial landscapes existed in Scotland, developed in response to episodic Neogene uplift. In the Outer Hebrides and Assynt, an extensive peripheral planation surface backed by mountains was drained by rivers flowing to The Minch and the Sea of the Hebrides (Le Coeur, 1999). The main watershed lay close to its present position in Northern Scotland (**Figure *3***) but later shifted eastward in places after glacial breaching (Godard, 1965; Jarman, 2007). From Glen Affric southwards towards the central lowlands, the watershed zone was highly dissected, with deep valleys set between narrow ridges (Godard, 1965). Further E in the Northern and Grampian Highlands, extensive plateaux, carrying fragments of elevated planation surfaces, were set between broad straths and basins (Godard, 1965; Hall & Bishop, 2002; Jarman, 2017). Peripheral planation surfaces extended across Caithness, Buchan and, probably, the Forth lowlands. The central lowlands held considerable relief due to differential weathering and erosion of Palaeozoic igneous and sedimentary rocks (Sissons, 1976). The Neogene geomorphology of the Southern Uplands has not been examined closely but, in its gross form, comprised broad uplands drained, as now, by rivers flowing towards the North Sea, North Channel and Solway Firth (Sissons, 1960). In all areas, sets of major landforms – hill masses and isolated hills, scarps, basins and valleys - had developed through the Neogene on a diverse geology in response to differential weathering and erosion acting under humid climates (Hall, 1991).

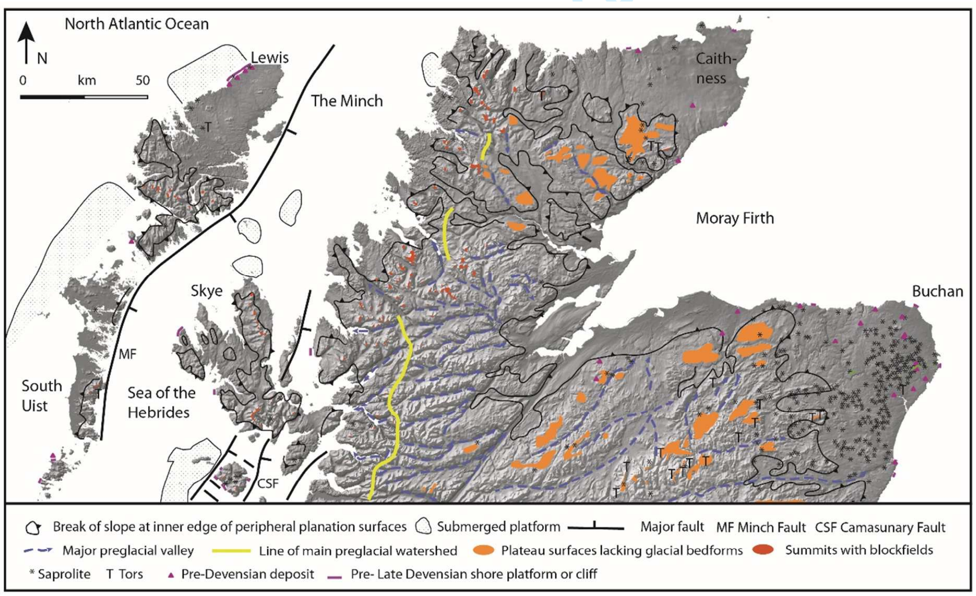

Figure 3 Non-glacial landforms and regolith in the northern Scottish Highlands. Submerged platforms in western Scotland after Le Coeur (1988). Other non-glacial landforms from Godard (1965) and Hall (1991). Plateau surfaces with no or weak development of glacial erosion forms mapped from NextMap imagery. Blockfield distribution in the NW and W Highlands from Ballantyne and others (see text below for references). Saprolites and tors from field mapping and literature reports. Coastal rock features from Smith *et al.* (2018).

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The forms of glacial erosion are cut into the smooth slopes of this older relief (**Figure *4***). Valley heads became settings for corrie glaciers, and river valleys provided ready conduits for glacier flow (Glasser, 1995) (**Figure *5***). Valley deepening, coupled with increasing valley connectivity, may have led to the adaptation of the topography towards more efficient evacuation of ice flow and to a reduction in valley incision rates through the Pleistocene (Kaplan *et al.*, 2009). In lowland areas with crystalline bedrock, smooth, low-relief surfaces were stripped of regolith, roughened and, in places, streamlined by glacial erosion (Krabbendam & Bradwell, 2011; Krabbendam & Bradwell, 2014). Computational experiments have suggested that low-relief plateaux on glaciated passive margins of the Northern Hemisphere were formed exclusively by glacial erosion (Egholm *et al.*, 2017). In Scotland, however, as in Scandinavia (Etzelmuller *et al.*, 2007; Ebert *et al.*, 2011), such plateaux are most extensive in eastern areas and lack bedforms indicative of efficient glacial erosion (Fig. 3) whereas, towards the W, plateaux become increasingly fragmented and glacially roughened. Morphological transition and transformation are consistent with Pleistocene glacial modification and dissection of pre-existing landsurfaces.

Figure 4 Landscape of selective linear glacial erosion at Lochnagar in the eastern Grampians. The glacial trough now occupied by Loch Muick is cut into the Mounth plateau, a fragment of an extensive planation surface now at 800 m a.s.l. A 200-300 m high scarp rises to the domed granite summits of Lochnagar.

Figure 5 Mountain scenery in the SW Grampians shaped by multiple episodes of fluvial, glacial, periglacial and paraglacial activity. Late Caledonian Etive igneous complex rocks dominate the area shown, with the fault-guided course of Glen Etive in the foreground. The forested hills in the middle ground probably represent remnants of a precursor valley floor of a broad strath, now standing at 310-390 m a.s.l. The glacial trough occupied by Loch Etive descends to 145 m below sea level in rock basins (Audsley *et al.*, 2016). The high summits show glacially roughened rock surfaces and were overwhelmed by warm-based glacier ice beneath the last and earlier ice sheets. During the Loch Lomond Stadial (12.9-11.7 ka), an outlet glacier drained from Rannoch Moor through Glen Etive. Extensive talus accumulations occur at the foot of slopes.

3. Glacial erosion

3.1 Erosion patterns

The variable impact of glacial erosion across Scotland was identified by Linton (1959). Comparisons of maps of non-glacial (**Figure *3***) and glacial (**Figure *6***) landforms and regolith for the northern Scottish Highlands reveal inverse correlations that can be linked to model results for former glacier basal thermal regimes (Fig. 7). Saprolites, tors and pre-Devensian tills are concentrated in NE Scotland and in the eastern parts of the Northern Highlands, areas which lack roughened or streamlined terrain typical where glacial erosion has been effective. Conversely, these non-glacial features are virtually absent from across the Lewisian lowlands over the Outer Hebrides, apart from N Lewis (Hall, 1996), and also from the NW Highlands, with its distinctive cnoc-and-lochain terrains. Similar observations led to the recognition of zones of glacial erosion at regional (Linton, 1963; Clayton, 1974; Haynes, 1983) and sub-regional (Gordon, 1979; Hall, 1986; Hall & Sugden, 1987) scales across Scotland.

The contrasting modes of mountain ice cap and full ice sheet glaciation interpreted from the oxygen isotope record from marine core DSDP 607 (Fig. 1) are also important for understanding patterns of glacial erosion and deposition across Scotland. Because of differences in ice extent, the zones of erosion and deposition beneath mountain ice caps and full ice sheets may not coincide, particularly in areas E of the main ice divide. Glacial landform distribution in western Scotland provides evidence for prolonged erosion by mountain ice caps. Alpine glacial topography is restricted to small areas on Skye and in Lochaber (Haynes, 1983). Glacial over-deepened rock basins are distributed mainly in 15-30 km wide zones on both sides of the main watershed throughout its length (Fig. 2). The basins include radial troughs around Rannoch Moor that were excavated by ice flowing from a large ice dome over the SW Grampian mountains (Linton, 1972). An axial ice-shed zone of low erosion exists along the watershed of the Northern Highlands, bounded by areally scoured landscapes and over-deepened valleys to W and E (Gordon, 1979) (Fig. 6). Belts of thick glacial deposits occur around the inner Moray Firth and in the lower Clyde basin that include, at depth, pre-MIS 3 tills (Section 6.2). Landform and sediment distribution appears to conform to the erosional and depositional zones of former mountain ice caps that developed through the Middle and Late Pleistocene. Mountain ice-cap extent may have been strongly influenced by calving at marine limits in the inner Moray Firth, the Forth and Clyde lowlands and within the Inner Hebrides (Sissons, 1981).

Areas of ice-roughened and ice-streamlined bedrock also occur far outside the mountain ice cap limits reached during the Loch Lomond Stadial. Ice roughening extends across much of the Outer Hebrides and beyond the present coastline of the Northern Highlands in Sutherland and Easter Ross (**Figure *6***). The onset zones for former ice streams in western Scotland also lie mainly outside Loch Lomond Stadial limits and extend across large areas of the sea bed in The Minch and the Sea of the Hebrides (Bradwell *et al.*, 2008a). Ice streams excavated deep basins in the Mesozoic rocks of The Minch (Sissons, 1967) and in the inner Moray Firth (Sutherland & Gordon, 1993). Streamlined terrains in the Tweed (Everest *et al.*, 2007) and Forth valleys (Golledge & Stoker, 2006) and around the Firth of Clyde (Finlayson *et al.*, 2010; Finlayson *et al.*, 2014) also continue across adjacent areas of the present sea bed. The main ice sheet depocentres were on the North Atlantic shelf and in the North Sea basin (Holmes, 1997). Glacial erosion and deposition in areas peripheral to the main ice centres must relate to large ice sheets. Bimodal patterns of glacial erosion and deposition linked to mountain ice cap and ice sheet glaciation have been recognised across Fennoscandia (Kleman *et al.*, 2008) but the smaller, highly dynamic glaciers and ice sheets that formerly covered the more complex topography of Scotland have received less attention (Haynes, 1977).

Glacial dissection of mountain areas is strongly developed in the western Highlands (Linton, 1949; Haynes, 1977; Jarman, 2007). An absence of inherited cosmogenic nuclides from low elevation sites requires removal of >2.5 m of rock in the last glacial cycle (Fame *et al.*, 2018). In Assynt, rates of valley deepening were rapid, estimated at 2 m/ka during periods of glaciation since 280 ka (Hebdon *et al.*, 1998). The density and interconnectivity of glacial valleys drops towards eastern areas (Haynes, 1977) (**Figure *6***). Progressive glacial modification of valley systems is evident moving E-W across the central Grampians. Little-modified fluvial valley networks remain in the Tarf basin but valleys become deeply incised in the Forest of Atholl, with the first stages of glacial breaching of watersheds, and pass westwards at Drumochter into highly dissected mountains with interconnected valley systems and deep glacial breaches and cols (Hall & Jarman, 2004). Valley-in-valley forms are common in Scotland, products of linear glacial excavation of trenches within broad straths (Hall, 1991) (Fig. 5). Where glacial valleys are developed from fluvial precursors, as in the Cairngorms (Sugden, 1968; Hall & Gillespie, 2016) and across much of the southern Highland boundary (Linton, 1940), the timescales for glacial modification likely span the Pleistocene (Fredin *et al.*, 2013). Large meltwater channels may have been re-occupied in successive glaciations, especially where meltwater flow was constrained by topography in cols, for example the many Nye channels in the eastern Grampians (Clapperton & Sugden, 1977), or against hill flanks, for example in the Ochils (Russell, 1995) and Lammermuirs (Sissons, 1961). The presence of pre- MIS 5 and younger deposits in channel floors in Moray, Buchan and Caithness (Section 6) indicates at least localised reoccupation.

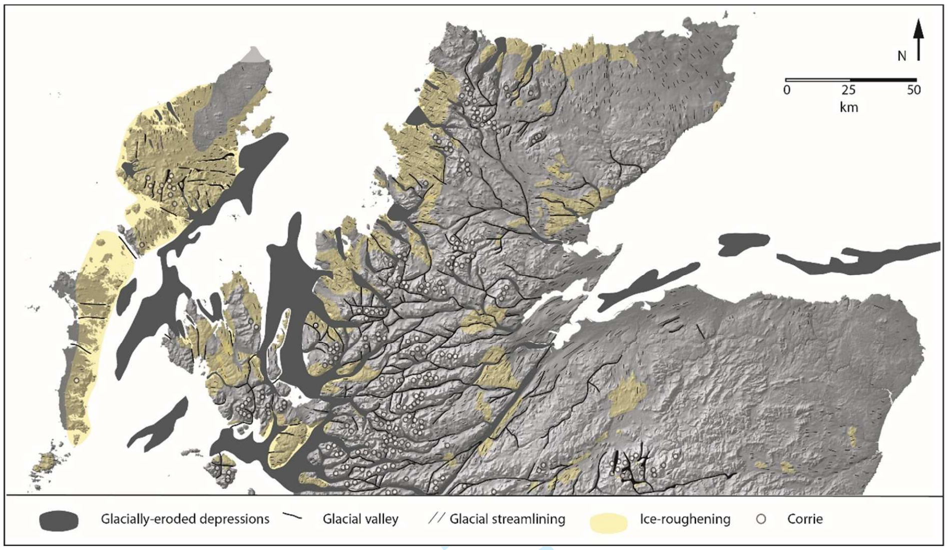

Figure 6 Glacial landscapes and landforms in the northern Scottish Highlands. Glacially eroded depressions from Sutherland & Gordon (1993). Corries from (Barr *et al.*, 2017). Glacial streamlining and roughening mapped from NextMap imagery.

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Glacial modification of landscapes had a marked vertical component. A morphological gradation, from ice-scoured valley floors to roughened valley flanks and smooth plateaux, is a conspicuous feature of many valley cross profiles in the central and eastern Scottish Highlands. Along the western seaboard, blockfields that predate the last glaciation (Hopkinson & Ballantyne, 2014) and which mark zones of very limited glacial erosion are confined to the highest summits (Ballantyne *et al.*, 1997; Ballantyne *et al.*, 1998). Many blockfields are associated with fragments of older, rounded montane topography, dissected by valleys and 'cookie-cut' by corries. Only in a few areas, such as Knoydart, does ice-roughening extend to summits and here blockfields are almost absent (Ballantyne, 2000) (**Figure *3***). Blockfields drop in altitude towards eastern Sutherland and Caithness (Ballantyne & Hall, 2008; Phillips *et al.*, 2008). Blockfields have not been mapped systematically in the eastern Grampians but tors drop from elevations of 1200-600 m in the Cairngorms to 400 m at the Cabrach, 40 km to the NE (Blyth, 1969), and to 100 m in Buchan (Hall, 2005). When compared to the distribution and height of low-relief upland surfaces lacking in glacial erosion forms (**Figure *3***), it is clear that the upper limit of effective glacial erosion also declines from W to E across much of the Highlands. This gradient is similar in trend to that seen in models of basal temperature for the last ice sheet (Fig. 7).

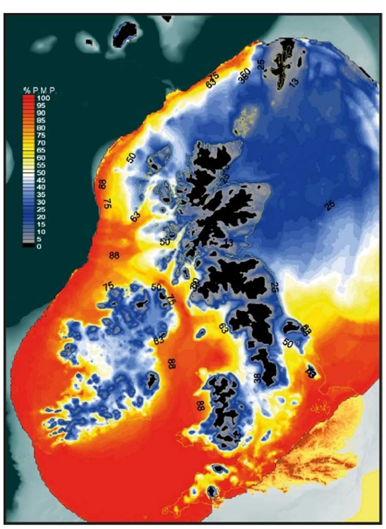


Figure 7 Cumulative time that the bed for the last (MIS 3-2) British-Irish Ice Sheet was at pressure melting point (PMP) expressed as a percentage of the total simulation time in experiment E102b2 (Hubbard *et al.*, 2009). Persistent frozen basal conditions are indicated by black shading (%PMP < 2.5%). Assuming that similar basal temperatures developed beneath Early and Middle Pleistocene ice sheets, comparison with Figs 3 and 6 indicates close correlations between: (i) distributions of areas with persistent cold-based ice and non-glacial landforms; and (ii) areas of more frequent warm-based conditions and landscapes of glacial roughening and streamlining.

3.2 Erosion depths

Depths of cumulative glacial erosion can be estimated by using non-glacial landforms and landsurfaces as reference points and surfaces for erosion. Glacial forms, mainly cnoc-and-lochain terrain, rock basins, valleys and corries, are cut into pre-glacial landsurfaces and so, along with any glacial lowering of hilltops and interfluves, represent total glacial erosion through the Pleistocene (Hall *et al.*, 2013b). Minor non-glacial forms and weathering mantles – such as many tors (Hall & Sugden, 2007) and blockfields (Ballantyne, 2010b) and some shallow saprolites (Wright, 1997) – are of Early to Middle Pleistocene age and indicate little or no glacial erosion through later glacial cycles. Non-glacial and glacially roughened slopes have been themselves lowered by weathering and erosion through the Pleistocene (Phillips *et al.*, 2006; Hopkinson & Ballantyne, 2014; Andersen *et al.*, 2018).

Increasing glacial erosion depths are evident moving W across the Grampians. In eastern Buchan, where Tertiary gravel deposits survive on ridge tops (Hall *et al.*, 2015a), erosion is locally of the order of metres. In the type landscape of selective linear erosion in the Cairngorms (Sugden, 1968), glacial erosion of plateau surfaces was negligible (Hall & Glasser, 2003), although non-glacial denudation of bare rock surfaces operated at 2.8 to 12.0 m/Ma (Phillips *et al.*, 2006). Most erosion resulted from glacial deepening of valleys by <200-350 metres (Sugden, 1968; Hall & Gillespie, 2016). Estimated Pleistocene erosion depths across the Dee catchment are estimated at 30-60 m, with a substantial contribution from the removal of saprock and saprolite (Glasser & Hall, 1997). In the western Grampians, inheritance of ^{10}Be cosmogenic nuclides is highest on ridge tops and declines or is absent at lower elevations. Modelled erosion rates decline eastwards from 40 to 20 m/Ma (Fame *et al.*, 2018).

Glacially streamlined terrain found along parts of the Great Glen, in much of Caithness and in patches along the lower Dee valley towards Aberdeen (Fig. 6) merges laterally with non-streamlined terrain of similar ridge-top elevations, suggesting that erosion has been restricted mainly to the excavation of valleys and depressions. Similarly, in terrain on the Lewisian basement gneiss of the western seaboard, it has long been thought that glacial erosion has been largely restricted to the removal of regolith (Godard, 1961), with deep erosion of basement only in basins and valleys (Krabbendam & Bradwell, 2014) . On the Ross of Mull (Fig. 8), the cnoc-and-lochain terrain has been interpreted as a glacially stripped and roughened tor field developed on an erosion platform of Pliocene age (Le Coeur, 1988). Depths of erosion above cnoc summits, however, remain poorly constrained in both streamlined and roughened terrains. The recognition of mega-grooves 0.1-6 km long, 10-100 m wide and 5-15 m deep on the streamlined bed of a former ice stream in Assynt (Bradwell *et al.*, 2008a) and the floors of The Minch (Bradwell *et al.*, 2007) and the Sea of the Hebrides (Dove *et al.*, 2015) demonstrate that, in zones of fast ice flow, glacial erosion of hard crystalline rock was, at least locally, highly efficient.

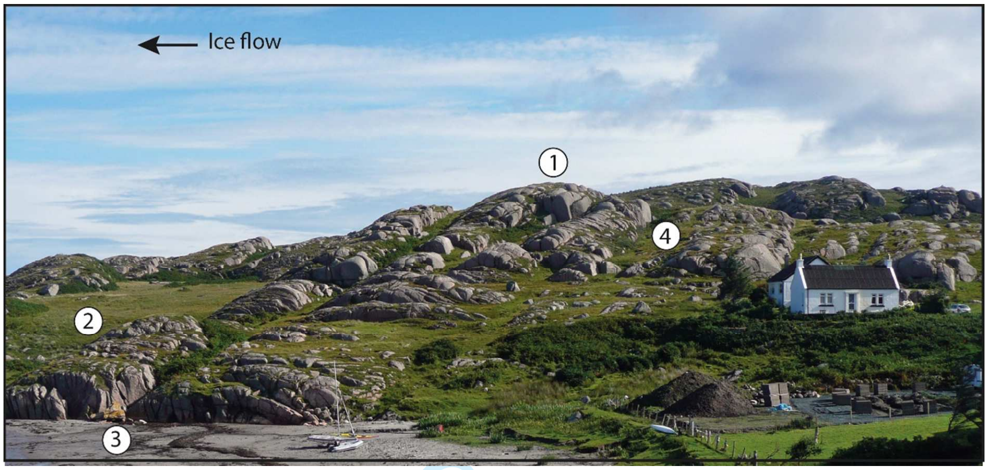


Figure 8 Cnoc-and-lochain terrain developed in Caledonian granite, Fionnphort, Ross of Mull. 1. Cnoc developed in massive granite. 2. Rock basin excavated in fractured granite. 3. Major fracture transverse to ice-flow. 4. Granite monoliths, with >10 m vertical fracture spacing, acting as resistant, stoss-side bastions.

Deep glacial erosion is manifest elsewhere. In the mountains of the western Highlands, glacial erosion has been highly effective, excavating basins and fjords below sea level and dissecting and lowering pre-existing watersheds (Sissons, 1967). Glacially polished surfaces above 500 m in Glen Shiel and Glen Nevis show little or no cosmogenic ^{10}Be inheritance, indicating ≥2.5 m of erosion in the last glacial cycle (Fame *et al.*, 2018). Ice tends to flow towards and stream along pre-existing fluvial valley systems, a confluent flow pattern leading to highly effective linear erosion (Sugden, 1968) (Nesje & Whillans, 1994), the main component of the glacial buzzsaw (Hall & Kleman, 2014). Transfluent ice flow in the western Highlands led to breaching of watersheds and to cutting of new valleys (Haynes 1977). Rock basins reach depths of 200-300 m below sea level in lochs Ness and Morar (Sissons, 1967), and basins in the Sound of Raasay and Loch Linnhe are of even greater depths (Sissons, 1976). In the upper Forth valley, sharp contrasts exist in depths of glacial erosion. Resistant lava plateaux and tapered interfluves developed in softer rocks but somewhat sheltered from glacial erosion in lee locations stand ~100 metres above the drift-filled floors of the Forth and Teith valleys (Linton, 1962) (**Figure *9***). Glacially excavated trenches and rock basins extend below these valley floors to depths below sea level of 100 m E of Stirling and 170 m at Bo'ness (Sissons, 1969; Francis *et al.*, 1970). Borehole records also show rockhead at 100 m below the Devon valley to the E (Soons, 1959)In W Fife, the thick Late Carboniferous dolerite sill between the M90 motorway and the Lomond Hills now forms a fragmented scarp that has been breached and lowered by ice flow. Many crag and tail forms in the glacially streamlined terrain of the Central Lowlands are erosional features, with crags formed in volcanic plugs and tails formed in sedimentary rock (Burke, 1969; Sissons, 1971; Evans & Hansom, 1996). The difference in elevation of beds on the stoss and lee sides provides a minimum depth of glacial erosion around the crags of 25 to 100 m (Geikie, 1887).

Little attention has been given to the substantial thicknesses of weakly consolidated Carboniferous to Neogene sedimentary rocks likely removed by glacial erosion from the basins and shelves surrounding Scotland. Major unconformities truncating Early and Middle Pleistocene sediments are mapped in the North Sea (Cameron *et al.*, 1987) and on the North Atlantic shelf (Stoker *et al.*, 1993). Progressively older Cenozoic to Palaeozoic rocks sequences are also truncated to landward (Andrews *et al.*, 1990). The mass balance of rock removal and its transfer to the shelf by glacial processes has not been fully quantified but preliminary investigations suggest that lowering of extensive areas of shelf by glacial erosion was required to produce the large volumes of Pleistocene sediment (Clayton, 1996; Glasser & Hall, 1997). Such scalping of inner shelves by glacial erosion and during episodes of low sea level is apparent in the URU off western Norway (Rise *et al.*, 2005). Mass transfer from Scotland may have been sufficient to induce isostatic rebound of the land area in response to Pleistocene erosion (Hall & Bishop, 2002) and tilting towards North Sea depocentres (Løseth *et al.*, 2013) but also awaits further quantification.

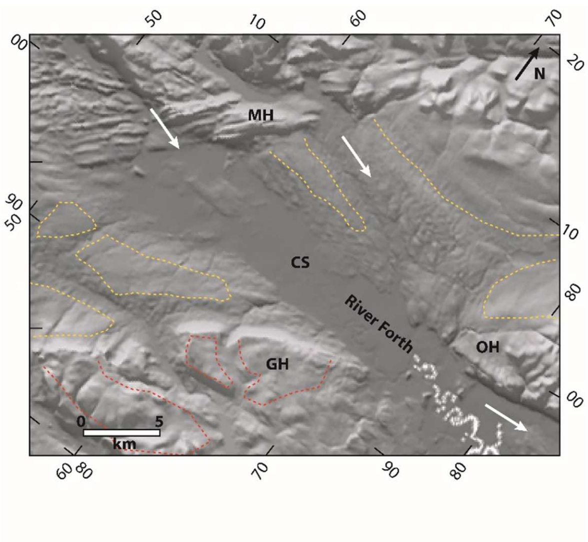


Figure 9 Uneven impact of glacial erosion in the upper Forth valley. Smooth, tapered interfluves (Linton, 1962) and benches are developed in sandstones of mainly Devonian age (brown dashed lines). Carboniferous lava plateaux, marked by red dashed lines, have been lowered, roughened and weakly streamlined by glacial erosion. The intervening valleys have been over-deepened and thick sediments infill rock basins below the Carse of Stirling (CS) that reach depths of >100 m (Sissons, 1967). GH Gargunnock Hills. MH Menteith Hills. OH Ochil Hills. General direction of ice flow is indicated by arrows.

3.3 Corries

Corries, or cirques, are striking components of Scottish mountain scenery. Many corries were occupied by small glaciers during the Loch Lomond Stadial but the small volumes of debris found in end moraines indicate that erosion of the corrie basins has extended over a much longer period (Sissons, 1976). Corrie dimensions are moderate, with headwalls generally ranging in height from 150-450 m and with width and length rarely exceeding 1 km (Gordon, 1977). Such dimensions, when averaged over Pleistocene time, indicate quite slow erosion but this is potentially misleading because cirque erosion rates were highly variable through the Pleistocene (Crest *et al.*, 2017) and also many corries may have been occupied by independent glaciers for only short periods before being overwhelmed by ice sheet advance (Richardson & Holmund, 1996). Corries with glacially-rounded upper slopes are common in the SW Grampians (Sissons, 1976), close to a major centre of ice sheet accumulation. Here, and perhaps elsewhere, the main phases of corrie erosion may have occurred during the many stadial periods of the Early Pleistocene, with long periods of burial beneath the ice sheets of the Middle and Late Pleistocene and more limited erosion in the short intervening phases of mountain glaciation. Some support for this hypothesis is provided by model results with an apparently short duration of warm-based conditions at high elevations across

Scotland beneath the last ice sheet (Fig. 7). The frequency of rock-slope failures and failure scarps within corries in NW Scotland suggests that cirque enlargement during successive glacial-interglacial cycles involved deepening by glacial erosion, headwall retreat by rock-slope failure and removal of RSF debris during subsequent glaciation (Ballantyne, 2013; Cave & Ballantyne, 2016).

Corrie distribution in Scotland is a function of climate, topography and time. Corrie floor elevations are low along the western seaboard but rise across the main Highland watershed towards the eastern Grampians. Snowfall from moisture-bearing North Atlantic air masses fed the corrie glaciers, with precipitation decreasing markedly with distance from the present shoreline (Barr *et al.*, 2017). Corries are typical of high mountain scenery in Scotland, indicating the effect of decreasing air temperature with altitude. Most corries face NE and N, the sector of least direct solar radiation and hence least ablation (Sissons, 1967). Topographic controls on corrie distribution exist at the regional and local scales (Gordon, 1977). Corries are largely absent from Caithness, eastern Sutherland, Moray and the central and eastern Southern Uplands because few hills stood above 700 m a.s.l. before glaciation. East of the main watershed in northern Scotland, corries are developed mainly in valley heads on the northern flanks of glens draining to the Moray Firth (**Figure *6***). Corrie floor altitudes vary in elevation by 350 and 400 m in parts of the Grampian Highlands and Cairngorms (Sissons, 1976). This broad range reflects local geological and topographical controls (Gordon, 1977) but corries with floors at different altitudes may also have been occupied at different times, a reminder that several generations of corries may exist within individual mountain groups (Godard, 1965; Sugden, 1969; Rudberg, 1994).

3.4 Controls on glacial erosion

Complex interactions between geological, topographic, climatic and glaciological factors influenced patterns of ice flow and depths of glacial erosion across Scotland.

- Ice streams developed on sticky, rigid beds only where lubricated by meltwater (Krabbendam & Bradwell, 2013). On soft beds, with slippery, fine-grained sedimentary rocks or deformable unconsolidated basal substrates (Boulton & Jones, 1979; Golledge & Stoker, 2006), basal sliding was facilitated, leading to draw-down of ice towards the Mesozoic basins of the Moray Firth, Minch and Forth Approaches. Thin-skinned glacitectonics triggered by high pore-water pressures contributed to erosion through the thrusting and transport of glacial rafts of rock and sediment (Phillips & Merritt, 2008; Phillips *et al.*, 2013). Such processes are highly effective along the margins of ice streams (Patterson, 1998) and help to account for the high frequency of glacial rafts found along the shores of the inner Moray Firth (Merritt *et al.*, 2003) and the Firths of Clyde (Merritt *et al.*, 2014) and Forth (Kendall & Bailey, 1908).
- The pre-glacial topography of the western Highlands was already at high elevation and fluvially dissected at the start of the Pleistocene and so provided gradients at the beds of alpine glaciers and ice sheets that were steeper than on the plateaux and lowlands more typical of the topography of eastern areas. Broad straths and lowland corridors established before the Pleistocene also guided ice flow towards major ice streams (Fig. 2).
- Climatic gradients across Scotland were probably more marked in the cold stages of the Pleistocene (Golledge *et al.*, 2008) but, as today, precipitation and air temperature were both higher on the mountains closest to the North Atlantic (Barr *et al.*, 2017), leading to high rates of snow accumulation and warmer ice temperatures (Boulton & Hagdorn, 2006; Hubbard *et al.*, 2009).
- Steeper gradients, higher accumulation rates and higher ice temperatures combined to generate fast-moving, wet-based glacier flow for longer periods in the west. In the east,

slower-moving and cold-based glaciers generally persisted for long periods, with short-lived, or no, phases of fast flow (Fig. 7).

Vertical contrasts in glacial erosion in glaciated uplands reflect greater ice thickness and flow velocity at low points in the landscapes (Glasser, 1995) and the fundamental importance of englacial thermal boundaries in providing sharp upper limits to effective glacial erosion (Sugden, 1968; Hall & Glasser, 2003; Fabel *et al.*, 2012).

Ice extent and dynamics varied in space and time as ice fronts advanced and retreated (Haynes, 1983) and as basal thermal conditions changed (Gordon, 1979). Simulations for the last ice sheet indicate the importance of long binge and short (10-30% relative duration) purge cycles. Ice sheet thickening produced extensive, protective cold-based glaciers (Hubbard *et al.*, 2009). During purges, warm-based ice became extensive, with ice streams propagating from the shelf edge towards onset zones on the present land area (Boulton & Hagdorn, 2006). High ice velocities promote rapid glacial erosion (Näslund *et al.*, 2003; Hubbard *et al.*, 2009), implying that roughened and streamlined rock landscapes are mainly products of relatively brief phases of erosion when ice thinned rapidly. The total duration of Pleistocene ice sheet cover was limited (~500 ka in build-up centres; Fig. 1) and was further reduced at increasing distances from the main ice accumulation centres (Hubbard *et al.*, 2009). Hence, whilst rates of glacial erosion may be high, the rather brief duration over which efficient glacial erosion operated through the Pleistocene reduced its impact on the landscape.

Scotland's maritime location and its 0.8-1.4 km high mountains create near-optimal conditions for the rapid development of mountain ice caps in response to moderate (3 to 6·5°C) falls in summer temperatures (Payne & Sugden, 1990; Golledge *et al.*, 2008). The $\delta^{18}0$ isotope record (**Figure *1***) suggests that during the Early Pleistocene, the dominant mode of glaciation was by mountain ice caps. During the Middle and Late Pleistocene, however, mountain ice caps existed mainly during the slow build-up to full ice sheet cover. One model for mountain ice cap and alpine glacier growth in Scotland is provided by the Loch Lomond Stadial when conditions of rapid temperature fall, steep precipitation gradients to north and east and persistent sea ice brought rapid build-up of ice caps in western Scotland (Hubbard, 1999; Golledge *et al.*, 2010). Markedly different configurations may have developed under conditions with more gradual temperature fluctuations, such as in the period of increasing ice volume at 38-32 ka, when an extensive ice cap is reconstructed over the Cairngorm mountains in mathematical simulations (Hubbard *et al.*, 2009). Full ice sheet growth required greater temperature falls (>6·5°C) (Payne & Sugden, 1990) of longer duration (3-10 ka) (Hubbard *et al.* 2009).

Large ice sheets developed over Scotland from ~1.2 Ma onwards and extended onto the North Atlantic shelf (**Figure *2***). As there is no reliable evidence for the existence of nunataks above the last ice sheet at its maximum (Fabel *et al.*, 2012) and models of the last ice sheet indicate ice surface elevation above 1.5 km (Kuchar *et al.*, 2012), then it is likely that earlier ice sheets of equivalent or greater extent also covered all of the Scottish mainland, including its highest summits. Streamlining of bedrock (Bradwell *et al.*, 2008a) and excavation of glacial valleys (Graf, 1970) contributed to the progressive adaptation of topography and the glacier bed towards more efficient ice flow through the Pleistocene. Middle Pleistocene ice sheets terminated near to the North Atlantic shelf edge (Stoker *et al.*, 1993) or against or near to the western edge of the FIS in the North Sea (Fig. 2). This apparent overstep of Early Pleistocene ice limits, also seen in the southern British Isles (Lee *et al.*, 2015), implies that the British-Irish Ice Sheet, unlike the Laurentide Ice Sheet (Balco & Rovey, 2010), did not approach or reach its maximum limits in the earliest Pleistocene. The position of the British Isles below 60˚N, where insolation intensity is less sensitive to changes in Earth's obliquity, may have prevented the build-up of large ice sheets under the 40 ka cycles of the Early Pleistocene (Huybers & Tziperman, 2008).

Figure 10 View N up Helmsdale towards Griam Mor and Griam Beag in Sutherland, isolated hill masses developed on Devonian conglomerate. Extensive low-relief surfaces have been only weakly dissected by fluvial and glacial erosion during the Pleistocene.

The varied glacial landscapes of Scotland can be seen as products of average conditions with two end members. Landscapes of little or no glacial erosion occur where cold-based conditions were established repeatedly and for long periods beneath successive ice sheets and ice caps through the Pleistocene (Fig. 7). Landscapes of deep and extensive glacial erosion are found where streams of fast, warm-based ice flow developed during successive glacial cycles. Most of the landscapes of Scotland, however, fall between these two extremes, with ice sheet models indicating long periods of cold-based ice cover and only brief phases of fast ice flow (Fig. 7). The morphological impact of glacial erosion on these intermediate landscapes was weak (**Figure *10***).

4. Weathering and non-glacial erosion

Through the Pleistocene, non-glacial processes operated whenever and wherever slopes were free of glacier ice and above sea level. The cumulative time over which these processes operated was long, over 1 Myr in the Early Pleistocene (Fig. 1), and greatest in areas peripheral to the main areas of ice sheet build-up. The duration of the post-glacial period has been short (15 - 20 kyr) but significant geomorphic change has occurred in this interval (Ballantyne, 2002), offering insights into the main impacts in earlier ice-free periods. In the mountains, rock walls that were steepened during glaciation became degraded and locally collapsed (Jarman, 2006), particularly in the Lateglacial paraglacial phase (Ballantyne *et al.*, 2013), generating large volumes of rock debris. Glacial and slope deposits have been reworked by mass movement and stream transport to accumulate on valley floors (**Figure *5***). In the lowlands, streams and rivers have eroded glacial and glacifluvial landforms and the sediment released, in part, has been built into large river terraces. Soil formation has extended to depths of up to 2 m in loose parent materials (Bain *et al.*, 1993) but scarcely begun on rock and boulder surfaces (Kirkbride, 2006; Kirkbride & Bell, 2010). Viewed against the background of multiple glacial-interglacial cycles in the Pleistocene, the main impact of processes operating through the present interglacial can be seen as producing and transporting debris and regolith. After earlier interglacials, debris of similar origin would have been entrained at the glacier bed as glaciers advanced.

Glacial steepening of rock slopes, debris production and evacuation operated across multiple glacial cycles. Only in zones of negligible glacial erosion in peripheral lowlands and on high plateaux is extensive evidence apparent of the processes of weathering and non-glacial erosion that operated before the last glacial cycle. The rock coasts of Scotland, however, preserve in many places till-covered rock platforms and cliffs (Fig. 3) that predate at least the last ice sheet. Buried features of rock coasts represent a largely overlooked record of marine erosion and sea level change earlier in the Pleistocene (Smith *et al.*, 2018).

4.1 Chemical weathering before and during the Pleistocene

The record of chemical weathering at and beneath the landsurface in Scotland is long and complex. Whilst the dating of saprolites that lack stratigraphic context is challenging (Hall, 1993a), most weathering profiles and soils appear to have developed in the near-surface during the Neogene and Pleistocene. A clay-rich, kaolinitic and base-poor saprolite type is found in E Buchan as part of a Palaeogene landscape that includes the Buchan Gravels Formation (Hall, 1985; Hall *et al.*, 2015a). Similar geochemically evolved saprolites found elsewhere in Scotland are probably either exhumed from beneath sedimentary cover (Humphries, 1961; Parnell *et al.*, 2000) or hydrothermal in origin, the latter including kaolins on Shetland (May & Phemister, 1968) and at Pittodrie, Bennachie (Hall, 1993d; Hall *et al.*, 2015a). Elsewhere, only gruss-type weathering profiles are found, with high sand and low fines contents and retention of weathering-susceptible primary minerals such as Ca-feldspar and biotite (Hall, 1985). Gruss localities are concentrated in NE Scotland, the Caithness-Sutherland border and NW Lewis but are almost certainly more widespread than shown in **Figure *3*** because large parts of Highland Scotland have not yet been surveyed for weathering remnants. The mineralogy of North Sea sediments (Dypvik, 1983; Nielsen *et al.*, 2015) indicates that the gruss weathering type started to develop from the Late Miocene onwards in response to climate cooling. Deep gruss profiles (Fig. 11), which can extend to depths of many tens of metres (Hall *et al.*, 1989b), probably developed mainly in the Pliocene period (5.333-2.588 Ma). Shallow weathering profiles, with depths of a few metres, almost certainly continued to develop in temperate interglacial and cool interstadials during the Early Pleistocene (Hall *et al.*, 1989b). We may suppose this because the total duration of such ice-free intervals was long (Fig. 1), rates of gruss development can be fast (Dethier & Lazarus, 2006) and grussification of clasts is typical in pre-MIS 5 weathered till units in Scotland (Connell *et al.*, 1982; Bloodworth, 1990) and northern England (Boardman, 1985). Where Middle to Late Pleistocene till units incorporate and overlie weathered rock, the period of weathering must predate deposition of the tills (Connell *et al.*, 1982; Gordon, 1993a; Hall, 1993b) (Fig. 11). On rocks with high susceptibility to granular disintegration or oxidation, near-surface weathering may be entirely of post-glacial origin. For example, the rapid breakdown of some quartz dolerites on exposure to air (Orr, 1979) may account partly for the extensive development of onion-skin weathering in Carboniferous sills and dykes in the Midland Valley (Henderson, 1893; Walker, 1935).

Figure 11 Gruss pocket at Cairngall Quarry, Mintlaw, Buchan, developed in medium-grained biotite granite below a thin till cover. Gruss

weathering profiles in this area reach known depths of >60 m (Hall, 1985).

Prior to glaciation, deep weathering covers were widespread but weathering penetrated most deeply in fractured, sheared and geochemically-susceptible rocks beneath basin and valley floors, whilst adjacent hills were developed in resistant and largely fresh rock types such as quartzite, acid granites and slate (Godard, 1962; Hall, 1986). One effect of glacial and non-glacial erosion was to progressively thin and finally remove gruss from wide areas through the Pleistocene (Clark & Pollard, 1998; Krabbendam & Bradwell, 2014; Hall *et al.*, 2015b). Particularly in western areas of high glacial erosion, the very limited survival of gruss means that tills of the last, Late Devensian glaciation are composed of clasts and matrix material released by the breakage and comminution of fresh rock debris. In contrast, in eastern areas where saprolite pockets remain, the tills may incorporate large amounts of former saprolite and soil materials (Wilson *et al.*, 1984).

4.2 Mountain-top detritus

Mountain-top detritus (MTD) refers to frost-riven regolith of diverse character found on Scottish hills (Ballantyne, 1998). The character of MTD is closely controlled by rock type and fracturing and by the time available for its formation. Three main types of MTD have been recognised (Ballantyne, 1984): (i) openwork blockfields; (ii) clast-rich, sandy diamictons; and (iii) clast-rich, silty and fine sand diamictons. Blockfields are typical of rocks with widely spaced fractures, such as quartzite and granite; sandy diamictons are developed mainly on sandstones and psammites; and silty diamictons are common on greywackes and mica schists. MTD generally forms only shallow regolith, reaching depths of 0.1-1.6 m, with surface concentrations of larger clasts and more matrix fines at depth. Clast angularity, local derivation and vertical sorting indicate an origin by frost-riving and frost-heaving, processes that have operated effectively at high elevations since the last deglaciation and probably earlier also (Ballantyne & Harris, 1994).

On many Scottish mountain summits there is evidence that MTD predates the last ice sheet. Where glacial erosion by the last ice sheet has left bare bedrock surfaces, MTD occurs only on densely-fractured rocks (**Figure *12***). MTD has not reformed on more massive rock types, indicating that it is slow to develop on these rocks (Fabel *et al.*, 2012). Where glacial erosion has been ineffective in removing regolith, MTD may contain assemblages of clay minerals, including gibbsite and kaolinite, that are distinct from those found on the same rock types on lower slopes (Ballantyne, 1994a). Many hill summits in the British Isles and Ireland show a distinct upslope limit to MTD (**Figure *3***). Earlier interpretations of this limit as a glacial trimline at the upper limit of the last ice sheet (Ballantyne, 1997) have given way in recent years to a recognition that the limit marks an englacial boundary between warm- and cold-based ice within the last ice sheet (Fabel *et al.*, 2012; McCarroll, 2016). Detailed mapping has shown that the elevation of this trimline drops away from the main watershed towards the Outer Hebrides and to the inner Moray Firth (Ballantyne, 2010a).

The age of the MTD found above trimlines on mountain plateaux is poorly constrained. MTD may have thickened in the post-glacial period but the main phase of its formation generally predates the last ice sheet (Hopkinson & Ballantyne, 2014). Development of MTD requires that summits and plateaux are free of permanent snow and glacier ice and exposed to frost action and weathering. Hence blockfields may have formed or thickened during MIS 5-3 or during earlier interstadial and interglacial phases of the Early and Middle Pleistocene. On relict, non-glacial plateau surfaces in northern Scandinavia, ^{10}Be and ^{26}Al inventories are consistent with formation of the present MTD layer through the Middle and Late Pleistocene (Goodfellow *et al.*, 2014a). In western Norway, cosmogenic nuclides indicate low erosion rates (4-6 m/Ma) (Andersen *et al.*, 2018). The residence times of regolith on the Cairngorm plateaux are short, with maximum erosion rates for exposed rock surfaces ranging from 2.8 to 12.0 m/Ma, and tor emergence rates after stripping of regolith at 11-35 m/Ma (Phillips *et al.*, 2006). There is also evidence, however, of low Middle to Late Pleistocene erosion rates. Cosmogenic exposure ages indicate that weathering pits deeper than 5–10 cm predate the last glacial cycle (Hall & Phillips, 2006b). Weathering pits up to 20 cm deep occur on large tabular blocks set within MTD. Blockfields that have been disrupted locally by ice flow and pass downslope into stripped, joint-bounded granite bedrock surfaces display weathering pits up to 12 cm deep. The weathering pits indicate formation and stripping of MTD in the Cairngorms in or before MIS 6. Evidence of a longer weathering history for plateau surfaces is also given by pockets of thick gruss-type saprolite of likely Pliocene to Early Pleistocene age found on high ground in the central and eastern Grampians (Hall & Mellor, 1988; Phillips *et al.*, 2006; Hall, 2007). However, for thin blankets of MTD to be maintained at even low erosion rates, formation of new detritus from frost weathering of bedrock is required over 100 ka timescales (Marquette *et al.*, 2004). Ballantyne (2010b) has proposed a dynamic model of long-term blockfield evolution in which Neogene regolith cover was gradually removed by subaerial surface lowering during ice-free periods and progressively replaced by the products of frost-wedging under periglacial conditions, with most existing MTD formed entirely within the last 135 ka (Hopkinson & Ballantyne, 2014). Where MTD is older, the uppermost trimlines mapped on Scottish mountains may predate the last ice sheet, a suggestion consistent with the more restricted extent of the last ice sheet compared to earlier ice sheets on the North Atlantic shelf (Ballantyne *et al.*, 2017)

Figure 12 Mountain top detritus on the Red Cuillin, Skye. Fine- to medium-grained granite is broken into a thin cover of MTD with many small, angular clasts in a granular sand matrix. The summit was probably over-topped by the last ice sheet but exposed as a nunatak in the Loch Lomond Stadial (Small *et al.*, 2012). Estimated erosion rates of 30-40 mm/ka are based on ^{10}Be cosmogenic inventories (Fame *et al.*, 2018)

4.3 Tors

Tors are small rock knobs produced by long-term differential weathering and erosion. At lower latitudes than Scotland, tors may be exhumed from thick saprolites but almost all Scottish tors sit on hill and ridge tops and have no close association with deep weathering. Rock compartments with low fracture spacing have emerged as tors through the repeated formation and stripping of thin regolith similar in properties to that which exists on surrounding slopes today (Hall & Sugden, 2007). This debris mantle, in areas such as the Cairngorms, is of complex origin, with elements that derive from hydrothermal alteration (Hall & Gillespie, 2016), multiple phases of chemical weathering (Hall & Mellor, 1988), granular disintegration due to stress release (Phillips *et al.*, 2006) and frost weathering (Ballantyne, 1994b). Studies in other humid, unglaciated granite terrains indicate rates of regolith formation of >5 m/Ma (Bierman, 1994; Duxbury *et al.*, 2015), comparable to known rates of MTD production. Such rates, when combined with evidence of significant Holocene chemical weathering in the Cairngorms (Soulsby *et al.*, 1998) and Late Devensian frost weathering and mass movement (Ballantyne, 1994b), suggest that much of the 0-2 m of regolith found around tors today has formed mainly in the Late Pleistocene. Thin regolith may be largely renewed in ice-free intervals during each interglacial- glacial cycle.

Figure 13 Tors developed in the Northern Arran Granite emplaced at ~60 Ma (Dickin *et al.*, 1981). Note the truncation of inclined, sub-parallel joints by the glacial slopes of Glen Sannox, the exposures of thin granular regolith and the weathering pits on granite surfaces.

In areas of Pleistocene glaciation, tors are absent from zones of areal scouring but may be present in landscapes of alpine glaciation (Small *et al.*, 1997), selective linear erosion (Sugden, 1968; Sugden & Watts, 1977) and in areas of little or no erosion (André, 2004). Tor landscapes in Scotland (**Figure *3***) also include isolated hill masses around which the last British ice sheet streamed at the Last Glacial Maximum, for example the hills of South Uist (Ballantyne & Hallam, 2001), northern Arran (Godard, 1969) (**Figure *13***) and Ben Loyal in Sutherland (Godard, 1965). Like blockfields, the existence of tors was formerly attributed to these areas standing as nunataks above the last ice sheet (Godard, 1965). The existence of glacial erratics and glacially displaced tor blocks, however, leaves no doubt that these and other summits were ice-covered. It appears that the tors have survived beneath protective covers provided by cold-based glaciers (Sugden 1968). Where no sliding of ice takes place across the glacier bed, then delicate features including tors and regolith may be preserved (Rapp, 1996). Evidence of localised glacial transport from the tor site is provided by displaced tor blocks and boulder trains (Hall & Phillips 2006a). Displaced tor blocks may reach sizes of 100 m^3 (**Figure *14***) and show the distinctive weathered surfaces typical of Cairngorm tor summits (Hall & Phillips 2006b). In the Cairngorms, such criteria can be used to trace the movement of former tor blocks, allowing distances and directions of transport to be identified. Tors formed of smaller blocks may be partly or wholly demolished to form boulder trains (Hall & Phillips 2006a).

Tors in glaciated regions have been referred to as *pre-glacial* landforms (e.g. Sugden 1968). The term is used in two senses – pre-Pleistocene or pre-glaciation, the latter where the tor predates one or more phases of glaciation. The advent of cosmogenic isotope analysis has allowed constraints to be placed on the exposure ages and erosion rates for rock surfaces on tors. Cosmogenic isotope data confirm that Cairngorm and Caithness tors are older than the last interglacial (Phillips *et al.*, 2006; Ballantyne & Hall, 2008). The oldest Cairngorm tor surface at Clach na Gnùis has a minimum exposure and burial age of 675 ka (Phillips *et al*. 2006). This tor carries weathering pits 1 m deep and is unmodified by glacial erosion, yet the accumulated nuclide inventory on its top indicates that this tor is not a pre-Pleistocene landform. Existing tors in the Cairngorms are dynamic landforms which have attained their present forms through the Middle Pleistocene.

Figure 14 Glacially-transported tor block, eastern Ben Avon in the eastern Cairngorms.. The tor in the background has lost superstructure to glacial entrainment. Extensive spreads of sandy MTD, with small blocks, are developed on the Cairngorm Granite.

Where tors or even tor roots survive in formerly glaciated areas, then the total glacial erosion since tor emergence has been confined to modification or removal of the protuberance, without significant lowering of surrounding surfaces. In glaciated tor fields, such as the Cairngorms (Gordon, 1993b), this means that glacial erosion has been only a few metres (Hall & Phillips, 2006a). On spurs that merge down slope into larger roche moutonnée forms, the survival of tor roots identifies a zone of very limited glacial erosion on the upper part of the spur (Sugden *et al.*, 1992). Tors are therefore useful indicators of terrain that has experienced minimal glacial erosion. In such terrain, known erosion rates indicate that the contribution of erosion from non-glacial processes exceeds that from glacial processes through the Pleistocene. In the Cairngorms, at least three separate phases of glacial modification of tors are recognised on the basis of exposure ages (Phillips *et al.*, 2006). On these and other granite hills in Scotland, the granite surfaces of tor plinths carry weathering pits > 10 cm deep formed during or before the last interglacial, requiring that tor removal by glacial processes occurred in MIS 6 or earlier (Hall & Phillips, 2006b).

4.4 Exfoliation or sheet joints in granite terrain

Exfoliation or sheet joints are joint sets with orientations subparallel to the present or former ground surface that occur at depths of 1-100 m in granite intrusions (Ziegler *et al.*, 2013). Exfoliation or sheeting develops where high maximum principal compressive stresses up to a few tens of MPa exist at shallow depths, oriented subparallel to the ground surface, and exceed the least surface-normal principal stress, a product of overburden thickness including topographic effects (Holzhausen, 1989). Extension and opening of exfoliation joints in the near-surface is a response to topographic curvature (Martel, 2017). Exfoliation joints guide weathering and erosion and have been identified in Scotland as an important control on the morphology of non-glacial forms, including domes (Hall *et al.*, 2013b), tors (Goodfellow *et al.*, 2014b) and blockfields (Hall & Glasser, 2003), and glacial forms, including valleys (Glasser, 1997), cirques (Haynes, 1968) and roches moutonnées (Gordon, 1981; Sugden *et al.*, 1992). In areas where Pleistocene glacial erosion has led to changes in topography, distinct sets of exfoliation joints can be related to palaeo-topography (Ziegler *et al.*, 2013). In the Cairngorms, at least two generations of sheet joints are recognised oriented sub-parallel to the slopes of plateaux and to glacial valleys and cirques (Glasser, 1997). Here and in other granite terrains in Scotland (Godard, 1969) (Fig. 13), sub-horizontal joint sets are also present that are not related to present slopes and so may relate to pre-glacial relief development.

5. Early Pleistocene terrestrial stratigraphy

Early Pleistocene sediments are preserved in formerly glaciated regions only where the first glaciations were the most extensive (e.g. Tasmania (Augustinus & Macphail, 1997), Midwest USA (Balco *et al.*, 2005a) and Patagonia (Rabassa *et al.*, 2005)) or in deep sediment traps or basins (Anne *et al.*, 2017). In the British Isles, the most extensive Pleistocene glaciations occurred during the Middle and Late Pleistocene (Bridgland *et al.*, 2015; Lee *et al.*, 2017) and removed older sediment and regolith through glacial erosion and transfer to the Atlantic shelf and slope and to the North Sea Basin (Sejrup *et al.*, 2005). In Scotland, no Early Pleistocene glacial sediments have been identified onshore, except perhaps for deeply buried channel-fill sands at the mouth of the River Spey (Merritt *et al.*, 2003). In a few locations, however, sediments or fossils of likely Early Pleistocene age have been reworked into Late Pleistocene glacigenic sequences. In eastern Buchan, the Kippet Hills Sand and Gravel Formation includes shells reworked from the Early Pleistocene Aberdeen Ground Formation offshore (Cambridge, 1982; Gordon, 1993c; Merritt *et al.*, 2003). The coeval Hatton Till Formation also incorporates Early Pleistocene shell fragments and dinoflagellate cysts derived from the same source (Merritt *et al*. 2003). At Leavad, in western Caithness, masses of laminated dark green shelly clay of possible Miocene to Early Pleistocene age, presumably derived from the inner Moray Firth, occur as rafts within a buried Late Pleistocene glacigenic sequence (Crampton & Carruthers, 1914; Gordon, 1993d). Apart from the Kippet Hills and Hatton Formations, published amino acid ratios for marine shells collected from tills in Caithness, Orkney and Buchan indicate reworking only of Middle and Late Pleistocene material (Bowen & Sykes, 1988; Bowen, 1991). An

Early Pleistocene age has been proposed for the Buchan Gravels Formation (Flett & Read, 1921) (Kesel & Gemmell, 1981)at Windy Hills (Gordon & Sutherland, 1993) and Moss of Cruden (Hall, 1993c), but stable oxygen and hydrogen isotopes for kaolinised clasts from the gravels indicate post-depositional weathering at high average temperatures attained in Scotland only during the Eocene or mid-Miocene (Hall et *al*. 2015a).

6. Middle Pleistocene terrestrial stratigraphy

The Middle Pleistocene terrestrial glacial stratigraphy of Scotland, as currently understood, does not replicate the complexity of the offshore record (Stewart *et al*. 2018). The oldest known till units found onshore in Scotland, at Kirkhill and Leys Quarries in Buchan, NE Scotland, are regarded as deposited by an ice sheet during MIS 8 (between 245 and 303 ka) (Merritt *et al*. 2003). Buried till beds elsewhere in Scotland (Fig. 15) are usually attributed to MIS 6 glaciation, at the latest (see below). There are several possible reasons for the apparently sparse preservation of old till units, the most likely being that successive ice sheets tend to erode or rework older deposits. Thus the latest MIS 3-2 ice sheet (>26-13 ka) is likely to have destroyed most pre-existing glacial, interglacial and interstadial sediment sequences. Yet the widespread survival of pre-glacial weathered rock in zones of limited glacial erosion in Scotland (Fig. 3) suggests that similarly fragile pre-Late Devensian glacial deposits should also have survived locally, at least in these zones. This is the case in central Buchan which shows the juxtaposition of Neogene-Early Pleistocene deep weathering and MIS 8-4 sediment sequences with MIS 3 glacial and non-glacial sediments (Hall & Sugden, 1987). Preservation of older deposits is particularly likely where deep valleys are orientated transverse to ice sheet flow that acted first as sediment traps and later as secure repositories for glacial sediments. Such locations are found to the E of Inverness (Fletcher *et al.*, 1996), and in Easter Ross (Peach *et al.*, 1912) and the Forth valley (Francis *et al.*, 1970; Sissons & Rhind, 1970) (Fig. 15). Another potentially favourable location is where advancing ice fronts moved along the main straths sending ice lobes into closed tributary valleys, ponding lakes and disgorging sediment, before bypassing these locations as ice thickened and topographic control over ice flow weakened. Examples of this type of accommodation space are seen in the central Grampians, where thick glacilacustrine sediments have been overridden by later ice movements and disturbed by glacitectonics (Smith *et al.*, 2011; Hall *et al.*, 2016). The possibility also exists that old tills are simply overlooked through incorrect attribution to younger phases of glaciation. In the virtual absence of dating constraints, the recognition of old tills usually rests on a position low in a stratigraphic sequence or beneath interglacial or interstadial sediments/soils or on the advanced weathering of till clasts. In situations where the upper part of a sediment pile is eroded during a glacial phase and soils and organic deposits are lost, then the till layers in the remaining lower part may be indistinguishable from till units of the last glaciation, particularly where ice flow has followed a similar path.

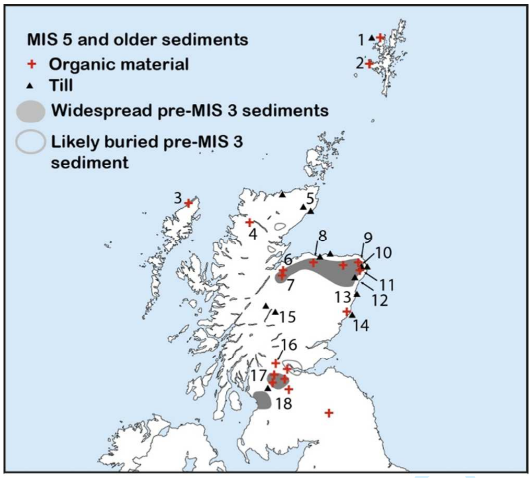


Figure 15 Sites with MIS 5 and older sediments in Scotland. 1. Fugla Ness (Hall *et al.*, 2002). 2. Sel Ayre (Hall *et al.*, 2002). 3. NW Lewis (Sutherland & Walker, 1984). 4. Inchnadamph (Lawson & Atkinson, 1995). 5. Caithness (Hall & Riding, 2016). 6. Dalcharn (Walker *et al.*, 1992). 7. Allt Odhar (Walker *et al.*, 1992). 8. Teindland (Hall *et al.*, 1995). 9. Kirkhill (Connell *et al.*, 1982). 10. Camp Fauld (Whittington *et al.*, 1993). 11. Toddlehills (Gemmell *et al.*, 2007) and Savock Quarry (Connell, 2015). 12. Pitlurg (Hall & Jarvis, 1995). 13. Nigg Bay (Gordon, 1993e). 14. Inverbervie (Auton *et al.*, 2000). 15. Pattack (Merritt *et al.*, 2013). 16. Balglass (Brown *et al.*, 2006). 17. Lower Clyde (Rolfe, 1966; Finlayson *et al.*, 2010). 18. Ayrshire (Jardine *et al.*, 1988; Finlayson *et al.*, 2010).

6.1 The Kirkhill sequence

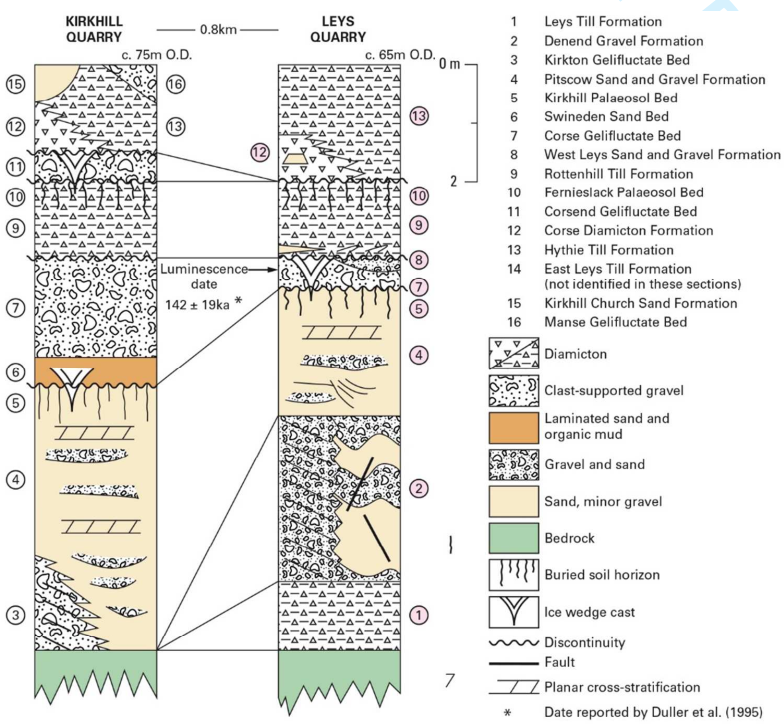
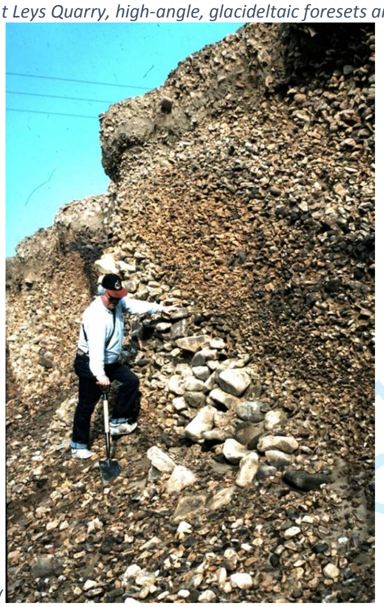


Figure 16 Kirkhill and Leys schematic Middle to Late Pleistocene stratigraphy (after (Merritt *et al.*, 2003).

The Pleistocene sequence in the Kirkhill area (Hall & Jarvis, 1993) is unique in the British Isles terrestrial record in providing a detailed record of at least three complex stadial–interstadial–interglacial cycles (Fig. 16).

- In the oldest cycle believed to date to MIS 8 (245-303 ka, Merritt *et al*. 2003), glaciation and the deposition of till was possibly succeeded by a phase of weathering, prior to erosion of the till surface, perhaps by the meltwater that deposited the overlying glacifluvial and glacideltaic gravels and sands. After deglaciation of the site, periglacial conditions were established, with frost shattering of bedrock and solifluction and later deposition of fluvial gravels. After a phase of erosion, a podzolic soil formed under humid temperate conditions on the gravel surface.
- The second cycle commenced with a climatic deterioration marked by development of arctic soil features and the onset of gelifluction. This was followed by glaciation of the site, with deposition of till. Subsequently, a further soil developed on this till surface and its pedogenic characteristics imply a return to interglacial conditions. This cycle is assigned to MIS 6 – MIS 5e (see below).
- The youngest cycle (Devensian) opened with deposition of a sequence of periglacial deposits, the subsequent development of permafrost, marked by ice-wedge casts, and the eventual deposition of three further till units. Subsequent deglaciation involved minor glacifluvial deposition and was accompanied, or succeeded, by a phase, or phases, of periglacial activity until soil formation began at the start of the Holocene interglacial.

The oldest event known in the Kirkhill/Leys area is the cutting of a linear depression into weathered basic igneous weathered basic igneous rock at Leys Quarry. The Leys Till Formation, containing quartzite erratics glacially transported glacially transported from the W, was laid down on its floor. The till contains grussified basic igneous clasts and appears to clasts and appears to have been weathered after deposition (although local incorporation of previously weathered bedrock previously weathered bedrock and subsequent limited glacial transport also occurred). The overlying Denend Gravel Denend Gravel Formation comprises 3 to 5 m of coarse, felsite-dominated, pebble to boulder gravel, with interstratified with interstratified sand units. The Denend Gravel was deposited by meltwater moving towards the W and SW, part of a W and SW, part of a valley sandur extending from an ice margin lying relatively close to, and E of, Leys. At Leys Quarry, *Leys. At Leys Quarry, high-angle, glacideltaic foresets are preserved, indicating the ponding of a glacial lake in the Ugie*



valley (

Figure *17*) at this time. It appears that ice blocked the valley E of Leys though it is unclear if this was ice flowing from the Moray Firth and curving S, or ice having flowed N up the western North Sea margin. The set of channels at Kirkhill Quarry in which these gravels and younger sediments accumulated may have been cut by meltwater flow at this time or earlier. Post-depositional disturbance of the gravels is widespread, with folding, faulting and development of wedge structures as the result of melt-out of glacier ice blocks originally buried within the gravels (Hall & Connell, 1986).

Figure 17 SW face of Leys Quarry in the 1990s showing high-angle,glacideltaic foreset gravels of the ?MIS 8 Denend Gravel Formation. Flow of water was towards the W and SW. Note extensive Fe and Mn staining and local cementation of the sediments. Excavations below this gravel unit exposed the Leys Till resting on bedrock.

At Kirkhill, an angular felsite rubble up to 2 m thick rests on channel floors. Clasts in the rubble show a well-developed downslope fabric, indicating transport by avalanche or gelifluction. Silt cappings indicate incipient pedogenesis (Connell & Romans, 1984). This Kirkton Gelifluctate Bed is, in turn, overlain by the Pitscow Sand and Gravel Formation, with up to 4 m of mainly horizontally stratified sands, with gravel lags marking former channel floors. This unit is interpreted as a periglacial fluvial or proglacial glacifluvia245l deposit. Cross-stratification indicates transport from the E. Syn-depositional ice-wedge casts indicate deposition of the basal beds under permafrost conditions. The declining numbers of angular clasts in the upper Pitscow beds at Kirkhill, together with the absence of ice-wedge casts and other periglacial features, may indicate the subsequent amelioration of climate.

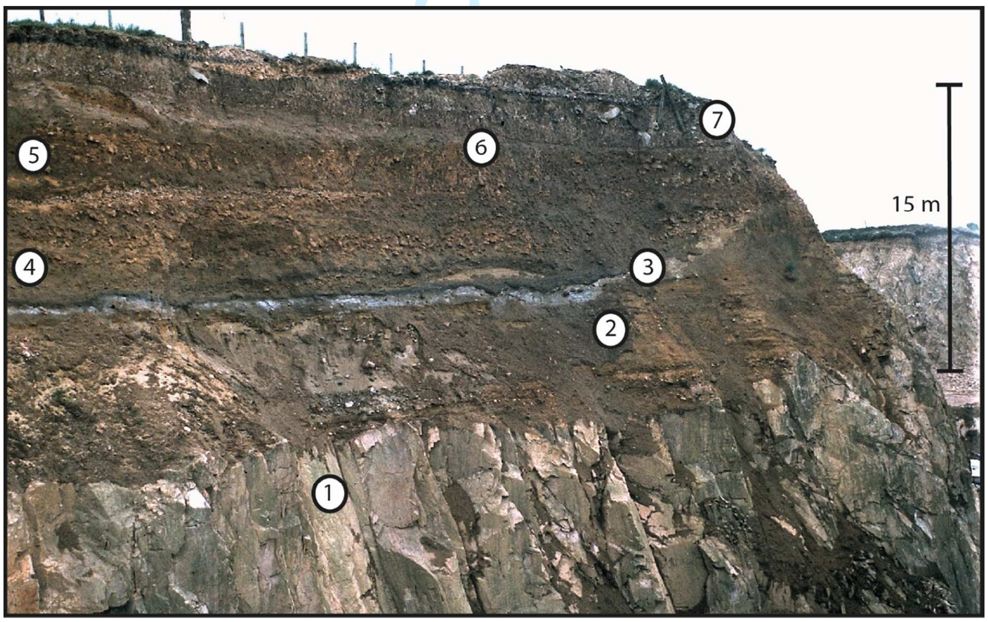


Figure 18 South Face 1 of Kirkhill Quarry in the late1970s. 1. Floor of meltwater channel cut in a felsite dyke. 2. Pitscow Sand and Gravel Formation. 3. Kirkhill Palaeosol Bed. 4. Camphill Gelifluctate Bed 5. Rottenhill Till. 6. Corsend Gelifluctate Bed. 7. Hythie Till.

The first cycle ended with an important phase of pedogenesis, with formation of the Kirkhill Palaeosol Bed on the eroded upper surface of the Pitscow Sand and Gravel (Fig. 18). A conspicuous bleached horizon, up to 19 cm thick with bleached and softened felsite clasts, was found throughout Kirkhill Quarry, and in the NE face of Leys Quarry. This represents the former Ea horizon of a podzolic soil, with a lower mottled Bs horizon locally enriched in organic carbon and free iron as a result of pedogenic translocation. An iron pan is also found towards the base of the profile (Connell *et al.*, 1982). Micromorphological analysis of the palaeosol has also revealed structures typical of soils of arctic environments (Connell & Romans, 1984). Superimposition of periglacial soil features on an earlier interglacial soil horizon seems to have produced a composite soil horizon. At both Kirkhill and

Leys, Fe and Mn staining associated with localised cementation occurs extensively to depths of several metres in underlying gravels and sands (Fig. 18). These indicators of former waterlogging or fluctuating groundwater levels contrast sharply with the leached horizon represented by the podzol, though the timing and number of weathering phases involved in Fe and Mn mobilisation is uncertain. At Kirkhill, the truncated Kirkhill Palaeosol Bed is overlain by thin, poorly stratified and weakly organic sands, the Swineden Sand Bed. These sands probably represent slope-wash deposits and are penetrated by a series of frost-cracks (Connell *et al.*, 1984). Beneath the sands lies a 1 to 5 cm thick bed of black to brown, weakly laminated organic mud that drapes the truncated palaeosol in the E face. The organic mud contains pollen of Poaceae, together with a marked arboreal component of mainly *Pinus* and *Alnus*, together with charcoal. The overlying sands show a reduction in arboreal pollen and an increase in grasses and *Calluna*, possibly reflecting the establishment of an open, treeless environment (Connell *et al.*, 1982). Sampling of an equivalent organic sequence in the W face at Kirkhill suggests that two components exist in the pollen spectra (Lowe, 1984). Open, grassland types represent pollen contemporaneous with sedimentation of the sands. Recycled pollen, with an important arboreal component, is perhaps derived from older soil horizons at the site. The stratigraphical position of the palaeosol indicates that it developed during a pre-Ipswichian interglacial, probably MIS 7 (245-186 ka; Merritt *et al*. 2003).

The start of the second cycle is seen at Kirkhill Quarry where up to 2.5 m of periglacial mass movement deposits, named the Camphill Gelifluctate Bed, are developed above the organic Swineden Sand Bed. The bed includes features indicating multiple phases of periglacial activity, including episodes of gelifluction, cryoturbation and development of an ice-wedge polygonal network. A luminescence date of 142 ± 19 ka BP (Duller *et al.*, 1995), if correct, falls within MIS 6. The West Leys Sand and Gravel Formation rests in shallow channels scoured into this periglacial landsurface. These thin, probably glacifluvial gravels and sands show planar cross-beds indicating water flow from the NW and probably represent outwash or subglacial meltwater deposits. The overlying Rottenhill Till Formation overlies with a weak unconformity these earlier deposits (Fig. 19). Its clast lithology (including boulders of Strichen granite) and fabric indicate deposition by ice moving from the NW. Whilst only three sites are known where the Rotten Hill till is found, all show NW-SE ice flow. It is possible that this flow direction was being “steered” by ice in the Moray Firth impinging on Buchan much as it did during both early and late stages of the Middle-Late Devensian glaciation (Merritt *et al*. 2017). After deglaciation, the Fernieslack Palaeosol Bed developed on the surface of the underlying Rottenhill Till Formation. This second major phase of soil development is marked by grussification of basic igneous and granite clasts, soil horizon development and clay mineral weathering and translocation. Soil characteristics are typical of the B- and C-horizons of gleyed brown earths developed on similar parent materials in eastern Scotland during the Holocene (Connell & Romans, 1984) and are in contrast to the podzolic soil (Kirkhill Paleosol Bed) which developed on the more acidic, free draining, parent materials available at the site during the MIS 7 interglacial. Support for this interpretation of the Fernieslack Palaeosol is provided by the presence of *Alnus*, with *Betula* and coryloid grains from a single sample in the profile (Connell *et al.*, 1982). On the simplest interpretation and in the light of the stratigraphically lower luminescence date, the Fernieslack Soil probably formed during the Ipswichian Interglacial (MIS 5e).

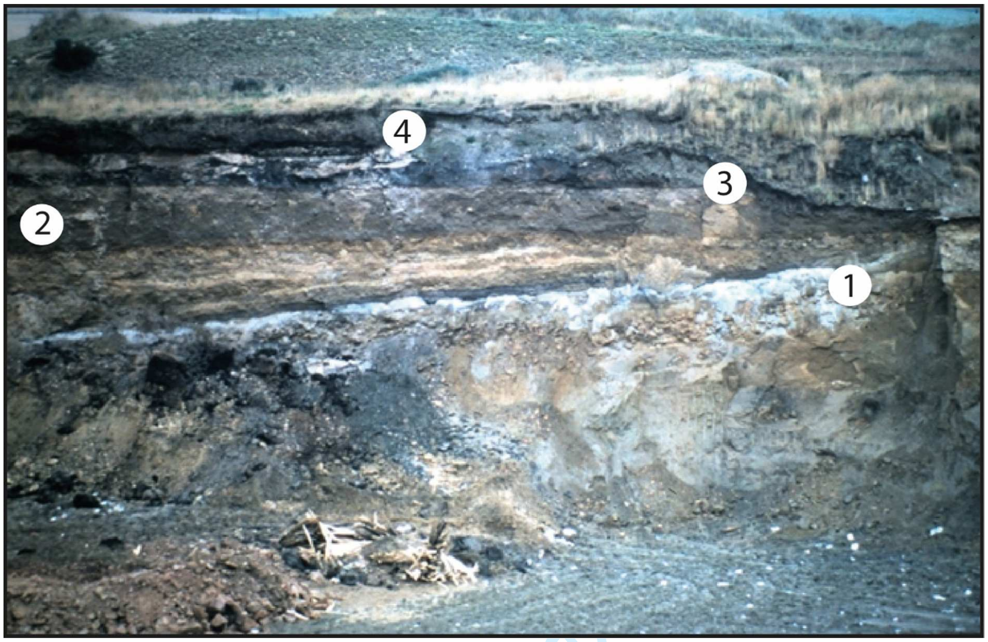


Figure 19 Kirkhill Quarry North Face in the 1980s. 1. Podzolic Kirkhill Palaeosol Bed. 2. Unconformable, sub-horizontal, base of the brown Rottenhill Till (within which the Fernieslacks Palaeosol Bed, developed). 3. The black Corse Diamicton (incorporating glacitectonically deformed pale coloured sand) overlies the Rottenhill Till. 4. Hythie Till. The section is approximately 15 m high.

The latest (Devensian) cycle began with cryoturbation and gelifluction, followed by incipient pedogenesis and ice-wedge growth recorded by successive units within the Corsend Gelifluctate Bed. Ice advance to the site occurred while ground ice remained in the wedge (Connell *et al.*, 1984). The Corse Diamicton Formation was first exposed at Kirkhill as a large mass of dark grey clay diamicton consisting largely of reworked Late Jurassic/Early Cretaceous mudstone. The overlying Hythie Till Formation has a clast lithology dominated by psammite and pelitic schist, with basic igneous rocks and felsite. A clast of rhomb porphyry typical of those found in the Oslo Graben was recovered from this unit and a second clast was recovered from talus below the NE face at Leys. The stratigraphic position of Scandinavian erratics in Buchan and their presence in tills of inland origin indicate that transport of these rock types into the inner Moray Firth probably occurred before MIS 5 (Hall & Connell, 1991), perhaps in the Anglian/Elsterian (MIS 12) (Merritt *et al.*, 2003). The dominance of quartzitic and basic igneous rocks in the Hythie Till Formation indicates a western provenance. The unit can be correlated on the basis of stratigraphy and lithology with tills along the valleys of the North and South Ugie Water, which also have strong W–E fabrics (Hall & Connell 1991). The succeeding East Leys Till Formation is a very dark grey, mud-rich diamicton. Clast lithologies are dominated by gneissose quartzite and psammite, with chalk, pelites and reddish brown (possibly Devonian) sandstone. Striated shell fragments appear below a near-surface Holocene weathering horizon and include specimens of *Macoma* sp. and *Astarte* sp. The matrix contains reworked Late Jurassic/Early Cretaceous dinoflagellate cysts, Mesozoic and Tertiary pollen, and Quaternary foraminifera. Together these organic remains indicate derivation of the matrix from Mesozoic mudstone, Palaeogene sediments and Quaternary glacimarine and marine muds in the Moray Firth basin. Southward transport by ice from the Moray Firth is supported by the presence of chalk clasts and by the transport of dark gneissose rocks comparable to the Inzie Head Gneiss of the Fraserburgh area. The East Leys Till represents the final phase of glacial deposition recorded at the site and is succeeded by thin glacifluvial sands and gravels. At Leys, there is evidence of a late phase of permafrost conditions from involutions with stone pillars, near-surface concentrations of frost-heaved clasts, erected and frost-cracked pebbles and associated development of ice-wedge casts (Hall & Connell, 1986).

The Kirkhill/Leys sequence provides wider insights into the sequence of environmental change in Scotland because of its peripheral position in the lowlands of Buchan. In the last glaciation, ice flow into this area came via three pathways: the inner Moray Firth, the western North Sea and the eastern Grampians. In the two early cycles of the Kirkhill sequence, only the Denend Gravel appears to relate to ice blocking the North Sea coast in a manner similar to the ponding of Glacial Lake Ugie in the Late Devensian (Merritt *et al.*, 2017). The earlier Leys Till and the later Rottenhill Till were deposited by eastern Grampian ice moving eastward toward the North Sea, a pattern of ice flow similar to that for the Hythie Till around the maximum of the Late Devensian. Each of these tills sits with only weak unconformity on older deposits indicating that, in the last three glacial cycles, eastern Grampian ice was effectively non-erosive in this area. The consequent layer cake stratigraphy includes evidence for two pre-Holocene interglacial phases in which significant weathering and soil development took place. Cold conditions were established in Buchan in at least two separate phases before the last interglacial, with ice wedges marking intervals with permafrost development (Fig. 16). With the three younger units also formed under periglacial conditions, it is clear that periglacial processes operated repeatedly in the lowlands of eastern Scotland through the Middle and Late Pleistocene (Connell & Hall, 1987). The Devensian sediments in the Kirkhill and Leys area are thin, with older sediments taking up most of the accommodation space within the once 10-15 m deep channels at these sites. Monitoring of gas pipeline trenches in the 1980s showed that Devensian glacial deposits are also thin across much of central Buchan yet still provide evidence of multiple events from attenuated stratigraphic units (Merritt *et al.*, 2003).

6.2 Deposits elsewhere in Scotland that predate MIS 5

At a few, widely scattered sites across Scotland, organic deposits or weathering horizons dated or attributed to MIS 5 are underlain by older sediments (Fig. 15). Till units found low in stratigraphic sections have also been assigned to MIS 6 (Saalian) or older glaciations. On the plain of Caithness, old glacial deposits sit in lows within glacially streamlined terrain, indicating that bedrock erosion largely predates the last glacial cycle (Hall & Riding, 2016).

On Shetland, at Fugla Ness, a till lies below a peat layer that probably formed in the last interglacial. This till has a strong NW–SE fabric (Hall *et al.*, 2002), a similar direction to movement of ice within the Shetland ice cap during the last glaciation (Hall, 2013). In Caithness, tills deposited by ice moving out of the inner Moray Firth and the Northern Highlands occur below multiple sequences referred to the Late Devensian glaciation (Gordon, 1993d; Hall & Riding, 2016). Amino acid racemization ratios for marine shells now incorporated in Late Devensian tills in Caithness and Orkney suggest that the oldest included shells date from MIS 7 and 9, respectively (Bowen & Sykes 1988). These ages imply reworking of shells from former marine or glacimarine sediments in the inner Moray Firth that included beds of MIS 6 age or older (Hall & Riding, 2016).

On northern Lewis, a raised shore platform is found at 6-12 m O.D. (von Weymarn, 1979; Gordon, 1993f). Weathered till occurs in pockets on its surface and contains erratic clasts of Torridonian sandstone and Cambrian quartzite, indicating ice movement from the Scottish Mainland (Peacock, 1984) during MIS 6 or earlier. This rock platform and one at a similar elevation on Barra and Vatersay (Selby, 1987) are overlain by beach gravels that probably date from MIS 5 high sea levels (Hall, 1996). In Assynt, a cave at Creag nan Uamh has yielded Uranium-series disequilibrium ages for speleothems of 122 +/-12 ka, 143+13/-16 ka, 181+24/-18 ka and 192+53/-39 ka, indicating the establishment of ice-free conditions during the last interglacial and MIS 6 (Lawson, 1993).

East of Inverness, organic deposits and palaeosol/weathering horizons of MIS 5 age have been described from Allt Odhar and Dalcharn. The weathered, sandstone-rich Dearg Till Formation at Dalcharn is older than the Devensian as it underlies an interglacial palaeosol and deeply weathered Craig an Daimh Gravel (Walker *et al.*, 1992; Merritt & Auton, 2017).The Moy Peat Bed and underlying gravel at the Allt Odhar site also overlie an older sandstone-rich diamict, the Suidheig Till Formation. Another weathered, sandstone-rich diamict, the Cassie Till Formation occurs nearby at the base of the sequence at Clava. These older tills are presently exposed within several valleys draining towards the River Nairn (Fletcher *et al.*, 1996) (Fig. 20). In lower Strath Spey, the podzolic Teindland Palaeosol, probably of last interglacial age, is underlain by beds of sand, gravel and till (Fig. 21). Erratic clasts in the Red Burn Till below the palaeosol indicate ice movement from the NW (Hall *et al.*, 1995). Each of these underlying tills probably relates to MIS 6 glaciation, as does weathered till found near Portsoy (Gordon, 1993a; Peacock & Merritt, 2000). These sequences hold an important record of Middle and Late Pleistocene environmental change preserved along the southern margin of ice streams moving towards and out of the inner Moray Firth (Merritt *et al.*, 2003).

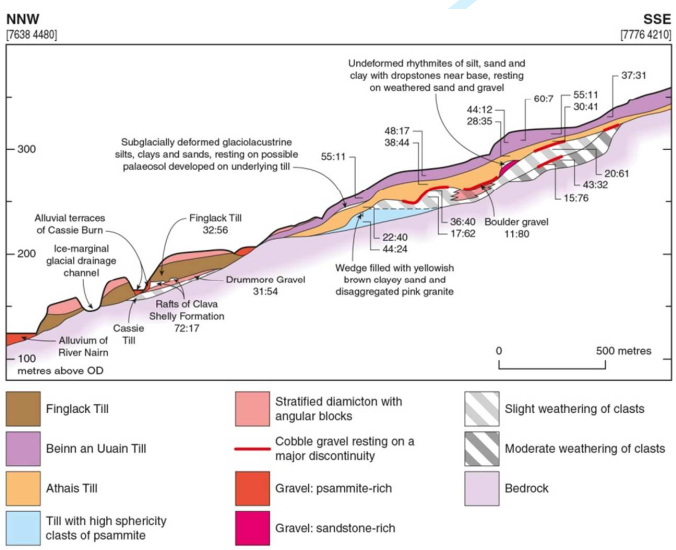


Figure 20 Longitudinal profile of the Allt Carn a'Ghranndaich valley upstream from Clava, E of Inverness, showing multiple, buried and locally weathered Middle Pleistocene till and gravel units (after Fletcher *et al*. 1996).

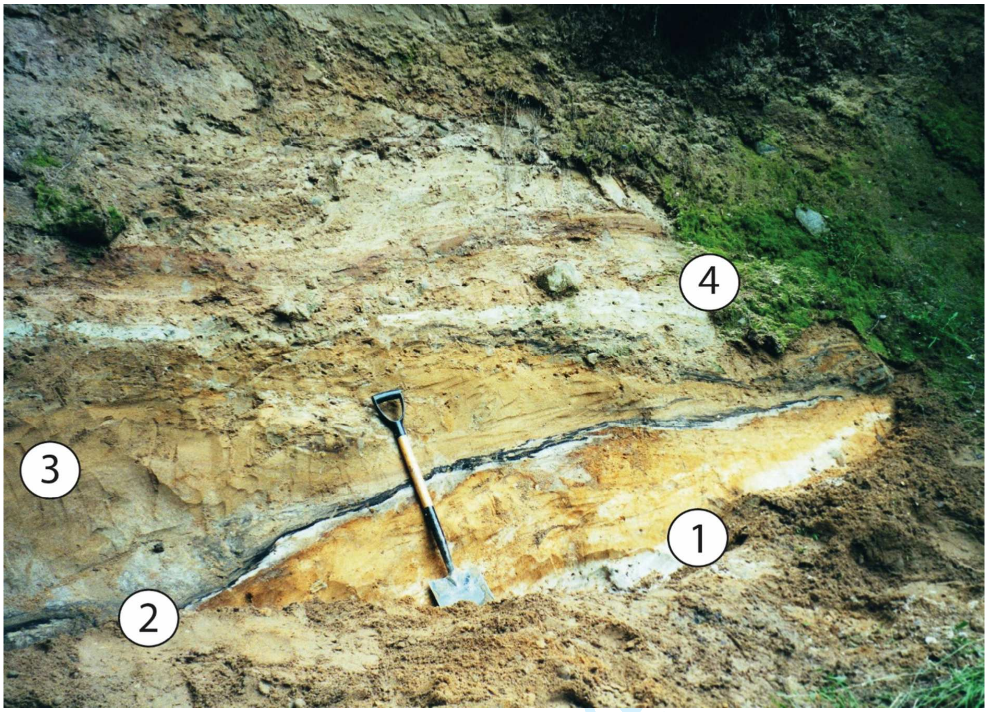


Figure 21 Teindland Quarry in 2000. 1. Teindland Lower Sand, 2. Teindland Buried Soil (MIS 5e). 3. Teindland Upper Sand. 4. Truncated and glacitectonically sheared units beneath overlying Teindland Till.

In the central Grampians, glacilacustrine sediments have been overridden by later ice movements and glacitectonically disturbed (Merritt, 2004; Smith *et al.*, 2011). These deposits locally rest on the Pattack Till Formation, typically a pale to moderate yellowish brown diamict that includes boulders of grey porphyritic granodiorite sourced from the SW (McMillan *et al.*, 2011). When compared to the longer sequences found in the Inverness area, where intervening interglacial and interstadial deposits have been located, the colour, iron staining and weathered condition of many clasts in the Pattack Till suggest that it has been exposed to full interglacial conditions and is pre-Devensian in age. The unit is overlain locally by heavily iron-stained, gravelly deposits that were probably laid down as moraines and ice-proximal fans during retreat of the penultimate ice sheet. This area is transitional between terrains of selective linear glacial erosion, with survival of deep weathering on plateaux (Hall & Mellor, 1988), and more extensively ice-moulded topography where fast-ice flow was directed along the main straths (Smith *et al.*, 2011). The preservation of pre-MIS 5 glacigenic sediments in Glen Pattack on the margin of a zone of ice streaming suggests that older sediments may occur in similar situations elsewhere in the Spey catchment.

The most widespread occurrences of Middle Pleistocene glacial deposits occur in Buchan (Hall & Connell, 1991). Deeply buried tills are recorded in numerous boreholes in the Ellon (Merritt, 1981) and Peterhead (McMillan & Aitken, 1981) areas. Around Kirkhill, the distinctive Fernieslack Palaeosol and the Rottenhill Till (see above) have been traced over a wide area (Hall *et al.*, 1989a). At two sites W of Peterhead, Toddlehills and Savock, complex glacigenic sequences are preserved (Gemmell *et al.*, 2007; Connell, 2015). Both sites lie adjacent to the S-N trending Aldie-Laeca and Dens channel systems (Merritt *et al*. 2003, Map 7; Fig. 13) that were covered by eastward advancing ice early during the late Middle-Late Devensian glaciation (Merritt *et al*. 2017). Correlatives of the Rottenhill

Till Formation (dated to MIS 6 at the Kirkhill/Leys sites) have been recorded at both sites (Figs. 22 and 23) and are overlain by fluvial sands at Toddlehills with a mean OSL age of 85 ka (Gemmell *et al*. 2007), again consistent with deposition of the till during MIS 6. Later, coastal ice advancing northward skirted the area but delivered meltwater northward through the channels into Glacial Lake Ugie. The sequences at Toddlehills escaped erosion at that time as it was on the western flank of the West Dens channel.

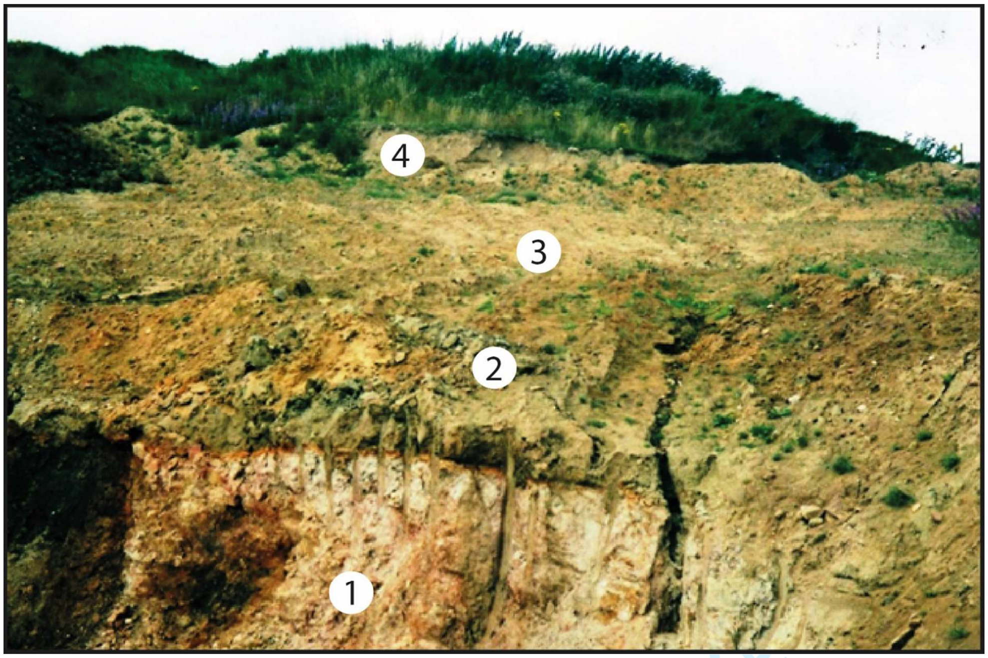


Figure 22 Toddlehills Quarry in 2006, N face. Section ca. 6 m hig. Weathered bedrock (1) is overlain by a till unit (2) correlated with the MIS 6 Rottenhill Till Formation at Kirkhill. OSL dated (mean 85 ka) sands are obscured by made ground in mid-section (3). Late Devensian Hythie Till Formation can be seen higher in the section beneath vegetated made ground (4).

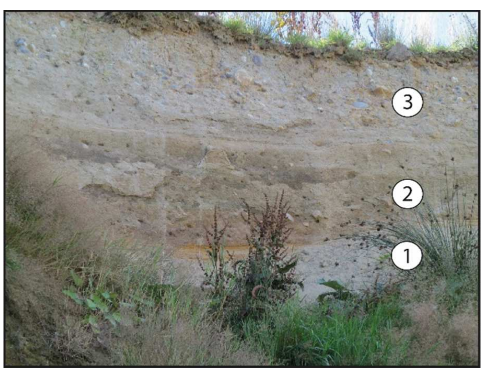


Figure 23 Savock Quarry in 2014. Section ca. 5 m high: 1. Middle Pleistocene sand and gravel channel fill. 2. Brown, possibly weathered till correlated with the MIS 6 Rottenhill Till Formation at Toddlehills, Leys and Kirkhill. 3. Upper clast-rich till correlated with the MIS 3-2 Hythie Till.

Highly mottled, red mud was exposed in a temporary pit [NGR NK 033409] on the north slope of the Moss of Cruden in 1984. A sample from its less weathered base contained palynomorphs typical of the Kimmeridge Clay and also Quaternary forms (L. A. Riley, pers. comm. 1984), indicating an early phase of glacial transport from the Moray Firth. North of Ellon (Fig. 15), the Pitlurg Till was deposited by ice moving S along the present North Sea coast from the Moray Firth. The age of this unit is uncertain, but amino acid ratios from included shells indicate that the till cannot be older than MIS 6. The Bellscamphie Till is the oldest unit identified in the Ellon area. It was deposited by ice moving from the NW or W, probably prior to MIS 5 (Hall & Jarvis, 1995). In western Buchan the Crossbrae Farm Peat bed of probable MIS 5a or 5c age overlies the Crossbrae Till, likely to be of MIS 6 age (Whittington *et al.*, 1998).

Further south, old tills may be present at Aberdeen (Hall & Connell, 1991), a grey till probably derived from the south (Bremner, 1934) and a weathered brown till derived from the west (Synge, 1956, 1963). Most of these tills likely date from MIS 6 and indicate a similar interplay of ice masses in Buchan as occurred in the last glaciation. At Nigg Bay, immediately south of Aberdeen city, a complex glacigenic sequence is exposed in the southern cliffs (Gordon, 1993e). The upper two tills are believed to date to ice advances during the Late Devensian. At the base of the exposed sequence, gravels and sands (the Ness Sand and Gravel Member) have recently provided an OSL age estimate of ~63 ka (Gemmell *et al.*, 2007), suggesting they relate to outwash deposition during an MIS 4 glaciation. Onshore and offshore borehole data indicate that a palaeo-valley form exists immediately N of the cliff section that has been eroded down to -30m O.D. (Merritt *at al*. 2003, Figure 46). It is unclear if this palaeo-channel represents a former course of the River Dee cut during lowered sea level events or has been partially excavated by subglacial processes. It is also unclear if this older valley preserves sediments that pre-date MIS 4. At Ellon, N of Aberdeen, borehole evidence also indicates a rock-cut channel of the River Ythan descending to at least -20m O.D. (Merritt, 1981) and again it is possible that this deep channel preserves pre-Devensian sediments.

South of Stonehaven, near Inverbervie, the Benholm Clay Formation is another old glacigenic sediment, laid down before peat formation in MIS 5 (Fig. 24) (Auton *et al.*, 2000). The Benholm Clay includes striated and polished marine shell fragments, Carboniferous, Early and Late Cretaceous and Palaeogene microfossils, and clasts of limestone, coal, chalk and flint derived from offshore in the North Sea basin (Auton *et al.*, 2000). It was laid down by ice that moved onshore during a post-Anglian and pre-Devensian glacial episode. Amino acid (D/L) ratios of ca. 0.34 have been obtained from fragments of the marine mollusc *Arctica islandica*, which indicate that they are of MIS 9 age, or older (Auton *et al.*, 2000). The clay was possibly derived from overridden sediments at the base of the Coal Pit Formation, or might represent the onshore feather edge of a till occurring in the Fisher Formation, generally considered to be of Saalian (MIS 6 – 10) age (Gatliff *et al.*, 1994).

Comment [AH3]: High res version now available.

Figure 24 Sheared lens of the Burn of Benholm Peat Bed within olive grey shelly clay and diamicton (Benholm Clay Formation) at Burn of Benholm. The shelly deposits are overlain by red-brown diamicton of the Late Devensian Mill of Forest Till Formation.

In the lower Clyde and the upper Forth lowlands, the Geological Memoirs refer to borehole records that show thicknesses of Pleistocene sediment that locally exceed 100 m (Clough *et al.*, 1925; Francis *et al.*, 1970; Paterson *et al.*, 1990; Forsyth *et al.*, 1996; Hall *et al.*, 1998). Only the upper part of these sediment accumulations is of Late Devensian age (Browne & McMillan, 1989). Tills of likely MIS 4 age, the Ballieston Till Formation in the Clyde basin, and the Littlestone Till Formation in Ayrshire, occur widely (Finlayson *et al.*, 2010) but the stratigraphy and age of older sediments below these tills remain poorly known (Sutherland, 1984).

6.3 Significance of the Middle Pleistocene terrestrial stratigraphic record

The Pleistocene stratigraphical record in Scotland includes glacigenic deposits and periglacial features that represent cold stages back at least to MIS 8, together with terrestrial sediments with a floral, faunal or pedological record of interstadial and interglacial conditions. Whilst Middle Pleistocene sediments are sparse or absent across wide areas of Scotland and are poorly dated generally, the stratigraphic record is important for the direct information it can provide on the pattern and sequence of environmental change on the land area. The increasingly detailed and nuanced interpretations of palaeoenvironmental proxies for the modern, post-glacial and late glacial periods in Scotland can be applied also to the fragmentary evidence of earlier periods. Periglacial sediments also provide a wealth of data on palaeo-temperatures and palaeo–precipitation (Ballantyne & Harris, 1994) and constrain former ice extent and thickness (Fabel *et al.*, 2012). Marine sediments and landforms from MIS 5 and perhaps earlier periods indicate former sea levels and wave environments (Smith *et al.*, 2018).

Glacial deposits older than MIS 5 allow constraints to be placed on former ice extent, dynamics and flow paths that can be compared with those of the last glacial cycle. The basal sediments of the Kirkhill sequence represent an interglacial-cold interstadial- stadial cycle that probably predates MIS 7. The sequence includes glacial and glacifluvial deposits that derive both from inland and from the North Sea coast. Patterns of ice flow in eastern Buchan were similar to those in later phases in MIS 6 and MISs 3-2 (Merritt *et al.*, 2017). In MIS 6, ice in northern Shetland was moving towards the NW, as in the Shetland ice cap in MIS 3-2 (Hall, 2013). Cnoc-and-lochain terrain had already formed on the Lewisian gneisses (Chapelhowe, 1965). In Caithness, till units record movements of inland and Moray Firth ice. The tills sit in bedrock depressions that are part of the streamlined bedrock terrain of the plain of Caithness and indicate that streamlining of bedrock was present before MIS 5 (Hall, 2013). In NW Lewis, the presence of Torridonian and Cambrian clasts in a weathered till indicate the operation of the Minch Ice Stream in MIS 6. Carry of these and other erratics further S may indicate that the mainland ice sheet crossed parts of the Outer Hebrides in MIS 6 (Flinn, 1978a). Across Moray and into lower Strath Spey, till fabrics and erratics for likely MIS 6 tills indicate similar pattern of ice flow as for MIS 3-2 (Merritt *et al.*, 2000) In Buchan, MIS 6 tills appear to have all been derived from inland. Extensive W-E flow is indicated that is consistent with granitic, schistose, basic igneous and red sandstone clast assemblages found in a Saalian till in the Fladen area derived from NE Scotland (Sejrup *et al.*, 1987). Combined evidence from blockfields and tors and glacial sediments indicates that the configuration, thermal regime and ice flow during MIS 6 were broadly comparable to those of the last ice sheet.

7. Conclusions and Next Steps

The Early and Middle Pleistocene periods in Scotland have received little previous specific attention despite a combined duration that far exceeds that of the last glacial cycle. Yet the 25 years since the publication of the *Quaternary of Scotland* Geological Conservation Review (GCR) volume (Gordon & Sutherland 1993b) have seen substantial advances in understanding the changing environments, developing landforms and terrestrial stratigraphy for this period in Scotland and on other glaciated passive margins.

The topography of Scotland retains landscapes – mountain blocks and peripheral lowlands - and large landforms – hills, basins and straths - that are of Neogene and older origin. This antecedent topography was modified and, in places, transformed by Pleistocene glacial and non-glacial processes. Glaciers were the dominant agents, made manifest by the frequency and size of glacial valleys and corries and by the extent of glacially dissected, roughened and streamlined terrain. Large areas of terrain, mainly in eastern areas and at higher elevations, lack well-developed glacial bedforms and were regarded previously as relict, pre-Pleistocene surfaces. Initial results from cosmogenic isotope inventories indicate, however, widespread non-glacial erosion on these surfaces through the Pleistocene. Mountain-top detritus and small landforms, such as tors, are dynamic features, maintained through the Middle and Late Pleistocene by weathering and erosion. Two research challenges are apparent: (i) to better constrain the landforms and tectonic, weathering and denudation history of Neogene landscapes; and (ii) to identify the spatial and temporal variability of erosion rates between and within zones of glacial erosion through the Pleistocene.

The Early Pleistocene was dominated by alternating 40 ka cycles of stadial conditions, with mountain ice cap and permafrost development to low elevations, and interstadial/interglacial conditions, without large glaciers and with cool to temperate conditions in the Scottish lowlands. After 1.2 Ma, a transition to 100 ka cycles led to the first advances of large ice sheets into the North Sea and onto the North Atlantic shelf. The sedimentary record from the shelves around Scotland is now yielding increasingly detailed information about the timing and extent of ice sheets before the last glacial cycle (Stewart *et al*. 2018). Glacial deposits and landforms in the North Sea and East Anglia can be correlated with ice advances in most of the main cold stages of the Middle Pleistocene but only the latest 4 to 5 Middle to Late Pleistocene advances are yet apparent from the terrestrial stratigraphic record in Scotland.

The British-Irish Ice Sheet was highly dynamic due to a position on the North Atlantic margin with high snowfall and air temperatures close to freezing point. Extension on to shallow shelves around Scotland made successive ice sheets vulnerable to rapid retreat under rising sea levels (Clark *et al.*, 2012). Two modes of ice sheet behaviour, with development of mountain ice caps and full ice sheets, are apparent in ice sheet models (Golledge *et al.*, 2008; Hubbard *et al.*, 2009) but should be explored for a wider range of climate scenarios to match the likely range of conditions earlier in the Pleistocene. The distributions of glacially roughened and streamlined terrain, over-deepened valleys and thick tills are consistent with bimodal ice extent and dynamics.

The impact of glaciers in modifying the pre-glacial topography of Scotland varied in space and time. Glacier basal thermal regimes, influenced strongly by W-E climatic gradients and also by varied substrates and topography, exerted a fundamental control over erosion patterns. Beneath mountain ice caps in western Scotland, warm-based, fast ice flow discharged via narrow and steep-sided glens with high-gradient floors and led to valley over-deepening and to advanced dissection of relief. Similar conditions may have prevailed under these and other ice sheet source areas during short phases of ice drawdown. During the slow build-up of ice sheets, however, the ice remained mainly cold-based and non-erosive. In the eastern lowlands, of which Buchan is the type area, and at higher elevations, glacier ice remained cold-based throughout multiple glacial cycles, allowing the preservation of delicate non-glacial landforms and materials. In extensive intermediate terrain, the impact of glacial erosion was limited by the short duration of warm-based conditions. Next steps involve further mapping and dating of the complex mosaics of Early and Middle Pleistocene landforms and landscapes found across Scotland. Recent advances in reconstructing the pattern of the last deglaciation across Scotland have demonstrated the potential of digital elevation models for comprehensive mapping of glacial bedforms (Hughes *et al.*, 2010; Hughes *et al.*, 2014), an approach that can be extended to include older glacial landscapes and landforms. Zones of glacial erosion also can be reassessed using LIDAR and other remote sensing data to map landforms, relief and terrain roughness (Grohmann *et al.*, 2011; Krabbendam & Bradwell, 2013) and to link morphometry to rock type, fracturing (Krabbendam & Bradwell, 2011) and glacial sediment distribution. Recognition of reference surfaces or landforms with little or no glacial erosion allows estimation of glacial erosion depths in neighbouring terrain using space-time transformations (Ebert *et al.*, 2015). Depths of erosion can be converted to long-term average rates of erosion using the duration of non-glacial and glacial conditions indicated by regional temperature proxies (Hall *et al.*, 2013a). Estimates of rock removal from different zones of glacial erosion across Scotland through the Pleistocene provide opportunities for calculating source to sink budgets using sediment volumes offshore for locations such as the Sula Sgeir Fan, where source and sink are well-defined (Stoker & Bradwell, 2005) and for examining the potential contribution of Pleistocene erosion to isostasy and uplift (Nielsen *et al.*, 2009).

There is great potential to use cosmogenic nuclides to explore long-term erosion rates for both glacial and non-glacial landforms found within different zones of glacial erosion (Stroeven *et al.*, 2002). ^{10}Be and ^{26}Al cosmogenic nuclide inventories inherited from exposure before MIS 3-2 glaciation are widely reported from glacially eroded bedrock surfaces in Fennoscandia (Stroeven *et al.*, 2016) and known to be present in Scotland (Stone *et al.*, 1998; Stone & Ballantyne, 2006; Phillips *et al.*, 2008; Fame *et al.*, 2018). This approach offers the prospect of testing the widespread assumption that rock landforms, such as roches moutonnées (Hall, 2013), streamlined ridges (Salt & Evans, 2004; Bradwell *et al.*, 2008a) and large meltwater channels (Greenwood *et al.*, 2007) are mainly products of erosion beneath the last ice sheet. Long-term average rates of erosion also may be derived from studies of muogenic nuclide inventories at depths below ~2.5 m in bedrock (Briner *et al.*, 2016) and from inherited ^{10}Be and ^{26}Al in deeply buried tills (Ebert *et al.*, 2012; Fame *et al.*, 2018).

Much further work is needed to link non-glacial landforms to rock properties and processes (Hopkinson & Ballantyne, 2014). The rates at which non-glacial processes operated over the Early and Middle Pleistocene in Scotland are also poorly known. More attention can be given to the subsurface where reactions between minerals and oxidising and reducing groundwater in saprolites and fracture zones have produced indicator secondary minerals. Emerging techniques that allow dating of minerals formed above and below the redox front allow the residence times of the minerals and the depth of post-formational erosion to be estimated. For example, age estimates can be derived from meteoric ^{10}Be inventories in saprolites (Ebert *et al.*, 2012; Duxbury *et al.*, 2015), K-Ar dating of authigenic illite soil clays (Fredin *et al.*, 2017) and Mn oxides (Dill *et al.*, 2010b) and high-resolution mass spectrometry of U phosphates and silicates (Dill *et al.*, 2010a). In zones of low glacial erosion, cosmogenic nuclide inventories from depth profiles in quarries and tor interiors (Bierman & Caffee, 2002), on quartz veins in MTD (Portenga *et al.*, 2013) and on dissected, till-covered shore platforms (Saillard *et al.*, 2009) also have potential for establishing erosion rates across a variety of geomorphological settings.

The search for new Middle Pleistocene sedimentary records on land in Scotland has slowed in recent decades but stratotype sequences, such as at Kirkhill, Dalcharn and in the Assynt caves, illustrate the potential value of these environmental archives. Pitting and drilling surveys are needed where complex sequences of Pleistocene sediments, including organic materials, are known to occur in the near-surface and at depth (Sutherland, 1984). Continuing efforts are needed to link offshore and terrestrial sedimentary records by improved stratigraphic control and dating, provenance studies (Busfield *et al.*, 2015), palynology (Lee *et al.*, 2002; Mudie & McCarthy, 2006) and new amino acid analyses of marine molluscs (Reinardy *et al.*, 2017). In dating, a major challenge ahead lies in extending the timeframe of the BRITICE Glacial Mapping Project beyond the last MIS 3-2 glaciation (Clark *et al.*, 2018) to examine earlier events. A major difficulty lies, however, in the limited constraints on the ages of sediments beyond the range of radiocarbon dating. Tephrochronology is increasingly important in dating post-glacial sediments (Lowe, 2016) but checks for the presence of tephra in older sediments are not routine. For glacigenic sediment sequences, there is a pressing need to revisit and extend earlier luminescence dating of sandy sediments intercalated with tills (Duller *et al.*, 1995; Gemmell *et al.*, 2007). This would require clear objectives and the need to experiment with potentially new luminescence techniques to provide robust chronologies in order to match, for example, those available for the Middle and Late Pleistocene sequences in northern Germany (Roskosch *et al.*, 2014) and Finland (Pitkäranta, 2009). Deeply buried old tills and palaeosols can also be dated using multiple cosmogenic nuclides (Balco *et al.*, 2005b; Balco *et al.*, 2005c). The complex relationships that exist between the deposition of multiple till units and ice flow phases can be further examined by detailed analysis of till mineralogy and clast content (McMartin & McClenaghan, 2001). Where transport distances for till constituents are short, glacial erosion is likely to be limited in depth (Salonen, 1986) or restricted in its duration.

Improved control over the ages of sediments, soils and saprolites and on long-term rates of weathering and erosion, combined with information on palaeoenvironments, ice extent and sea level, will allow future testing and calibration of new mathematical models of Early and Middle Pleistocene ice dynamics, isostasy, sea-level change, permafrost and non-glacial process impacts. A shift of focus away from the chronology and pattern of the last glaciation in Scotland is overdue. Emerging dating techniques applied to a wider range of materials and landforms have potential to greatly improve our understanding of weathering, erosion and landscape development over 0.1-10 Ma timescales in Scotland.

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References

Andersen, J. L., Egholm, D. L., Knudsen, M. F., Linge, H., Jansen, J. D., Pedersen, V. K., Nielsen, S. B., Tikhomirov, D., Olsen, J. & Fabel, D. (2018) Widespread erosion on high plateaus during recent glaciations in Scandinavia. *Nature Communications* **9**, 830.

André, M.-F. (2004) The geomorphic impact of glaciers as indicated by tors in North Sweden (Aurivaara, 68º N). *Geomorphology* **57**, 403-421.

Andrews, I. J., Long, D., Richards, P. C., Thomson, A. R., Brown, S., Chesher, J. A. & McCormac, M. 1990. *United Kingdom Offshore Regional Report: the geology of the Moray Firth*. London: HMSO for the British Geological Survey.

Anne, C., Naki, A., Susan, I.-O., Fritz, S., Peter, K. W., Andreas, D., Joachim, K., Meinert, R. & Christian, S. (2017) Timing of early Quaternary gravel accumulation in the Swiss Alpine Foreland. *Geomorphology* **276**, 71-85.

Audsley, A., Arosio, R. & Howe, J. A. (2016) A geomorphological reconstruction of the deglaciation of Loch Etive during the Loch Lomond Stadial. *Scottish Journal of Geology* **52**, 55-63.

Augustinus, P. C. & Macphail, M. K. (1997) Early Pleistocene stratigraphy and timing of the Bulgobac Glaciation, Western Tasmania, Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **128**, 253-267.

Auton, C. A., Gordon, J. E., Merritt, J. W. & Walker, M. J. C. (2000) The glacial and interstadial sediments at the Burn of Benholm, Kincardineshire: evidence for onshore pre-Devensian ice movement in northeast Scotland. *Journal of Quaternary Science* **15**, 141-156.

Bailey, I., Hole, G. M., Foster, G. L., Wilson, P. A., Storey, C. D., Trueman, C. N. & Raymo, M. E. (2013) An alternative suggestion for the Pliocene onset of major Northern Hemisphere glaciation based on the geochemical provenance of North Atlantic Ocean ice-rafted debris. *Quaternary Science Reviews* **75**, 181-194.

Bain, D. C., Mellor, A., Robertson-Rintoul, M. & Buckland, S. (1993) Variations in weathering processes and rates with time in a chronosequence of soils from Glen Feshie, Scotland. *Geoderma* **57**, 275-293.

Balco, G. & Rovey, C. W. (2010) Absolute chronology for major Pleistocene advances of the Laurentide Ice Sheet. *Geology* **38**, 795-798.

Balco, G., Rovey, C. W. & Stone, J. O. H. (2005a) The First Glacial Maximum in North America. *Science* **307**, 222.

Balco, G., Stone, J. O. & Mason, J. A. (2005b) Numerical ages for Plio-Pleistocene glacial sediment sequences by 26 Al/10 Be dating of quartz in buried paleosols. *Earth and Planetary Science Letters* **232**, 179-191.

Balco, G., Stone, J. O. H. & Jennings, C. (2005c) Dating Plio-Pleistocene glacial sediments using the cosmic-ray-produced radionuclides Be-10 and Al-26. *American Journal of Science* **305**, 1-41.

Ballantyne, C. K. (1984) The Late Devensian periglaciation of upland Scotland. *Quaternary Science Reviews* **3**, 10-30.

Ballantyne, C. K. (1994a) Gibbsitic soils on former nunataks: implications for ice sheet reconstruction. *Journal of Quaternary Science* **9**, 73-80.

Ballantyne, C. K. (1994b) Scottish Landform Examples - 10: the tors of the Cairngorms. *Scottish Geographical Magazine* **110**, 54-59.

Ballantyne, C. K. (1997) Periglacial trimlines in the Scottish Highlands. *Quaternary International* **38/39**, 119-136.

Ballantyne, C. K. (1998) Age and signficance of mountain-top detritus. *Permafrost and Periglacial Processes* **9**, 327-345.

Ballantyne, C. K. (2000) A Late Devensian nunatak on the Knoydart Peninsula, NW Scotland: Implications for ice-sheet reconstruction. *Scottish Geographical Magazine* **115**, 319-328.

Ballantyne, C. K. (2002) Paraglacial geomorphology. *Quaternary Science Reviews* **21**, 1935-2017.

Ballantyne, C. K. (2010a) Extent and deglacial chronology of the last British-Irish Ice Sheet: implications of exposure dating using cosmogenic isotopes. *Journal of Quaternary Science* **25**, 515-534.
Ballantyne, C. K. (2010b) A general model of autochthonous blockfield evolution. *Permafrost and Periglacial Processes* **21**.
Ballantyne, C. K. (2013) Lateglacial Rock-Slope Failures in the Scottish Highlands. *Scottish Geographical Journal* **129**, 67-84.
Ballantyne, C. K., Fabel, D., Gheorghiu, D., Rodés, Á., Shanks, R. & Xu, S. (2017) Late Quaternary glaciation in the Hebrides sector of the continental shelf: cosmogenic nuclide dating of glacial events on the St Kilda archipelago. *Boreas*.
Ballantyne, C. K. & Hall, A. M. (2008) The altitude of the last ice sheet in Caithness and east Sutherland, Northern Scotland. *Scottish Journal of Geology* **44**, 169-181.
Ballantyne, C. K., Hall, A. M., Phillips, W. M., Binnie, S. & Kubik, P. (2007) Age and significance for former low-altitude corrie glaciers on Hoy, Orkney Islands. *Scottish Journal of Geology* **43**, 107-114.
Ballantyne, C. K. & Hallam, G. E. (2001) Maximum altitude of Late Devensian glaciation on South Uist, Outer Hebrides, Scotland. *Proceedings of the Geologists Association* **112**, 155-167.
Ballantyne, C. K. & Harris, C. 1994. *The Periglaciation of Great Britain*: Cambridge University Press.
Ballantyne, C. K., McCarroll, D., Nesje, A. & Dahl, S. O. (1997) Periglacial trimlines, former nunataks and the altitude of the last ice sheet in Wester Ross, northwest Scotland. *Journal of Quaternary Science* **12**, 225-238.
Ballantyne, C. K., McCarroll, D., Nesje, A., Dahl, S. O. & Stone, J. O. (1998) The last ice sheet in north-west Scotland: reconstruction and implications. *Quaternary Science Reviews* **17**, 1149-1184.
Ballantyne, C. K. & Small, D. (2018) The last ice sheet in Scotland. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 1-39.
Ballantyne, C. K., Wilson, P., Gheorghiu, D. & Rodés, À. (2013) Enhanced rock-slope failure following ice-sheet deglaciation: timing and causes. *Earth Surface Processes and Landforms*, n/a-n/a.
Barr, I. D., Ely, J. C., Spagnolo, M., Clark, C. D., Evans, I. S., Pellicer, X. M., Pellitero, R. & Rea, B. R. (2017) Climate patterns during former periods of mountain glaciation in Britain and Ireland: Inferences from the cirque record. *Palaeogeography, Palaeoclimatology, Palaeoecology*.
Bartsch, A., Gude, M. & Gurney, S. (2009) Quantifying sediment transport processes in periglacial mountain environments at a catchment scale using geomorphic process units. *Geografiska Annaler: Series A, Physical Geography* **91**, 1-9.
Batchelor, C. L., Ottesen, D. & Dowdeswell, J. A. (2017) Quaternary evolution of the northern North Sea margin through glacigenic debris-flow and contourite deposition. *Journal of Quaternary Science* **32**, 416-426.
Bendixen, C., Lamb, R. M., Huuse, M., Boldreel, L. O., Jensen, J. B. & Clausen, O. R. (2017) Evidence for a grounded ice sheet in the central North Sea during the early Middle Pleistocene Donian Glaciation. *Journal of the Geological Society*, jgs2017-2073.
Bierman, P. R. (1994) Using in situ produced cosmogenic isotopes to estimate rates of landscape evolution; a review from the geomorphic perspective. *Journal of Geophysical Research, B, Solid Earth and Planets* **99**, 13885-13896.
Bierman, P. R. & Caffee, M. (2002) Cosmogenic exposure and erosion history of Australian bedrock landforms. *Geological Society of America Bulletin* **114**, 787-803.
Bloodworth, A. J. (1990) Clay mineralogy of Quaternary sediments from the Dalcharn Interglacial site, *In*: Auton, C. A. & Firth, C. R., & Merritt, J. W. (eds), *Beauly to Nairn, Field Guide*, 60-61. Cambridge: Quaternary Research Association.
Blyth, F. G. H. (1969) Structures in the southern part of the Cabrach igneous area, Banffshire. *Proceedings of the Geologists' Association* **80**, 63-79.
Boardman, J. (1985) The Troutbeck Palaeosol, Cumbria England, *In*: Boardman, J. (ed), *Soils and Quaternary landscape evolution*, 231-260. London: Wiley.

Boulton, G. S. & Hagdorn, M. (2006) Glaciology of the British Isles Ice Sheet during the last glacial cycle: form, flow, streams and lobes. *Quaternary Science Reviews* **25**, 3359-3390.
Boulton, G. S. & Jones, A. S. (1979) Stability of temperate ice caps and ice sheets resting on beds of deformable sediment. *Journal of Glaciology* **24**, 29-44.
Bowen, D. Q. (1991) Time and space in the glacial sediment systems of the British Isles., *In*: Ehlers, J. & Gibbard, P. L., & Rose, J. (eds), *Glacial deposits in Great Britain and Ireland.*, 3-12. Rotterdam: Balkema.
Bowen, D. Q. & Sykes, G. A. (1988) Correlation of marine events and glaciations on the north-east Atlantic margin. *Philosophical Transactions of the Royal Society of London* **B318**, 619-635.
Bradwell, T., Stoker, M. & Krabbendam, M. (2008a) Megagrooves and streamlined bedrock in NW Scotland: the role of ice streams in landscape evolution. *Geomorphology* **97**, 135-156.
Bradwell, T., Stoker, M. S., Golledge, N. R., Wilson, C., Merrit, J. W., Long, D., Everest, J. D., Hestvik, O. B., Stevenson, A., Hubbard, A., Finlayson, A. & Mathers, H. (2008b) The northern sector of the Last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews* **88**, 207-226.
Bradwell, T., Stoker, M. S. & Larter, R. (2007) Geomorphological signature and flow dynamics of The Minch palaeo-ice stream, northwest Scotland. *Journal of Quaternary Science* **22**, 609-617.
Bremner, A. (1934) The glaciation of Moray and ice movements in the north of Scotland. *Transactions of the Edinburgh Geological Society* **13**, 17-56.
Bridgland, D. R., Howard, A. J., White, M. J., White, T. S. & Westaway, R. (2015) New insight into the Quaternary evolution of the River Trent, UK. *Proceedings of the Geologists' Association* **126**, 466-479.
Bridgland, D. R., Saville, A. & Sinclair, J. M. (1997) New evidence for the origin of the Buchan Ridge Gravel, Aberdeenshire. *Scottish Journal of Geology* **33**, 43-50.
Briner, J. P., Goehring, B. M., Mangerud, J. & Svendsen, J. I. (2016) The deep accumulation of ^{10}Be at Utsira, southwestern Norway: implications for cosmogenic nuclide exposure dating in peripheral ice sheet landscapes. *Geophysical Research Letters* **43**, 9121-9129.
Brown, E. J., Rose, J., Coope, R. G. & Lowe, J. J. (2006) An MIS 3 age organic deposit from Balglass Burn, central Scotland: palaeoenvironmental significance and implications for the timing of the onset of the LGM ice sheet in the vicinity of the British Isles. *Journal of Quaternary Science* **22**, 295-308.
Browne, M. A. E. & McMillan, A. A. 1989. *Quaternary Geology of the Clyde valley*: British Geological Survey.
Buckley, F. A. (2017) A glaciogenic sequence from the Early Pleistocene of the Central North Sea. *Journal of Quaternary Science* **32**, 145-168.
Burke, M. J. (1969) The Forth valley: an ice-moulded lowland. *Transactions of the Institute of British Geographers* **48**, 51-59.
Busfield, M. E., Lee, J. R., Riding, J. B., Zalasiewicz, J. & Lee, S. V. (2015) Pleistocene till provenance in east Yorkshire: reconstructing ice flow of the British North Sea Lobe. *Proceedings of the Geologists' Association* **126**, 86-99.
Cambridge, P. G. (1982) A note on the supposed Crag shells from the Kippett Hills, Aberdeenshire. *Bulletin of the Geological Society of Norfolk* **32**, 37-38.
Cameron, T. D. J., Stoker, M. S. & Long, D. (1987) The history of Quaternary sedimentation in the UK sector of the North Sea basin. *Journal of the Geological Society* **144**, 43-58.
Cave, J. A. S. & Ballantyne, C. K. (2016) Catastrophic Rock-Slope Failures in NW Scotland: Quantitative Analysis and Implications. *Scottish Geographical Journal* **132**, 185-209.
Chapelhowe, R. (1965) On the glaciation in North Roe, Shetland. *Geographical Journal* **131**, 60-70.
Clapperton, C. M. (1997) Greenland Ice Cores and North Atlantic Sediments: Implications for the Last Glaciation in Scotland, *In*: Gordon, J. E. (ed), *Reflections on the Ice Age in Scotland*, 45-58. Edinburgh: Scottish Natural Heritage.
Clapperton, C. M. & Sugden, D. E. (1977) The Late Devensian glaciation of north-east Scotland, *In*: Gray, J. M., & Lowe, J. J. (eds), *Studies in the Scottish Lateglacial environment*, 1-13. Oxford: Pergamon.

Clark, C. D., Ely, J. C., Greenwood, S. L., Hughes, A. L. C., Meehan, R., Barr, I. D., Bateman, M. D., Bradwell, T., Doole, J., Evans, D. J. A., Jordan, C. J., Monteys, X., Pellicer, X. M. & Sheehy, M. (2018) BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British-Irish Ice Sheet. *Boreas* **47**, 11-e18.
Clark, C. D., Hughes, A. L. C., Greenwood, S. L., Jordan, C. J. & Sejrup, H.-P. (2012) Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews* **44**, 112-146.
Clark, P. U., Archer, D., Pollard, D., Blum, J. D., Rial, J. A., Brovkin, V., Mix, A. C., Pisias, N. G. & Roy, M. (2006) The middle Pleistocene transition: characteristics, mechanisms, and implications for long-term changes in atmospheric CO_2. *Quaternary Science Reviews* **25**, 3150-3184.
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. (2009) The last glacial maximum. *Science* **325**, 710-714.
Clark, P. U. & Pollard, D. (1998) Origin of the middle Pleistocene transition by ice sheet erosion of regolith. *Palaeoceanography* **13**, 1-9.
Clayton, K. (1996) Quantification of the impact of glacial erosion on the British Isles. *Transactions of the Institute of British Geographers NS* **21**, 124-140.
Clayton, K. M. (1974) Zones of glacial erosion, *In*: Brown, E. H., & Waters, R. S. (eds), *Institute of British Geographers Special Publication*, 163-176.
Clough, C. T., Hinxman, L. W., Wilson, J. S. G., Crampton, C. B., Wright, W. B., Bailey, E. B., Anderson, E. M., Carruthers, R. G. & Grabham, G. W. 1925. *The geology of the Glasgow District*: HM Stationery Office.
Connell, E. R. (2015) The Pleistocene sediments at Savock Quarry, Buchan, NE Scotland. *Quaternary Newsletter* **136**, 22-25.
Connell, E. R., Edwards, K. J. & Hall, A. M. (1982) Evidence for two pre-Flandrian palaeosols in Buchan, Scotland. *Nature* **297**, 570-572.
Connell, E. R. & Hall, A. M. (1987) The periglacial history of Buchan, Scotland., *In*: Boardman, J. (ed), *Periglacial Processes and Landforms in Britain and Ireland.*, 277-285. Cambridge: Cambridge University Press.
Connell, E. R., Hall, A. M. & Romans, J. C. C. (1984) Kirkhill Quarry, *In*: Hall, A. M. (ed), *Buchan Field Guide*, 57-81. Cambridge: Quaternary Research Association.
Connell, E. R. & Romans, J. C. C. (1984) Palaeosols, *In*: Hall, A. M. (ed), *Buchan Field Guide*, 70-76. Cambridge: Quaternary Research Association.
Crampton, C. B. & Carruthers, R. G. 1914. *The geology of Caithness*. Edinburgh: Geological Survey of Scotland.
Crest, Y., Delmas, M., Braucher, R., Gunnell, Y. & Calvet, M. (2017) Cirques have growth spurts during deglacial and interglacial periods: Evidence from 10Be and 26Al nuclide inventories in the central and eastern Pyrenees. *Geomorphology* **278**, 60-77.
Croll, J. 1875. *Climate and Time in their Geological Relations.* London: Daldy.
Dethier, D. P. & Lazarus, E. D. (2006) Geomorphic inferences from regolith thickness, chemical denudation and CRN erosion rates near the glacial limit, Boulder Creek catchment and vicinity, Colorado. *Geomorphology* **75**, 384-399.
Dickin, A., Moorbath, S. & Welke, H. (1981) Isotope, trace element and major element geochemistry of Tertiary igneous rocks, Isle of Arran, Scotland. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* **72**, 159-170.
Dill, H. G., Gerdes, A. & Weber, B. (2010a) Age and mineralogy of supergene uranium minerals—tools to unravel geomorphological and palaeohydrological processes in granitic terrains (Bohemian Massif, SE Germany). *Geomorphology* **117**, 44–65.
Dill, H. G., Hansen, B., Keck, E. & Weber, B. (2010b) Cryptomelane: A tool to determine the age and the physical–chemical regime of a Plio-Pleistocene weathering zone in a granitic terrain (Hagendorf, SE Germany). *Geomorphology* **121**, 370-377.

Dove, D., Arosio, R., Finlayson, A., Bradwell, T. & Howe, J. A. (2015) Submarine glacial landforms record Late Pleistocene ice-sheet dynamics, Inner Hebrides, Scotland. *Quaternary Science Reviews* **123**, 76-90.
Dowdeswell, J. & Ottesen, D. (2013) Buried iceberg ploughmarks in the early Quaternary sediments of the central North Sea: A two-million year record of glacial influence from 3D seismic data. *Marine Geology* **344**, 1-9.
Duller, G. A. T., Wintle, A. G. & Hall, A. M. (1995) Luminescence dating and its application to key pre-Late Devensian sites in Scotland. *Quaternary Science Reviews* **14**, 495-519.
Duxbury, J., Bierman, P. R., Portenga, E. W., Pavich, M. J., Southworth, S. & Freeman, S. P. H. T. (2015) Erosion rates in and around Shenandoah National Park, Virginia, determined using analysis of cosmogenic 10Be. *American Journal of Science* **315**, 46-76.
Dypvik, H. (1983) Clay mineral transformations in Tertiary and Mesozoic sediments from North Sea. *AAPG bulletin* **67**, 160-165.
Ebert, K., Hall, A. M., Kleman, J. & Andersson, J. (2015) Unequal ice sheet erosional impacts across low-relief shield terrain in northern Fennoscandia. *Geomorphology* **233**, 64-74.
Ebert, K., Hättestrand , C., Hall, A. M. & Alm, G. (2011) DEM identification of macro-scale stepped relief in arctic northern Sweden. *Geomorphology* **132**, 339-350.
Ebert, K., Willenbring, J. K., Norton, K. P., Hall, A. M. & Hättestrand, C. (2012) Meteoric ^{10}Be concentrations from saprolite and till in northern Sweden saprolite: Implications for genesis and age. *Quaternary Geochronology* **12**, 11-22.
Egholm, D. L., Jansen, J. D., Brædstrup, C. F., Pedersen, V. K., Andersen, J. L., Ugelvig, S. V., Larsen, N. K. & Knudsen, M. F. (2017) Formation of plateau landscapes on glaciated continental margins. *Nature Geoscience*.
Eldrett, J. S., Harding, I. C., Wilson, P. A., Butler, E. & Roberts, A. P. (2007) Continental ice in Greenland during the Eocene and Oligocene. *Nature* **446**, 176-179.
Etzelmuller, B., Romstad, B. & Fjellanger, J. (2007) Automatic regional classification of topography in Norway. *Norsk Geologisk Tidsskrift* **87**, 167-180.
Evans, D. J. & Hansom, J. D. (1996) The Edinburgh Castle crag-and-tail. *Scottish Geographical Magazine* **112**, 129-131.
Everest, J. D., Bradwell, T. & Golledge, N. R. (2007) Subglacial Landforms of the Tweed Palaeo-Ice Stream. *Scottish Geographical Journal* **121**, 163-173.
Fabel, D., Ballantyne, C. K. & Xu, S. (2012) Trimlines, blockfields, mountain-top erratics and the vertical dimensions of the last British–Irish Ice Sheet in NW Scotland. *Quaternary Science Reviews* **55**, 91-102.
Fame, M. L., Owen, L. A., Spotila, J. A., Dortch, J. M. & Caffee, M. W. (2018) Tracking paraglacial sediment with cosmogenic 10Be using an example from the northwest Scottish Highlands. *Quaternary Science Reviews* **182**, 20-36.
Finlayson, A., Fabel, D., Bradwell, T. & Sugden, D. (2014) Growth and decay of a marine terminating sector of the last British–Irish Ice Sheet: a geomorphological reconstruction. *Quaternary Science Reviews* **83**, 28-45.
Finlayson, A., Merritt, J., Browne, M., Merritt, J., McMillan, A. & Whitbread, K. (2010) Ice sheet advance, dynamics, and decay configurations: evidence from west central Scotland. *Quaternary Science Reviews* **29**, 969-988.
Firth, C. R. & Stewart, I. S. (2000) Postglacial tectonics of the Scottish glacio-isostatic uplift centre. *Quaternary Science Reviews* **19**, 1469-1493.
Flesche Kleiven, H., Jansen, E., Fronval, T. & Smith, T. (2002) Intensification of Northern Hemisphere glaciations in the circum Atlantic region (3.5–2.4 Ma) – ice-rafted detritus evidence. *Palaeogeography, Palaeoclimatology, Palaeoecology* **184**, 213-223.
Fletcher, T. P., Auton, C. A., Highton, A. J., Merritt, J. W., Robertson, S. & Rawlin, K. E. 1996. *Geology of the Fortrose and eastern Inverness District*.

Flett, J. S. & Read, H. H. (1921) Tertiary gravels of the Buchan district of Aberdeenshire. *Geological Magazine* **58**, 215-225.
Flinn, D. (1978a) The glaciation of the Outer Hebrides. *Geological Journal* **13**, 195-199.
Flinn, D. (1978b) The most recent glaciation of the Orkney-Shetland Channel and adjacent areas. *Scottish Journal of Geology* **14**, 109-123.
Forsyth, I. H., Hall, I. H. S. & McMillan, A. 1996. *Geology of the Airdrie district: memoir for 1: 50 000 geological sheet 31W (Scotland)*: HMSO.
Francis, E., Forsyth, I. H., Read, W. A. & Armstrong, M. 1970. *The Geology of the Stirling District (Explanation of One-inch Geological Sheet 39)*, 357. Edinburgh: HM Stationery Office.
Fredin, O., Bergstrøm, B., Eilertsen, R., Hansen, L., Longva, O., Nesje, A. & Sveian, H. (2013) Glacial landforms and Quaternary landscape development in Norway. *Geological Survey of Norway, Special Publication* **13**, 5-25.
Fredin, O., Viola, G., Zwingmann, H., Sørlie, R., Brönner, M., Lie, J.-E., Grandal, E. M., Müller, A., Margreth, A. & Vogt, C. (2017) The inheritance of a Mesozoic landscape in western Scandinavia. *Nature Communications* **8**, 14879.
Gatliff, R. W., Richards, P. C., Smith, K., Graham, C. C., McCormac, M., Smith, N. J. P., Long, D., Cameron, T. D. J., Evans, D., Stevenson, A. G., Bulat, J. & Ritchie, J. D. 1994. *The geology of the central North Sea*. London: HMSO.
Geikie, A. 1887. *The scenery of Scotland*. London: Macmillan.
Geikie, A. 1901. *The scenery of Scotland*. London: Macmillan.
Gemmell, A. M. D., Murray, A. S. & Connell, E. R. (2007) Devensian glacial events in Buchan (NE Scotland): A progress report on new OSL dates and their implications. *Quaternary Geochronology* **2**, 237-242.
Glasser, N. F. (1995) Modelling the effect of topography on ice sheet erosion, Scotland. *Geografiska Annaler* **77A**.
Glasser, N. F. (1997) The origin and significance of sheet joints in the Cairngorm granite. *Scottish Journal of Geology* **33**, 125-132.
Glasser, N. F. & Hall, A. M. (1997) Calculating Quaternary erosion rates in North East Scotland. *Geomorphology* **20**, 29-48.
Godard, A. (1961) L'efficacité de l'erosion glaciare en Écosse du Nord. *Revue de Géomorphologie Dynamique* **12**, 32-42.
Godard, A. (1962) Essais de corrélation entre l'altitudes des reliefs et les caracteres pétrographiques des roches dans les socles de l'Écosse du Nord. *Compte Rendus Academie des Sciences* **255**, 139-141.
Godard, A. 1965. *Recherches en géomorphologie en Écosse du Nord-Ouest*. Paris: Masson et Cie.
Godard, A. (1969) L'île d'Arran (Écosse): contribution a l'étude géomorphologique des racines de volcans. *Revue de Géographie Physique et de Géologie Dynamique* **11**, 3-30.
Golledge, N., Hubbard, A. & Bradwell, T. (2010) Influence of seasonality on glacier mass balance, and implications for palaeoclimate reconstructions. *Climate Dynamics* **35**, 757-770.
Golledge, N. & Stoker, M. S. (2006) A palaeo-ice stream of the British Ice Sheet in eastern Scotland. *Boreas* **35**, 231-243.
Golledge, N. R., Hubbard, A. & Sugden, D. E. (2008) High-resolution numerical simulation of Younger Dryas glaciation in Scotland. *Quaternary Science Reviews* **27**, 888-904.
Goodfellow, B., Stroeven, A., Fabel, D., Fredin, O., Derron, M., Bintanja, R. & Caffee, M. (2014a) Arctic-alpine blockfields in northern Sweden: Quaternary not Neogene. *Earth Surface Dynamics Discussions* **2**, 47-93.
Goodfellow, B. W., Skelton, A., Martel, S. J., Stroeven, A. P., Jansson, K. N. & Hättestrand, C. (2014b) Controls of tor formation, Cairngorm Mountains, Scotland. *Journal of Geophysical Research: Earth Surface* **119**, 225–246.
Gordon, J. E. (1977) Morphometry of cirques in the Kintail-Affric-Cannich area of northwest Scotland. *Geografiska Annaler* **59A**, 177-194.

Gordon, J. E. (1979) Reconstructed Pleistocene ice sheet temperatures and glacial erosion in northern Scotland. *Journal of Glaciology* **22**, 331-344.
Gordon, J. E. (1981) Ice-scoured topography and its relationships to bedrock structure and ice movement in parts of northern Scotland and west Greenland. *Geografiska Annaler, Series A: Physical Geography* **63**, 55-65.
Gordon, J. E. (1993a) Boyne Quarry, *In*: Gordon, J. E. a. S., D. G. (ed), *Quaternary of Scotland*, 233-236. London: Chapman and Hall.
Gordon, J. E. (1993b) The Cairngorms, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *Quaternary of Scotland*, 259-276. London: Chapman and Hall.
Gordon, J. E. (1993c) Kippet Hills, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *Quaternary of Scotland*, 242-245. London: Chapman and Hall.
Gordon, J. E. (1993d) Leavad, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *The Quaternary of Scotland*, 94-95: Chapman and Hall.
Gordon, J. E. (1993e) Nigg Bay, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *Quaternary of Scotland*, 479-481. London: Chapman and Hall.
Gordon, J. E. (1993f) North-west coast of Lewis, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *Quaternary of Scotland*, 414-421. London: Chapman and Hall.
Gordon, J. E. & Sutherland, D. G. (1993) Windy Hills, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *Quaternary of Scotland*, 216-218. London: Chapman and Hall.
Graf, W. L. (1970) The geomorphology of the glacial valley cross section. *Arctic and Alpine Research*, 303-312.
Graham, A. G., Stoker, M. S., Lonergan, L., Bradwell, T. & Stewart, M. A. (2011) The Pleistocene glaciations of the North Sea Basin, *In*: Ehlers, J. & Gibbard, P. L., & Hughes, P. D. (eds), *Developments in Quaternary Science*, 261-278. Amsterdam: Elsevier.
Graham, A. G. C., Lonergan, L. & Stoker, M. S. (2007) Evidence for Late Pleistocene ice stream activity in the Witch Ground Basin, central North Sea, from 3D seismic reflection data. *Quaternary Science Reviews* **26**, 627-643.
Graham, A. G. C., Lonergan, L. & Stoker, M. S. (2010) Depositional environments and chronology of Late Weichselian glaciation and deglaciation in the central North Sea. *Boreas* **39**, 471-491.
Greenwood, S. L., Clark, C. D. & Hughes, A. L. (2007) Formalising an inversion methodology for reconstructing ice-sheet retreat patterns from meltwater channels: application to the British Ice Sheet. *Journal of Quaternary Science* **22**, 637-645.
Gregersen, U. & Johannessen, P. (2007) Distribution of the Neogene Utsira Sand and the succeeding deposits in the Viking Graben area, North Sea. *Marine and Petroleum Geology* **24**, 591-606.
Grohmann, C. H., Smith, M. J. & Riccomini, C. (2011) Multiscale analysis of topographic surface roughness in the Midland Valley, Scotland. *IEEE Transactions on Geoscience and Remote Sensing* **49**, 1200-1213.
Hall, A. M. (1985) Cenozoic weathering covers in Buchan, Scotland, and their significance. *Nature* **315**, 392-395.
Hall, A. M. (1986) Deep weathering patterns in north-east Scotland and their geomorphological significance. *Zeitschrift für Geomorphologie NF* **30**, 407-422.
Hall, A. M. (1991) Pre-Quaternary landscape evolution in the Scottish Highlands. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **82**, 1-26.
Hall, A. M. (1993a) Deep weathering in Scotland: a review, *In*: Dawson, A. H. & Jones, H. R. & Small, A., & Soulsby, J. A. (eds), *Scottish Geographical Studies*, 37-46. St. Andrews: Universities of Dundee and St. Andrews.
Hall, A. M. (1993b) Hill of Longhaven, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *Quaternary of Scotland*, 223-225. London: Chapman and Hall.
Hall, A. M. (1993c) Moss of Cruden, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *Quaternary of Scotland*, 218-221. London: Chapman and Hall.

Hall, A. M. (1993d) Pittodrie, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *Quaternary of Scotland*, 221-223. London: Chapman and Hall.
Hall, A. M. (1996) Quaternary geomorphology of the Outer Hebrides, *In*: Gilbertson, D. & Kent, M., & Grattan, J. (eds), *The Outer Hebrides: the last 14,000 years*, 5-12: Sheffield Academic Press.
Hall, A. M. (2005) The Buchan Surface. *Scottish Geographical Journal* **121**, 107-118.
Hall, A. M. (2007) The shaping of Lochnagar: pre-glacial, glacial and post-glacial processes, *In*: Rose, N. (ed), *Lochnagar: The natural history of a mountain lake*, 51-62. Dordrecht: Springer.
Hall, A. M. (2013) The last glaciation of Shetland: local ice cap or invasive ice sheet? *Norwegian Journal of Geology* **93**, 229-242.
Hall, A. M., Binnie, S. A., Sugden, D., Dunai, T. J. & Wood, C. (2016) Late readvance and rapid final deglaciation of the last ice sheet in the Grampian Mountains, Scotland. *Journal of Quaternary Science* **31**, 869-878.
Hall, A. M. & Bishop, P. (2002) Scotland's denudational history: an integrated view of erosion and sedimentation at an uplifted passive margin. *Geological Society, London, Special Publications* **196**, 271-290.
Hall, A. M. & Connell, E. R. (1986) A preliminary report on the Quaternary sediments at Leys gravel pit, Buchan. *Quaternary Newsletter* **48**, 17-28.
Hall, A. M. & Connell, E. R. (1991) The glacial deposits of Buchan, north-east Scotland., *In*: Ehlers, J. & Gibbard, P. L., & Rose, J. (eds), *Glacial Deposits in Great Britain and Ireland*, 129-136. Rotterdam: Balkema.
Hall, A. M., Ebert, K. & Hättestrand, C. (2013a) Pre-glacial landform inheritance in a glaciated shield landscape. *Geografiska Annaler Series A, Physical Geography* **95**, 33–49.
Hall, A. M., Gilg, H. A., Fallick, A. E. & Merritt, J. (2015a) Kaolins in gravels and saprolites in north-east Scotland: evidence from stable H and O isotopes for Palaeocene-Miocene deep weathering. *Palaeogeography, Palaeoclimatology, Palaeoecology* **424**, 6–16.
Hall, A. M. & Gillespie, M. (2016) Fracture control on valley persistence: the Cairngorm Granite pluton, Scotland. *International Journal of Earth Sciences*.
Hall, A. M., Gillespie, M., Thomas, C. & Ebert, K. (2013b) The Cairngorms - a pre-glacial upland granite landscape. *Scottish Geographical Journal* **129**, 2-14.
Hall, A. M. & Glasser, N. F. (2003) Reconstructing former glacial basal thermal regimes in a landscape of selective linear erosion: Glen Avon, Cairngorm Mountains, Scotland. *Boreas* **32**, 191-207.
Hall, A. M., Gordon, J. E., Whittington, G., Duller, G. A. T. & Heijnis, H. (2002) Sedimentology, palaeoecology and geochronology of Marine Isotope Stage 5 deposits on the Shetland Isles, Scotland. *Journal of Quaternary Science* **17**, 51-68.
Hall, A. M. & Jarman, D. (2004) Quaternary landscape evolution - plateau dissection by glacial breaching, *In*: Lukas, S. & Merritt, J. W., & Mitchell, W. A. (eds), *The Quaternary of the Central Grampian Highlands*, 26-40. London: Quaternary Research Association.
Hall, A. M. & Jarvis, J. (1993) Kirkhill, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *Quaternary of Scotland*, 225-230. London: Chapman and Hall.
Hall, A. M. & Jarvis, J. (1995) A multiple till sequence near Ellon, Grampian Region : T. F. Jamieson's Indigo Boulder Clay re-examined. *Scottish Journal of Geology* **31**, 53-59.
Hall, A. M., Jarvis, J. & Duck, R. W. 1989a. Survey of Quaternary deposits adjacent to Kirkhill Quarry, Banff and Buchan district, and recommendations for site conservation., 72: Nature Conservancy Council.
Hall, A. M. & Kleman, J. (2014) Glacial and periglacial buzzsaws: fitting mechanisms to metaphors. *Quaternary Research* **81**, 189-192.
Hall, A. M. & Mellor, T. (1988) The characteristics and significance of deep weathering in the Gaick area, Grampian Highlands, Scotland. *Geografiska Annaler* **70A**, 309-314.
Hall, A. M., Mellor, T. & Wilson, M. J. (1989b) The clay mineralogy and age of deeply weathered rock in north-east Scotland. *Zeitschrift für Geomorphologie SupplementBand* **72**, 97-108.

Hall, A. M. & Phillips, W. M. (2006a) Glacial modification of granite tors in the Cairngorms, Scotland. *Journal of Quaternary Science* **21**, 811-830.
Hall, A. M. & Phillips, W. M. (2006b) Weathering pits as indicators of the relative age of granite surfaces in the Cairngorm Mountains, Scotland. *Geografiska Annaler* **88A**, 135-150.
Hall, A. M. & Riding, J. (2016) The last glaciation in Caithness, Scotland: revised till stratigraphy and ice-flow paths indicate multiple ice flow phases. *Scottish Journal of Geology* **52**, 77-89.
Hall, A. M., Sarala, P. & Ebert, K. (2015b) Late Cenozoic deep weathering patterns on the Fennoscandian shield in northern Finland: a window on ice sheet bed conditions at the onset of Northern Hemisphere glaciation. *Geomorphology* **246**, 472–488.
Hall, A. M. & Sugden, D. E. (1987) Limited modification of mid-latitude landscapes by ice sheets: the case of north-east Scotland. *Earth Surface Processes and Landforms* **12**, 531-542.
Hall, A. M. & Sugden, D. E. (2007) The significance of tors in glaciated lands: a view from the British Isles, *In*: Andre, M.-F. (ed), *Du continent au bassin versant : theories et practiques en géographie physique (Hommage au Professeur Alain Godard)*, 301-311. Lyon: Presses Universitaires Blaise-Pascal.
Hall, A. M., Whittington, G., Duller, G. A. T. & Jarvis, J. (1995) Late Pleistocene environments in lower Strathspey, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **85**, 253-273.
Hall, I. H. S., Browne, M. & Forsyth, I. H. 1998. *Geology of the Glasgow district*, **30**: Stationery Office Books (TSO).
Haynes, V. M. (1968) The influence of glacial erosion and rock structure on corries in Scotland. *Geografiska Annaler* **50A**, 221-234.
Haynes, V. M. (1977) The modification of valley patterns by ice sheet activity. *Geografiska Annaler* **59A**, 195-207.
Haynes, V. M. (1983) Scotland's Landforms, *In*: Clapperton, C. M. (ed), *Scotland: a new study*, 28-63. Newton Abbott: David and Charles.
Head, M. J. & Gibbard, P. L. (2005) Early-Middle Pleistocene transitions: an overview and recommendation for the defining boundary. *Geological Society, London, Special Publications* **247**, 1-18.
Hebdon, N. J., Atkinson, T. C., Lawson, T. J. & Young, I. R. (1998) Rate of glacial valley deepening during the late Quaternary in Assynt, Scotland. *Earth Surface Processes and Landforms* **22**, 307-315.
Henderson, J. (1893) On sections exposed on the line of the Barnton railway. *Transactions of the Edinburgh Geological Society* **6**, 297-300.
Holmes, R. (1997) Quaternary Stratigraphy: the Offshore Record, *In*: Gordon, J. E. (ed), *New Light on the Ice Age in Scotland*, 72-94. Edinburgh: Scottish Natural Heritage.
Holzhausen, G. R. (1989) Origin of sheet structure, 1. Morphology and boundary conditions. *Engineering Geology* **27**, 225-278.
Hopkinson, C. & Ballantyne, C. K. (2014) Age and Origin of Blockfields on Scottish Mountains. *Scottish Geographical Journal* **130**, 116-141.
Hubbard, A. (1999) High-Resolution Modeling of the Advance of the Younger Dryas Ice Sheet and Its Climate in Scotland. *Quaternary Research* **52**, 27-43.
Hubbard, A., Bradwell, T., Golledge, N. R., Hall, A. M., Patton, H., Sugden, D. E., Cooper, R. & Stoker, M. S. (2009) Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British–Irish ice sheet. *Quaternary Science Reviews* **28**, 758-776.
Hughes, A. L. C., Clark, C. D. & Jordan, C. J. (2010) Subglacial bedforms of the last British Ice Sheet. *Journal of Maps*, 543-563.
Hughes, A. L. C., Clark, C. D. & Jordan, C. J. (2014) Flow-pattern evolution of the last British Ice Sheet. *Quaternary Science Reviews* **89**, 148-168.
Humphries, D. W. (1961) The Upper Cretaceous White Sandstone of Loch Aline, Argyll, Scotland. *Proceedings of the Yorkshire Geological Society* **33**, 47-76.
Huybers, P. & Tziperman, E. (2008) Integrated summer insolation forcing and 40,000-year glacial cycles: The perspective from an ice-sheet/energy-balance model. *Paleoceanography* **23**.

Japsen, P. (1997) Regional Neogene exhumation of Britain and the western North Sea. *Journal of the Geological Society, London* **154**, 239-247.
Jardine, W. G., Dickson, J. H., Haughton, P. D. W., Harkness, D. D., Bowen, D. Q. & Sykes, G. A. (1988) A late Middle Devensian site at Sourlie, near Irvine, Strathclyde. *Scottish Journal of Geology* **24**, 288-295.
Jarman, D. (2006) Large rock slope failures in the Highlands of Scotland: Characterisation, causes and spatial distribution. *Engineering Geology* **83**, 161-182.
Jarman, D. (2007) Alain Godard on the NW Highlands of Scotland: present relevance for long-term landscape evolution studies. *Géomorphologie: relief, processus, environnement* **13**, 177-203.
Jarman, D. (2017) Very long-term landscape evolution - a geomorphological contextual approach, *In*: Merritt, J. & Auton, C. A., & Phillips, E. R. (eds), *The Quaternary around Nairn and the Inverness Firth: Field Guide.*, 18-27. London: Quaternary Research Association.
Kaplan, M. R., Hein, A. S., Hubbard, A. & Lax, S. M. (2009) Can glacial erosion limit the extent of glaciation? *Geomorphology* **103**, 172-179.
Kendall, P. F. & Bailey, E. B. (1908) The glaciation of East Lothian south of the Garleton Hills. *Transactions of the Royal Society of Edinburgh* **46**, 1-31.
Kesel, R. H. & Gemmell, A. M. D. (1981) The 'Pliocene' gravels of Buchan: a reappraisal. *Scottish Journal of Geology* **17**, 185-203.
Kirkbride, M. P. (2006) Boulder edge-roundness as an indicator of relative age: a Lochnagar case study. *Scottish Geographical Journal* **121**, 219-236.
Kirkbride, M. P. & Bell, C. M. (2010) Edge-roundness of boulders of Torridonian Sandstone (northwest Scotland): applications for relative dating and implications for warm and cold climate weathering rates. *Boreas* **39**, 187-198.
Kleman, J., Stroeven, A. P. & Lundqvist, J. (2008) Patterns of Quaternary ice sheet erosion and deposition in Fennoscandia and a theoretical framework for explanation. *Geomorphology* **97**, 73-90.
Krabbendam, M. & Bradwell, T. (2011) Glacial erosion and bedrock properties in NW Scotland: Abrasion and plucking, hardness and joint spacing. *Geomorphology* **130**, 374-383.
Krabbendam, M. & Bradwell, T. 2013. Glacial erosion of gneiss terrains: a re-assessment of the'landscape of areal scouring'and implications for bed roughness below ice sheets, *EGU General Assembly Conference Abstracts*, 4102.
Krabbendam, M. & Bradwell, T. (2014) Quaternary evolution of glaciated gneiss terrains: pre-glacial weathering vs. glacial erosion. *Quaternary Science Reviews* **95**, 20-42.
Kuchar, J., Milne, G., Hubbard, A., Patton, H., Bradley, S., Shennan, I. & Edwards, R. (2012) Evaluation of a numerical model of the British–Irish ice sheet using relative sea-level data: implications for the interpretation of trimline observations. *Journal of Quaternary Science* **27**, 597–605.
Larsen, E., Sejrup, H.-P., Janocko, J., Landvik, J. Y., Stalsberg, K. & Steinsund, P. I. (2000) Recurrent interaction between the Norwegian Channel Ice Stream and terrestrial-based ice across southwest Norway. *Boreas* **29**, 185-203.
Lawson, T. J. (1993) Creag nan Uamh, *In*: Gordon, J. E. a. S., D. G. (ed), *Quaternary of Scotland*, 127=132. London.
Lawson, T. J. & Atkinson, T. C. (1995) Quaternary chronology, *In*: Lawson, T. J. (ed), *The Quaternary of Assynt and Coigach*, 12-18. Cambridge: Quaternary Research Association.
Le Coeur, C. (1988) Late Tertiary warping and erosion in western Scotland. *Geografiska Annaler* **70A**, 361-368.
Le Coeur, C. (1999) Rythmes de denudation tertiaire et quaternaire en Ecosse occidentale. *Geomorphologie* **1999**, 291-304.
Lee, J. R., Busschers, F. S. & Sejrup, H. P. (2012) Pre-Weichselian Quaternary glaciations of the British Isles, The Netherlands, Norway and adjacent marine areas south of 68°N: implications for long-term ice sheet development in northern Europe. *Quaternary Science Reviews* **44**, 213–228.

Lee, J. R., Phillips, E., Rose, J. & Vaughan-Hirsch, D. (2017) The Middle Pleistocene glacial evolution of northern East Anglia, UK: a dynamic tectonostratigraphic–parasequence approach. *Journal of Quaternary Science* **32**, 231-260.
Lee, J. R., Rose, J., Riding, J. B., Moorlock, B. S. P. & Hamblin, R. J. O. (2002) Testing the case for a Middle Pleistocene Scandinavian glaciation in Eastern England: evidence for a Scottish ice source for tills within the Corton Formation of East Anglia, UK. *Boreas* **31**, 345-355.
Lee, J. R., Woods, M. A. & Moorlock, B. S. P. 2015. *British Regional Geology: East Anglia (fifth edition)*, 272. Keyworth, Nottingham: British Geological Survey.
Linton, D. L. (1940) Some aspects of the evolution of the rivers Earn and Tay. *Scottish Geographical Magazine* **56**, 69-79.
Linton, D. L. (1949) Watershed breaching by ice in Scotland. *Transactions of the Institute of British Geographers* **15**, 1-16.
Linton, D. L. (1959) Morphological contrasts between eastern and western Scotland., *In*: Miller, R., & Watson, J. W. (eds), *Geographical essays in memory of Alan G. Ogilvie.*, 16-45. Edinburgh: Nelson.
Linton, D. L. (1962) Glacial erosion on soft-rock outcrops in central Scotland. *Biuletyn Peryglacjalny* **11**, 247-257.
Linton, D. L. (1963) The forms of glacial erosion. *Transactions of the Institute of British Geographers* **33**, 1-28.
Linton, D. L. (1972) Radiating valleys in glaciated lands, *Glaciers and Glacial Erosion*, 130-148: Springer.
Løseth, H., Raulline, B. & Nygård, A. (2013) Late Cenozoic geological evolution of the northern North Sea: development of a Miocene unconformity reshaped by large-scale Pleistocene sand intrusion. *Journal of the Geological Society* **170**, 133-145.
Lowe, J. J. (1984) A critical evaluation of pollen-stratigraphic investigations of pre-Late Devensian sites in Scotland. *Quaternary Science Reviews* **3**, 405-432.
Lowe, J. J. (2016) Volcanic Ash Stratigraphy: An Emerging Dating Tool Helping to Refine the Glacial History of Scotland During the Late Devensian. *Scottish Geographical Journal* **132**, 171-176.
Marquette, G. C., Gray, G. T., Gosse, J. C., Courchesne, F., Stockli, L., Macpherson, G. & Finkel, R. C. (2004) Felsenmeer persistence under non-erosive ice in the Torngat and Kaumajet mountains, Quebec and Labrador, as determined by soil weathering and cosmogenic nuclide exposure dating. *Canadian Journal of Earth Science* **41**, 19-38.
Martel, S. J. (2017) Progress in understanding sheeting joints over the past two centuries. *Journal of Structural Geology* **94**, 68-86.
May, F. & Phemister, J. 1968. Kaolin deposits in the Shetland Islands, *U.K. Proceedings XXIII International Geological Congress*, 23-29.
McCarroll, D. (2016) Trimline Trauma: The Wider Implications of a Paradigm Shift in Recognising and Interpreting Glacial Limits. *Scottish Geographical Journal*, 1-10.
McMartin, I. & McClenaghan, M. B. (2001) Till geochemistry and sampling techniques in glaciated shield terrain: a review. *Geological Society, London, Special Publications* **185**, 19-43.
McMillan, A. A. & Aitken, A. M. 1981. The sand and gravel resources of the country west of Peterhead, Grampian Region., *Mineral Assessment Report*, 107: Institute of Geological Sciences.
McMillan, A. A., Hamblin, R. J. O. & Merritt, J. W. 2011. A lithostratigraphical framework for onshore Quaternary and Neogene (Tertiary) superficial deposits of Great Britain and the Isle of Man, *British Geological Survey Research Report*, 343.
Merrit, J., Hall, A. M., Gordon, J. E. & Connell, E. R. (2018) Late Pleistocene sediments, landforms and events in Scotland: a review of the terrestrial record. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*.
Merritt, J. (2004) The glacial stratigraphy along the southern margin of the Gaick Plateau, *In*: Lukas, S. & Merritt, J. W., & Mitchell, W. A. (eds), *The Quaternary of the Central Grampian Highlands*, 133-138. London: Quaternary Research Association.

Merritt, J. & Auton, C. A. (2017) The Dalcharn interglacial site, *In*: Merritt, J. & Auton, C. A., & Phillips, E. R. (eds), *The Quaternary around Nairn and the Inverness Firth: Field Guide.*, 132-144. London: Quaternary Research Association.
Merritt, J. W. 1981. The sand and gravel resources of the country around Ellon, Grampian Region., *Mineral Assessment Report*, 114: Institute of Geological Sciences.
Merritt, J. W., Akhurst, M. C., Wilkinson, I. P., Riding, J. B., Phillips, E. R., Smith, R. A., Finlayson, A. & Dean, M. T. (2014) The Late Pleistocene Afton Lodge Clay Formation, Ayrshire, Scotland: evidence for Early to Middle Devensian climatic changes and Late Devensian onshore ice flow and rafting from the Firth of Clyde. *Proceedings of the Geologists' Association* **125**, 195-214.
Merritt, J. W., Auton, C. A., Boston, C. M., Everest, J. D. & Merritt, J. E. (2013) An overview of the main Late Devensian glaciation of the Central Grampian Highlands, *In*: Boston, C. & Lukas, S., & Merritt, J. (eds), *The Quaternary of the Monadhliath Mountains and the Great Glen: field guide. Quaternary Research Association.*, 25-40: Quaternary Research Association.
Merritt, J. W., Auton, C. A., Connell, E. R., Hall, A. M. & Peacock, J. D. 2003. *Cainozoic geology and landscape evolution of north-east Scotland. Memoir of the British Geological Survey, Sheets 66E, 67, 76E, 77, 86E, 87W, 87E, 95, 96W, 96E and 97 Scotland)*, 178. Keyworth, Nottingham: NERC.
Merritt, J. W., Connell, E. R. & Hall, A. M. (2017) Middle to Late Devensian glaciation of north-east Scotland: implications for the north-eastern quadrant of the last British-Irish ice sheet. *Journal of Quaternary Science* **32**, 276-294.
Merritt, J. W., Connell, E. R., Hall, A. M. & Peacock, J. D. (2000) An introduction to the Cainozoic geology of coastal Morayshire, Banffshire and Buchan, *In*: Merritt, J. W., Connell, E. R. and Bridgland, D. R. (ed), *The Quaternary of the Banffshire coast and Buchan: Field Guide*, 1-20. London: Quaternary Research Association.
Mudie, P. J. & McCarthy, F. M. G. (2006) Marine palynology: potentials for onshore—offshore correlation of Pleistocene—Holocene records. *Transactions of the Royal Society of South Africa* **61**, 139-157.
Näslund, J. O., Rodhe, L., Fastook, J. L. & Holmlund, P. (2003) New ways of studying ice sheet flow directions and glacial erosion by computer modelling--examples from Fennoscandia. *Quaternary Science Reviews* **22**, 245-258.
Nesje, A. & Whillans, I. M. (1994) Erosion of Sognefjord, Norway. *Geomorphology* **9**, 33-45.
Nielsen, O. B., Rasmussen, E. S. & Thyberg, B. I. (2015) Distribution of Clay Minerals In the Northern North Sea Basin During the Paleogene and Neogene: A Result of Source-Area Geology and Sorting Processes. *Journal of Sedimentary Research* **85**, 562-581.
Nielsen, S. B., Gallagher, K., Leighton, C., Balling, N., Svenningsen, L., Jacobsen, B. H., Thomsen, E., Nielsen, O. B., Heilmann-Clausen, C. & Egholm, D. L. (2009) The evolution of western Scandinavian topography: a review of Neogene uplift versus the ICE (isostasy–climate–erosion) hypothesis. *Journal of Geodynamics* **47**, 72-95.
Orr, C. (1979) Rapid weathering dolerites. *Civil Engineer in South Africa* **21**, 161-167.
Ottesen, D., Dowdeswell, J. A. & Bugge, T. (2014) Morphology, sedimentary infill and depositional environments of the Early Quaternary North Sea Basin (56°–62°N). *Marine and Petroleum Geology* **56**, 123-146.
Parnell, J., Baron, M. & Boyce, A. (2000) Controls on kaolinite and dickite distribution, Highland Boundary Fault Zone, Scotland and Northern Ireland. *Journal of the Geological Society* **157**, 635-640.
Paterson, I. B., Hall, I. H. S., Stephenson, D. & Forsyth, I. H. 1990. *Geology of the Greenock district: memoir for 1: 50 000 geological sheet 30W and part of sheet 29E (Scotland)*: HMSO.
Patterson, C. J. (1998) Laurentide glacial landscapes: The role of ice streams. *Geology* **26**, 643-646.
Payne, A. J. & Sugden, D. E. (1990) Topography and ice sheet growth. *Earth Surface Processes and Landforms* **15**, 625-639.
Peach, B. N., Gunn, W., Clough, C. T., Hinxman, L. W., Crampton, C., Anderson, Ė. & Flett, J. S. 1912. *The Geology of Ben Wyvis, Carn Chuinneag, Inchbae and the Surrounding County, Including Grave, Evanton, Alness and Kincardine.(Explanation of Sheet 93.)*, 207. Edinburgh: HM Stationery Office.

Peacock, J. D. (1984) Quaternary Geology of the Outer Hebrides. *Report of the British Geological Survey* **16**, 1-26.
Peacock, J. D. & Merritt, J. W. (2000) Glacial deposits at the Boyne Bay Limestone Quarry, Portsoy, and their place in the late Pleistocene history of northeast Scotland. *Journal of Quaternary Science* **15**, 543-556.
Phillips, E., Everest, J. & Reeves, H. (2013) Micromorphological evidence for subglacial multiphase sedimentation and deformation during overpressurized fluid flow associated with hydrofracturing. *Boreas* **42**, 395-427.
Phillips, E. & Merritt, J. (2008) Evidence for multiphase water-escape during rafting of shelly marine sediments at Clava, Inverness-shire, NE Scotland. *Quaternary Science Reviews* **27**, 988-1011.
Phillips, W. M., Hall, A. M., Ballantyne, C. K., Binnie, S., Kubik, P. & Freeman, S. (2008) Extent of the last ice sheet in northern Britain tested with cosmogenic ^{10}Be exposure ages. *Journal of Quaternary Science* **23**, 101-107.
Phillips, W. M., Hall, A. M., Mottram, R., Fifield, K. & Sugden, D. E. (2006) Cosmogenic exposure ages of tors and erratics on the Cairngorm plateau, Scotland: timescales for the development of a classic landscape of selective linear glacial erosion. *Geomorphology* **73**, 222-245.
Pitkäranta, R. (2009) Lithostratigraphy and age estimations of the Pleistocene erosional remnants near the centre of the Scandinavian glaciations in western Finland. *Quaternary Science Reviews* **28**, 166-180.
Portenga, E. W., Bierman, P. R., Rizzo, D. M. & Rood, D. H. (2013) Low rates of bedrock outcrop erosion in the central Appalachian Mountains inferred from in situ ^{10}Be. *Geological Society of America Bulletin* **125**, 201-215.
Pound, M. J. & Riding, J. B. (2015) Palaeoenvironment, palaeoclimate and age of the Brassington Formation (Miocene) of Derbyshire, UK. *Journal of the Geological Society*.
Praeg, D., Stoker, M. S., Shannon, P. M., Ceramicola, S., Hjelstuen, B., Laberge, J. S. & Mathiesen, A. (2005) Episodic Cenozoic tectonism and the development of the NW European 'passive' continental margin. *Marine and Petroleum Geology* **22**, 1007-1030.
Rabassa, J., Coronato, A. M. & Salemme, M. (2005) Chronology of the Late Cenozoic Patagonian glaciations and their correlation with biostratigraphic units of the Pampean region (Argentina). *Journal of South American Earth Sciences* **20**, 81-103.
Rapp, A. (1996) Impact of mountain glaciations on tors, blockfields and cryoplanation features. Nunataks or non-scoured zones as refugia?, *In*: McCann, S. B., & Ford, D. C. (eds), *Geomorphology Sans Frontières*, 137-152. Chichester: Wiley.
Raymo, M. & Ruddiman, W. F. (1992) Tectonic forcing of late Cenozoic climate. *Nature* **359**, 117-122.
Reinardy, B. T. I., Hjelstuen, B. O., Sejrup, H. P., Augedal, H. & Jørstad, A. (2017) Late Pliocene-Pleistocene environments and glacial history of the northern North Sea. *Quaternary Science Reviews* **158**, 107-126.
Renssen, H. & Vandenberghe, J. (2003) Investigation of the relationship between permafrost distribution in NW Europe and extensive winter sea-ice cover in the North Atlantic Ocean during the cold phases of the Last Glaciation. *Quaternary Science Reviews* **22**, 209-223.
Richardson, C. & Holmund, P. (1996) Glacial cirque formation in northern Scandinavia. *Annals of Glaciology* **22**, 102-106.
Rise, L., Ottesen, D., Berg, K. & Lundin, E. (2005) Large-scale development of the mid-Norwegian margin during the last 3 million years. *Marine and Petroleum Geology* **22**, 33-44.
Rolfe, W. D. I. (1966) Woolly rhinceros from the Scottish Pleistocene. *Scottish Journal of Geology* **2**, 253-258.
Rose, J., Boardman, J., Kemp, R. & Whiteman, C. (1985) Palaeosols and the interpretation of the British Quaternary stratigraphy, *In*: KS Richards, R. A., and S. Ellis (ed), *Geomorphology and soils*. London: : G. Allen & Unwin, 1985.
Roskosch, J., Winsemann, J., Polom, U., Brandes, C., Tsukamoto, S., Weitkamp, A., Bartholomäus, W. A., Henningsen, D. & Frechen, M. (2014) Luminescence dating of ice-marginal deposits in northern

Germany: evidence for repeated glaciations during the Middle Pleistocene (MIS 12 to MIS 6). *Boreas*, n/a-n/a.
Rudberg, S. (1994) Glacial cirques in Scandinavia. *Norsk Geografisk Tidskrift* **48**, 179-197.
Ruddiman, W. F., Raymo, M. E., Martinson, D. G., Clement, B. M. & Backman, J. (1989) Pleistocene evolution: Northern Hemisphere ice sheets and North Atlantic Ocean. *Paleoceanography* **4**, 353-412.
Russell, A. J. (1995) Late Devensian meltwater movement and storage within the Ochil Hills, central Scotland. *Scottish Journal of Geology* **31**, 65-78.
Saillard, M., Hall, S., Audin, L., Farber, D., Hérail, G., Martinod, J., Regard, V., Finkel, R. & Bondoux, F. (2009) Non-steady long-term uplift rates and Pleistocene marine terrace development along the Andean margin of Chile (31 S) inferred from 10 Be dating. *Earth and Planetary Science Letters* **277**, 50-63.
Salonen, V.-P. (1986) Glacial transport distance distributions of surface boulders in Finland. *Bulletin of the Geological Survey of Finland* **338**.
Salt, K. E. & Evans, D. J. A. (2004) Superimposed subglacially streamlined landforms of southwest Scotland. *Scottish Geographical Journal* **120**, 133-148.
Sejrup, H.-P., Larsen, E., Haflidason, H., Berstad, I. M., Hjelstuen, B. O., Jonsdottir, H. E., King, E. L., Landvik, J., Longva, O., Nygård, A., Ottesen, D., Raunholm, S., Rise, L. & Stalsberg, K. (2003) Configuration, history and impact of the Norwegian Channel Ice Stream. *Boreas* **32**, 18-36.
Sejrup, H. & Larsen, E. (1991) Eemian-early weichselian NS temperature gradients; North Atlantic-NW Europe. *Quaternary International* **10**, 161-166.
Sejrup, H. P., Aarseth, I., Ellingsen, K. L., Lovlie, R., Reither, E., Bent, A., Brigham-Grette, J., Jansen, E., Larsen, E. & Stoker, M. S. (1987) Quaternary stratigraphy of the Fladen area, central North Sea: A multidisciplinary study. *Journal of Quaternary Science* **2**, 35-58.
Sejrup, H. P., Hjelstuen, B. O., Torbjorn Dahlgren, K. I., Haflidason, H., Kuijpers, A., Nygard, A., Praeg, D., Stoker, M. S. & Vorren, T. O. (2005) Pleistocene glacial history of the NW European continental margin. *Marine and Petroleum Geology* **22**, 1111-1129.
Selby, I. C. (1987) Glaciated shorelines in Barra and Vatersay. *Quaternary Newsletter* **53**, 16-22.
Sissons, J. (1971) The geomorphology of central Edinburgh. *Scottish Geographical Magazine* **87**, 185-196.
Sissons, J. B. (1960) Erosion Surfaces, Cyclic Slopes and Drainage Systems in Southern Scotland and Northern England. *Transactions and Papers (Institute of British Geographers)*, 23-38.
Sissons, J. B. (1961) Some aspects of glacial drainage channels in Britain.- Part II. *Scottish Geographical Magazine* **76**, 15-36.
Sissons, J. B. 1967. *The evolution of Scotland's scenery*. Edinburgh: Oliver and Boyd.
Sissons, J. B. (1969) Drift stratigraphy and buried morphological features in the Grangemouth-Falkirk-Airth area, central Scotland. *Transactions of the Institute of British Geographers* **55**, 145-159.
Sissons, J. B. 1976. *Scotland*. London: Methuen.
Sissons, J. B. (1981) British shore platforms and ice-sheets. *Nature* **291**, 473-475.
Sissons, J. B. & Rhind, D. W. (1970) Drift stratigraphy and buried morphology beneath the Forth at Rosyth. *Scottish Journal of Geology Scottish Journal of Geology* **6**, 272-284.
Small, D. & Fabel, D. (2016) Was Scotland deglaciated during the Younger Dryas? *Quaternary Science Reviews* **145**, 259-263.
Small, D., Rinterknecht, V., Austin, W., Fabel, D. & Miguens-Rodriguez, M. (2012) In situ cosmogenic exposure ages from the Isle of Skye, northwest Scotland: implications for the timing of deglaciation and readvance from 15 to 11 ka. *Journal of Quaternary Science* **27**, 150-158.
Small, E. E., Anderson, R. S., Repka, J. L. & Finkel, R. (1997) Erosion rates of alpine bedrock summit surfaces deduced from in situ ^{10}Be and ^{26}Al. *Earth and Planetary Science Letters* **150**, 413-425.
Smith, D., Barlow, N., Bradley, S., Firth, C., Hall, A. M., Jordan, J. & Long, D. (2018) Quaternary sea level change in Scotland. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 1-38.

Smith, D. E., Stewart, I. S., Harrison, S. & Firth, C. R. (2009) Late Quaternary neotectonics and mass movement in South East Raasay, Inner Hebrides, Scotland. *Proceedings of the Geologists' Association* **120**, 145-154.
Smith, R. A., Merritt, J. W., Leslie, A. G., Krabbendam, M. & Stephenson, D. 2011. Geology of the Newtonmore – Ben Macdui district, *Geology and Landscape Open Report*: British Geological Survey.
Soons, J. M. (1959) The sub-drift surface of the lower Devon valley. *Transactions of the Geological Society of Glasgow* **24**, 1-7.
Soulsby, C., Chen, M., Ferrier, R. C., Helliwell, R. C., Jenkins, A. & Harriman, R. (1998) Hydrogeochemistry of shallow groundwater in an upland catchment. *Hydrological Processes* **12**, 1111-1127.
Stewart, M. A. & Lonergan, L. (2011) Seven glacial cycles in the middle-late Pleistocene of northwest Europe: Geomorphic evidence from buried tunnel valleys. *Geology* **39**, 283–286.
Stewart, M. A., Lonergan, L. & Hampson, G. (2013) 3D seismic analysis of buried tunnel valleys in the central North Sea: morphology, cross-cutting generations and glacial history. *Quaternary Science Reviews* **72**, 1-17.
Stoker, M. & Bradwell, T. (2009) Neotectonic deformation in a Scottish fjord, Loch Broom, NW Scotland. *Scottish Journal of Geology* **45**, 107-116.
Stoker, M. S. (1997) Mid-to late Cenozoic sedimentation on the continental margin off NW Britain. *Journal of the Geological Society* **154**, 509-515.
Stoker, M. S. & Bent, A. J. A. (1985) Middle Pleistocene glacial and glaciomarine sedimentation in the west central North Sea. *Boreas* **14**, 325-332.
Stoker, M. S. & Bradwell, T. (2005) The Minch palaeo-ice stream, NW sector of the British–Irish Ice Sheet. *Journal of the Geological Society* **162**, 425-428.
Stoker, M. S., Hitchen, K. & Graham, C. C. 1993. *United Kingdom Offshore Regional Report: the geology of the Hebrides and the West Shetland shelves, and adjacent deep water areas.* London: HMSO.
Stoker, M. S., Holford, S. P., Hillis, R. R., Green, P. F. & Duddy, I. R. (2010) Cenozoic post-rift sedimentation off northwest Britain: Recording the detritus of episodic uplift on a passive continental margin. *Geology* **38**, 595-598.
Stone, J. O. & Ballantyne, C. K. (2006) Dimensions and deglacial chronology of the Outer Hebrides Ice Cap, northwest Scotland: implications of cosmic ray exposure dating. *Journal of Quaternary Science* **21**, 75-84.
Stone, J. O., Ballantyne, C. K. & Fifield, L. K. (1998) Exposure dating and validation of periglacial weathering limits, northwest Scotland. *Geology* **26**, 587-590.
Stroeven, A. P., Fabel, D., Harbor, J., Hättestrand, C. & Kleman, J. (2002) Reconstructing the erosion history of glaciated passive margins: applications of in situ produced cosmogenic nuclide techniques. *Geological Society, London, Special Publications* **196**, 153-168.
Stroeven, A. P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B. W., Harbor, J. M., Jansen, J. D. & Olsen, L. (2016) Deglaciation of Fennoscandia. *Quaternary Science Reviews* **147**, 91-121.
Sugden, D. E. (1968) The selectivity of glacial erosion in the Cairngorm Mountains, Scotland. *Transactions of the Institute of British Geographers* **45**, 79-92.
Sugden, D. E. (1969) The age and form of corries in the Cairngorms. *Scottish Geographical Magazine* **85**, 34-46.
Sugden, D. E., Glasser, N. & Clapperton, C. M. (1992) Evolution of large roches moutonnées. *Geografiska Annaler* **74A**, 253-264.
Sugden, D. E. & Watts, S. H. (1977) Tors, felsenmeer, and glaciation in northern Cumberland Peninsula, Baffin Island. *Canadian Journal of Earth Sciences* **14**, 2817-2823.
Sutherland, D. G. (1984) The Quaternary deposits and landforms of Scotland and the neighbouring shelves: a review. *Quaternary Science Reviews* **3**, 157-254.

Sutherland, D. G. & Gordon, J. E. (1993) The Quaternary in Scotland, *In*: Gordon, J. E., & Sutherland, D. G. (eds), *Quaternary of Scotland*, 13-47. London: Chapman and Hall.
Sutherland, D. G. & Walker, M. J. C. (1984) A late Devensian ice-free area and possible interglacial site on the Isle of Lewis, Scotland. *Nature* **309**, 701-703.
Synge, F. M. (1956) The glaciation of North-East Scotland. *Scottish Geographical Magazine* **72**, 129-143.
Synge, F. M. (1963) The Quaternary succession around Aberdeen, North-East Scotland. *Report of the VIth International Congress on Quaternary* **3**, 353-361.
Thierens, M., Pirlet, H., Colin, C., Latruwe, K., Vanhaecke, F., Lee, J., Stuut, J. B., Titschack, J., Huvenne, V. & Dorschel, B. (2011) Ice-rafting from the British-Irish ice sheet since the earliest Pleistocene (2.6 million years ago): implications for long-term mid-latitudinal ice-sheet growth in the North Atlantic region. *Quaternary Science Reviews* **44**, 229–240.
Vandenberghe, J. (2001) Permafrost during the Pleistocene in north west and central Europe, *Permafrost response on economic development, environmental security and natural resources*, 185-194: Springer.
von Weymarn, J. (1979) A new concept of glaciation in Lewis and Harris, Outer Hebrides. *Proceedings of the Royal Society of Edinburgh* **77B**, 97-105.
Walker, F. (1935) The late Palaeozoic quartz dolerites and tholeiites of Scotland. *Mineralogical Magazine* **24**, 131-159.
Walker, M. J. C., Merritt, J. W., Auton, C. A., Coope, G. R., Field, M. H., Heijnis, H. & Taylor, B. J. (1992) Allt Odhar and Dalcharn: two pre-Late Devensian/Late Weichselian sites in northern Scotland. *Journal of Quaternary Science* **7**, 69-86.
West, R. G. (1962) Vegetational history of the Early Pleistocene of the Royal Society Borehole at Ludham, Norfolk. *Proceedings of the Royal Society of London. Series B. Biological Sciences* **155**, 437-453.
Westaway, R. (2009) Quaternary uplift of northern England. *Global and Planetary Change* **68**, 357-382.
Westaway, R. (2016) Isostatic compensation of Quaternary vertical crustal motions: coupling between uplift of Britain and subsidence beneath the North Sea. *Journal of Quaternary Science*.
White, T. S., Bridgland, D. R., Westaway, R. & Straw, A. (2017) Evidence for late Middle Pleistocene glaciation of the British margin of the southern North Sea. *Journal of Quaternary Science* **32**, 261-275.
Whittington, G., Connell, E. R., Coope, G. R., Edwards, K. J., Hall, A. M., Hulme, P. D. & Jarvis, J. (1998) Devensian organic interstadial deposits and glacier extent in Buchan, Scotland. *Journal of Quaternary Science* **13**, 309-324.
Whittington, G., Hall, A. M. & Jarvis, J. (1993) A pre-Late Devensian pollen site from Camp Fauld, Buchan, Grampian Region. *New Phytologist* **125**, 867-874.
Wilson, M. J., Bain, D. C. & Duthie, D. M. L. (1984) The soil clays of Great Britain: II Scotland. *Clay Minerals* **19**, 709-735.
Wright, J. S. (1997) Deep weathering profiles (saprolites) in north east Scotland. *Scottish Geographical Magazine* **113**, 189-194.
Ziegler, M., Loew, S. & Moore, J. R. (2013) Distribution and inferred age of exfoliation joints in the Aar Granite of the central Swiss Alps and relationship to Quaternary landscape evolution. *Geomorphology* **201**, 344-362.

Figure 1 The $\delta^{18}O$ record for benthic foraminifera from marine core DSDP 607 (Ruddiman et al., 1989) interpreted as a proxy for glacier extent in Scotland. The cut-off value of >3.7‰ $\delta^{18}O$ indicates when conditions were equivalent to the Younger Dryas event (Small & Fabel, 2016) when mountain ice caps, valley and corrie glaciers formed in Scotland (Clapperton 1997). The cut off value of >4.2‰ $\delta^{18}O$ is that at 37.5 ka in DSDP 607, a time when the last ice sheet started to build up in Scotland (Hubbard et al. 2009). IG - interglacial; IS - interstadial; MIC - mountain ice cap; MPT - Mid-Pleistocene Transition. Marine isotope stages (MIS) marked are equivalent to the following British and NW European stages: MIS 16 (676-621 ka; Happisburgh-Donian), MIS 12 (478-424 Ma; Anglian-Elsterian), MIS 6 (186-130 ka) (Wolstonian-Saalian) and 2 (29-14 ka; Late Devensian-Late Weichselian)....... 5

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Figure 6 Glacial landscapes and landforms in the northern Scottish Highlands. Glacially eroded depressions from Sutherland & Gordon (1993). Corries from (Barr et al., 2017). Glacial streamlining and roughening mapped from NextMap imagery. 12

Figure 7 Cumulative time that the bed for the last (MIS 3-2) British-Irish Ice Sheet was at pressure melting point (PMP) expressed as a percentage of the total simulation time in experiment E102b2 (Hubbard *et al.*, 2009). Persistent frozen basal conditions are indicated by black shading (%PMP < 2.5%). Assuming that similar basal temperatures developed beneath Early and Middle Pleistocene ice sheets, comparison with Figs 3 and 6 indicates close correlations between: (i) distributions of areas with persistent cold-based ice and non-glacial landforms; and (ii) areas of more frequent warm-based conditions and landscapes of glacial roughening and streamlining. 12

Figure 8 Cnoc-and-lochain terrain developed in Caledonian granite, Fionnphort, Ross of Mull. 1. Cnoc developed in massive granite. 2. Rock basin excavated in fractured granite. 3. Major fracture transverse to ice-flow. 4. Granite monoliths, with >10 m vertical fracture spacing, acting as resistant, stoss-side bastions. 14

Figure 9 Uneven impact of glacial erosion in the upper Forth valley. Smooth, tapered interfluves (Linton, 1962) and benches are developed in sandstones of mainly Devonian age (brown dashed lines). Carboniferous lava plateaux, marked by red dashed lines, have been lowered, roughened and weakly streamlined by glacial erosion. The intervening valleys have been over-deepened and thick sediments infill rock basins below the Carse of Stirling (CS) that reach depths of >100 m (Sissons, 1967). GH Gargunnock Hills. MH Menteith Hills. OH Ochil Hills. General direction of ice flow is indicated by arrows.......15

Figure 10 View N up Helmsdale towards Griam Mor and Griam Beag in Sutherland, isolated hill masses developed on Devonian conglomerate. Extensive low-relief surfaces have been only weakly dissected by fluvial and glacial erosion during the Pleistocene.......18

Figure 11 Gruss pocket at Cairngall Quarry, Mintlaw, Buchan, developed in medium-grained biotite granite below a thin till cover. Gruss weathering profiles in this area reach known depths of >60 m (Hall, 1985).......19

Figure 12 Mountain top detritus on the Red Cuillin, Skye. Fine- to medium-grained granite is broken into a thin cover of MTD with many small, angular clasts in a granular sand matrix. The summit was probably over-topped by the last ice sheet but exposed as a nunatak in the Loch Lomond Stadial (Small et al., 2012). Estimated erosion rates of 30-40 mm/ka are based on ^{10}Be cosmogenic inventories (Fame et al., 2018).......21

Figure 13 Tors developed in the Northern Arran Granite emplaced at ~60 Ma (Dickin et al., 1981). Note the truncation of inclined, sub-parallel joints by the glacial slopes of Glen Sannox, the exposures of thin granular regolith and the weathering pits on granite surfaces.......22

Figure 14 Glacially-transported tor block, eastern Ben Avon in the eastern Cairngorms.. The tor in the background has lost superstructure to glacial entrainment. Extensive spreads of sandy MTD, with small blocks, are developed on the Cairngorm Granite.......23

Figure 15 Sites with MIS 5 and older sediments in Scotland. 1. Fugla Ness (Hall et al., 2002). 2. Sel Ayre (Hall et al., 2002). 3. NW Lewis (Sutherland & Walker, 1984). 4. Inchnadamph (Lawson & Atkinson, 1995). 5. Caithness (Hall & Riding, 2016). 6. Dalcharn (Walker et al., 1992). 7. Allt Odhar (Walker et al., 1992). 8. Teindland (Hall et al., 1995). 9. Kirkhill (Connell et al., 1982). 10. Camp Fauld (Whittington et al., 1993). 11. Toddlehills (Gemmell et al., 2007) and Savock Quarry (Connell, 2015). 12. Pitlurg (Hall & Jarvis, 1995). 13. Nigg Bay (Gordon, 1993e). 14. Inverbervie (Auton et al., 2000). 15. Pattack (Merritt et al., 2013). 16. Balglass (Brown et al., 2006). 17. Lower Clyde (Rolfe, 1966; Finlayson et al., 2010). 18. Ayrshire (Jardine et al., 1988; Finlayson et al., 2010).......26

Figure 16 Kirkhill and Leys schematic Middle to Late Pleistocene stratigraphy (after (Merritt et al., 2003).......27

Figure 17 SW face of Leys Quarry in the 1990s showing high-angle,glacideltaic foreset gravels of the ?MIS 8 Denend Gravel Formation. Flow of water was towards the W and SW. Note extensive Fe and Mn staining and local cementation of the sediments. Excavations below this gravel unit exposed the Leys Till resting on bedrock.......28

Figure 18 South Face 1 of Kirkhill Quarry in the late1970s. 1. Floor of meltwater channel cut in a felsite dyke. 2. Pitscow Sand and Gravel Formation. 3. Kirkhill Palaeosol Bed. 4. Camphill Gelifluctate Bed 5. Rottenhill Till. 6. Corsend Gelifluctate Bed. 7. Hythie Till.......29

Figure 19 Kirkhill Quarry North Face in the 1980s. 1. Podzolic Kirkhill Palaeosol Bed. 2. Unconformable, sub-horizontal, base of the brown Rottenhill Till (within which the Fernieslacks Palaeosol Bed, developed). 3. The black Corse Diamicton (incorporating glacitectonically deformed pale coloured sand) overlies the Rottenhill Till. 4. Hythie Till. The section is approximately 15 m high. 30

Figure 20 Longitudinal profile of the Allt Carn a'Ghranndaich valley upstream from Clava, E of Inverness, showing multiple, buried and locally weathered Middle Pleistocene till and gravel units (after Fletcher et al. 1996). 33
Figure 21 Teindland Quarry in 2000. 1. Teindland Lower Sand, 2. Teindland Buried Soil (MIS 5e). 3. Teindland Upper Sand. 4. Truncated and glacitectonically sheared units beneath overlying Teindland Till. 33
Figure 22 Toddlehills Quarry in 2006, N face. Section ca. 6 m hig. Weathered bedrock (1) is overlain by a till unit (2) correlated with the MIS 6 Rottenhill Till Formation at Kirkhill. OSL dated (mean 85 ka) sands are obscured by made ground in mid-section (3). Late Devensian Hythie Till Formation can be seen higher in the section beneath vegetated made ground (4). 35
Figure 23 Savock Quarry in 2014. Section ca. 5 m high: 1. Middle Pleistocene sand and gravel channel fill. 2. Brown, possibly weathered till correlated with the MIS 6 Rottenhill Till Formation at Toddlehills, Leys and Kirkhill. 3. Upper clast-rich till correlated with the MIS 3-2 Hythie Till. 35
Figure 24 Sheared lens of the Burn of Benholm Peat Bed within olive grey shelly clay and diamicton (Benholm Clay Formation) at Burn of Benholm. The shelly deposits are overlain by red-brown diamicton of the Late Devensian Mill of Forest Till Formation. 36

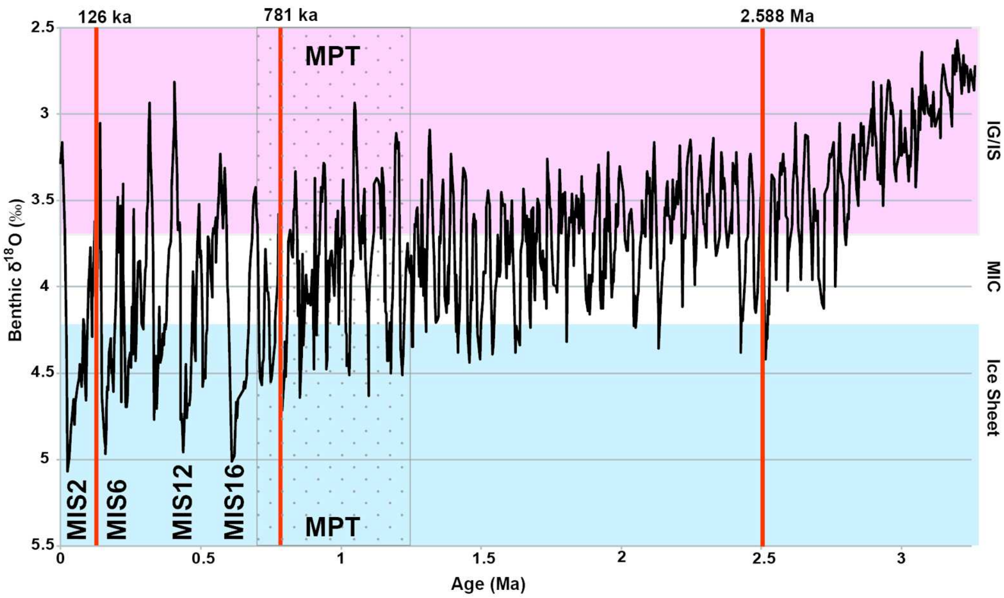

Fig. 1 Pleistocene timescale

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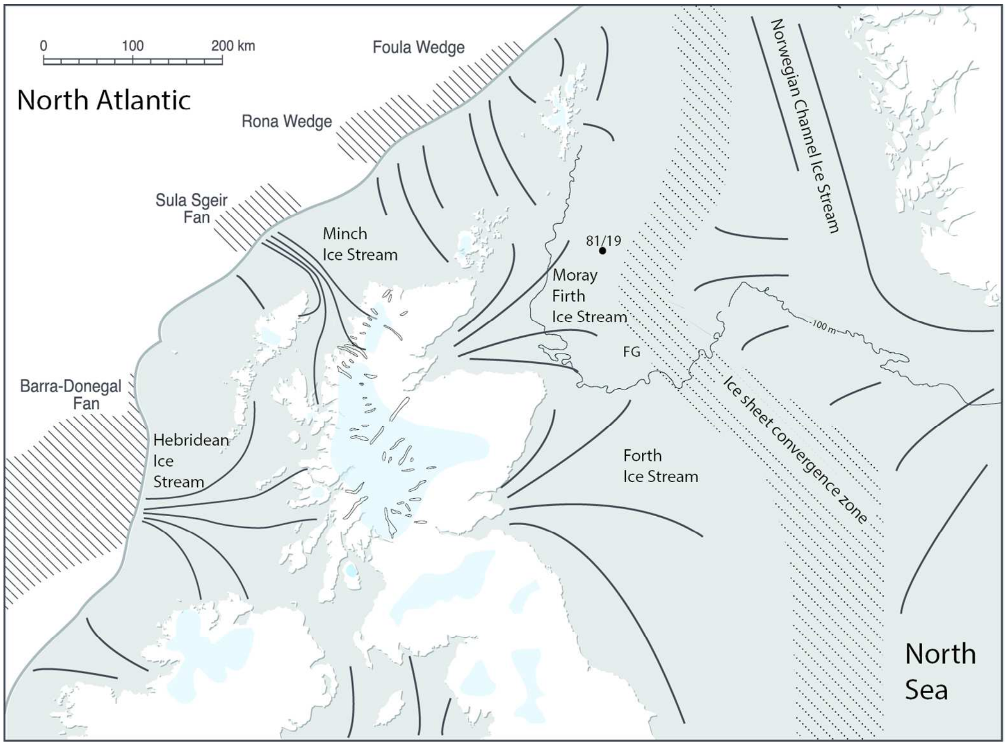

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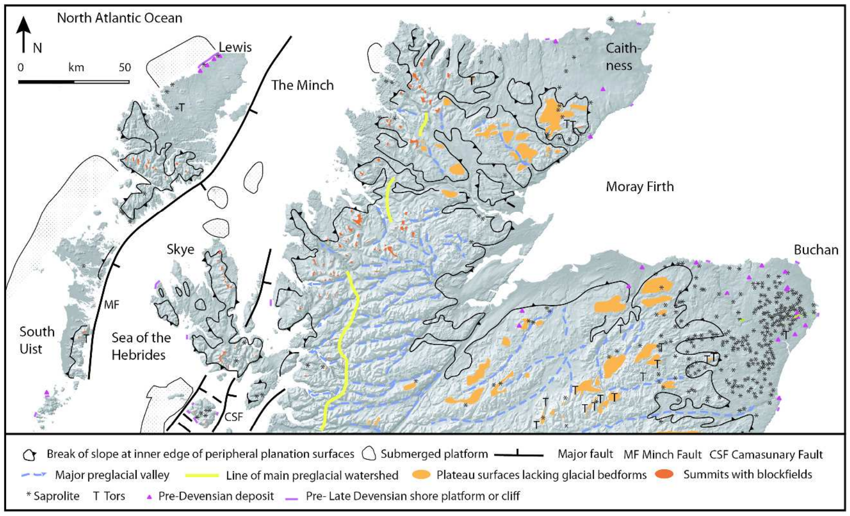

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343x183mm (300 x 300 DPI)

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126x94mm (220 x 220 DPI)

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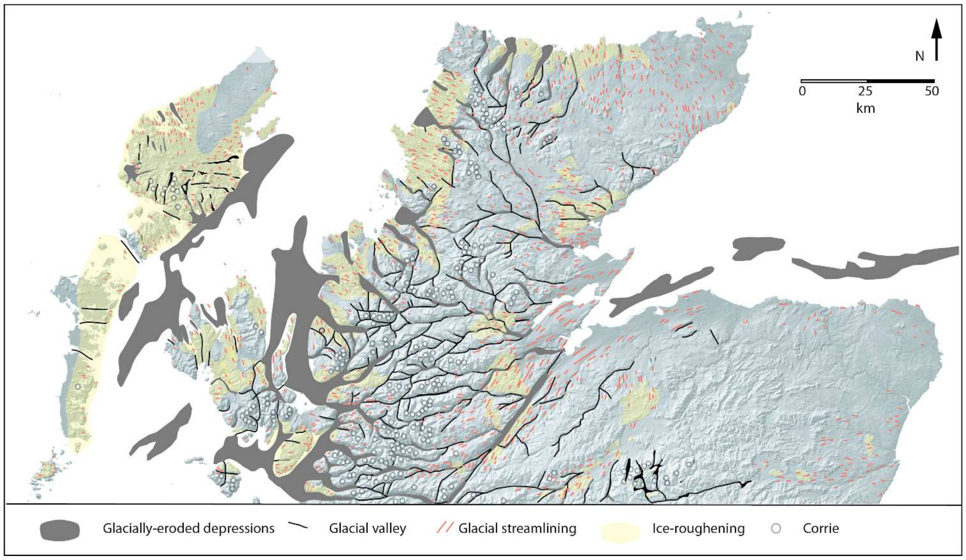

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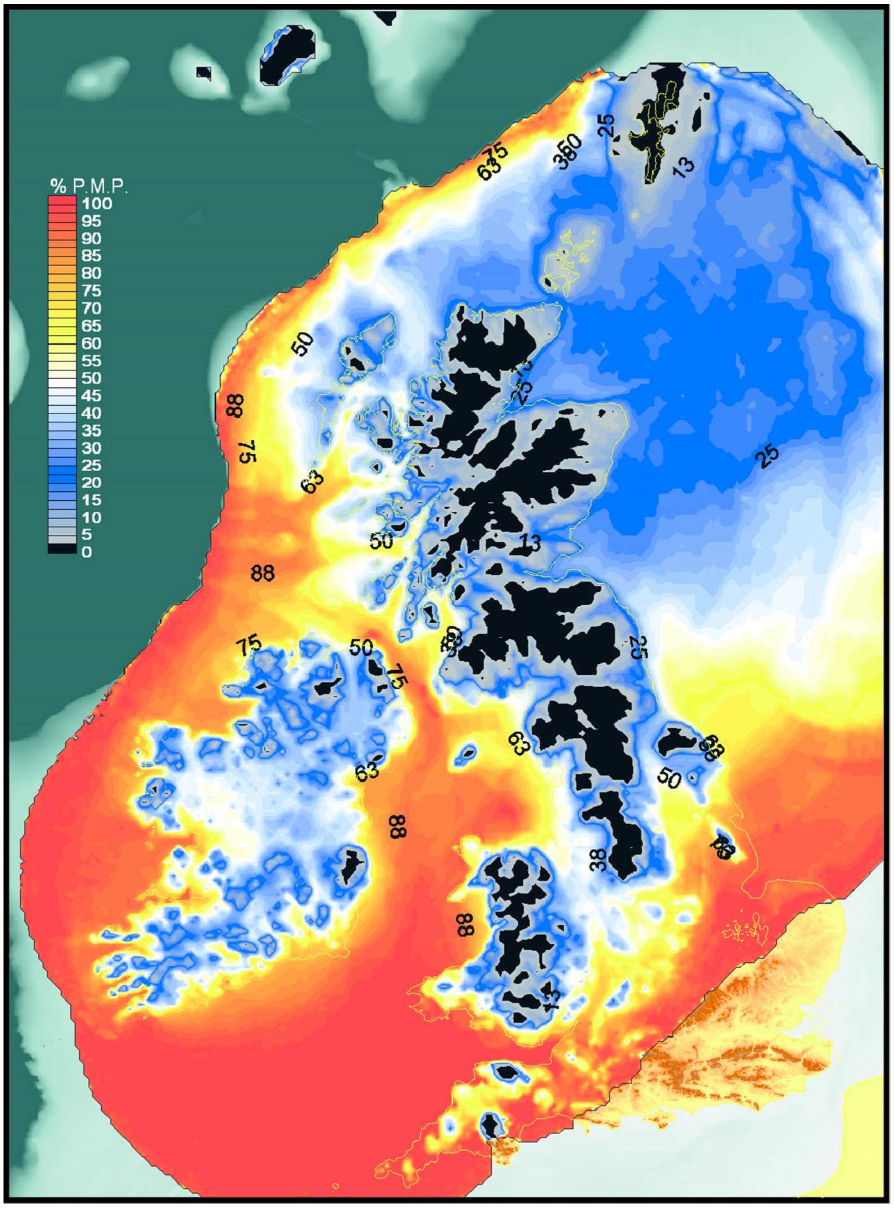

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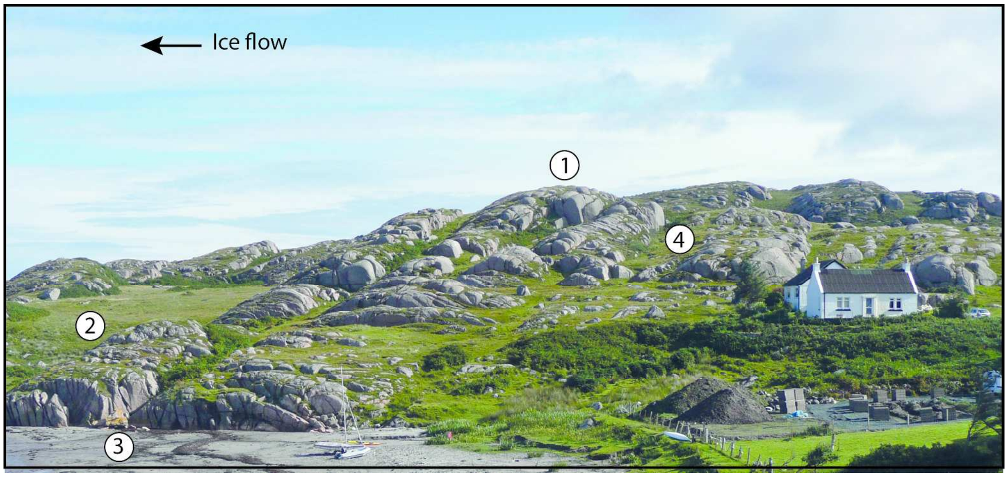

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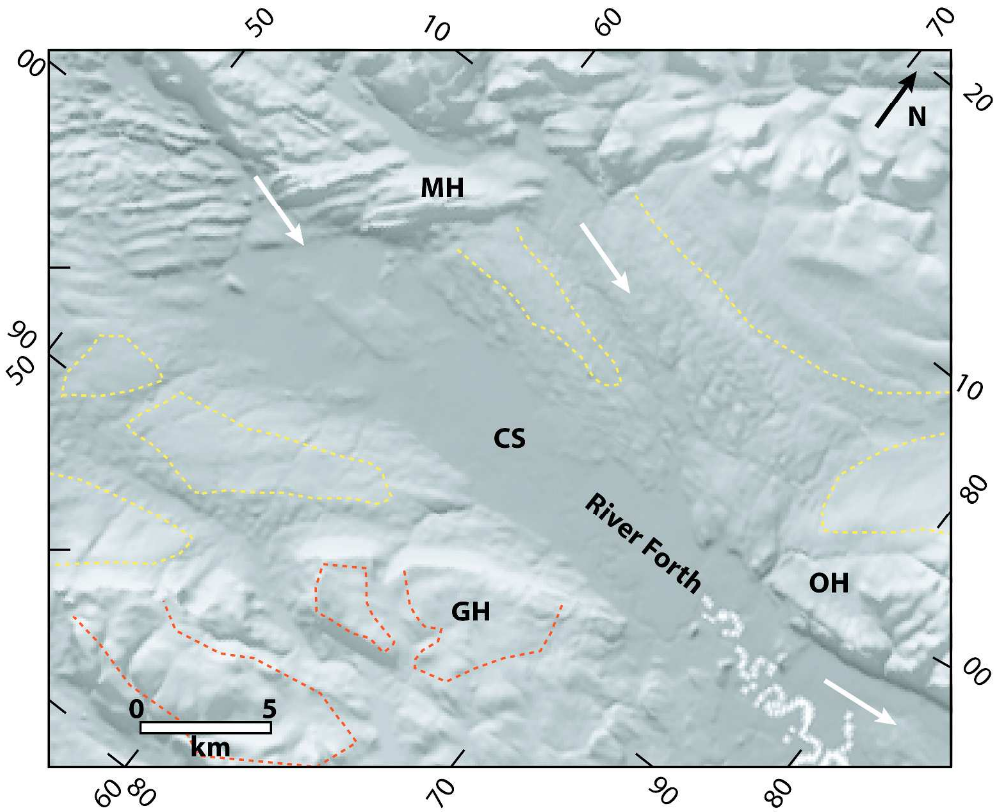

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21x13mm (600 x 600 DPI)

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159x89mm (220 x 220 DPI)

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159x119mm (220 x 220 DPI)

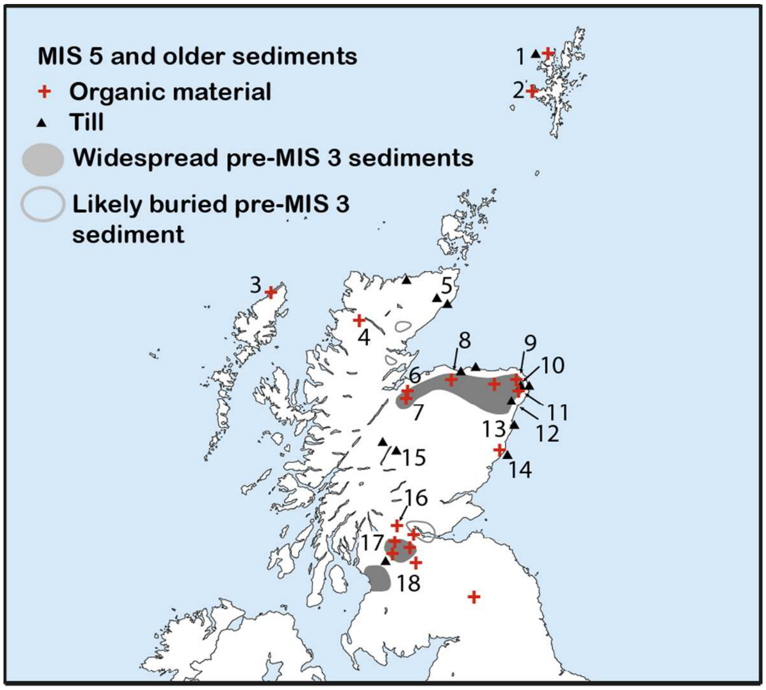

Figure 15. Sites with MIS 5 and older sediments in Scotland. 1. Fugla Ness (Hall et al., 2002). 2. Sel Ayre (Hall et al., 2002). 3. NW Lewis (Sutherland & Walker, 1984). 4. Inchnadamph (Lawson & Atkinson, 1995). 5. Caithness (Hall & Riding, 2016). 6. Dalcharn (Walker et al., 1992). 7. Allt Odhar (Walker et al., 1992). 8. Teindland (Hall et al., 1995). 9. Kirkhill (Connell et al., 1982). 10. Camp Fauld (Whittington et al., 1993). 11. Toddlehills (Gemmell et al., 2007) and Savock Quarry (Connell, 2015). 12. Pitlurg (Hall & Jarvis, 1995). 13. Nigg Bay (Gordon, 1993e). 14. Inverbervie (Auton et al., 2000). 15. Pattack (Merritt et al., 2013). 16. Balglass (Brown et al., 2006). 17. Lower Clyde (Rolfe, 1966; Finlayson et al., 2010). 18. Ayrshire (Jardine et al., 1988; Finlayson et al., 2010).

85x134mm (300 x 300 DPI)

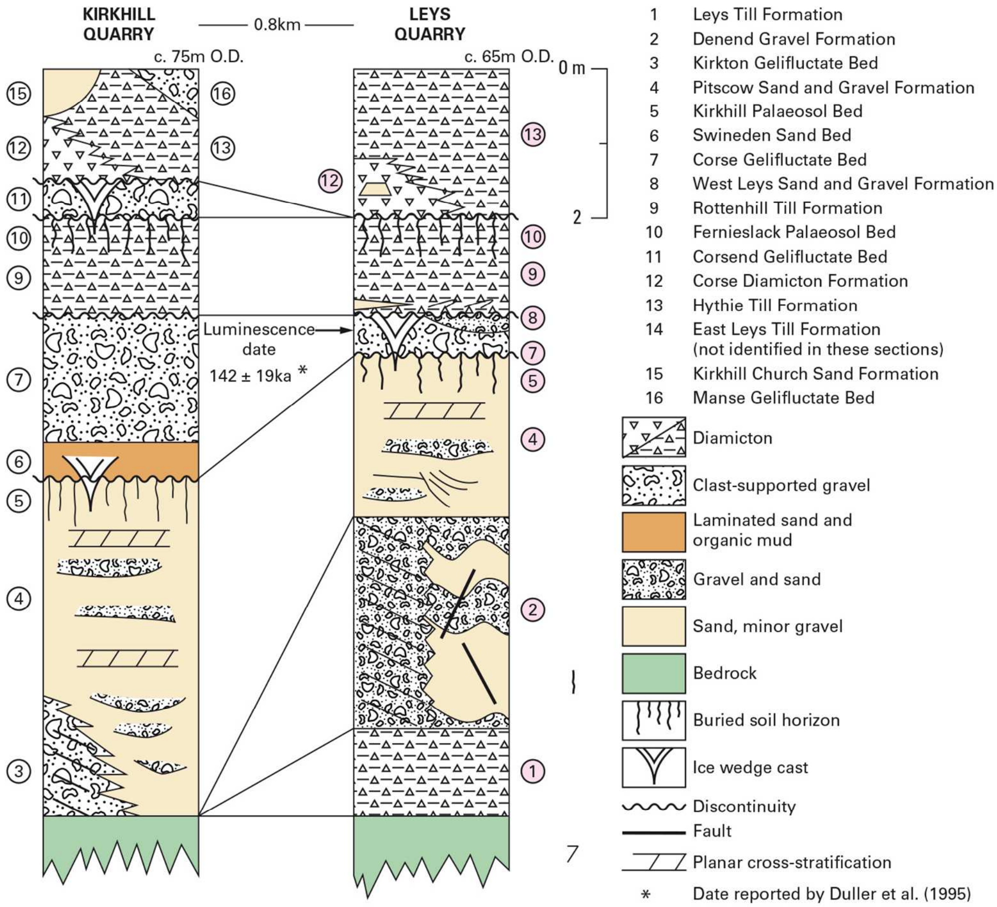

Figure 16. Kirkhill and Leys schematic Middle to Late Pleistocene stratigraphy (after Merritt et al., 2003). 1. Leys Till Formation. 2. Denend Gravel Formation. 3. Kirkton Gelifluctate Bed. 4. Pitscow Sand and Gravel Formation. 5. Kirkhill Palaeosol Bed. 6. Swineden Sand Bed 7. Camphill Gelifluctate Bed. 8. West Leys Sand and Gravel Formation. 9. Rottenhill Till Formation. 10. Fernieslack Palaeosol Bed. 11. Corsend Gelifluctate Bed. 12. Corse Diamicton Bed. 13. Hythie Till Formation. 14. East Leys Till Formation. 15. Kirkhill Church Sand Formation. 16. Manse Gelifluctate Bed.

127x115mm (300 x 300 DPI)

Figure 17. SW face of Leys Quarry 1990s. High-angle glacideltaic foreset gravels of the ?MIS 8 Denend Gravel Formation. Flow towards the W and SW. Note extensive Fe and Mn staining and local cementation of the sediments. Excavations below this gravel unit exposed the Leys Till resting on bedrock.

59x94mm (220 x 220 DPI)

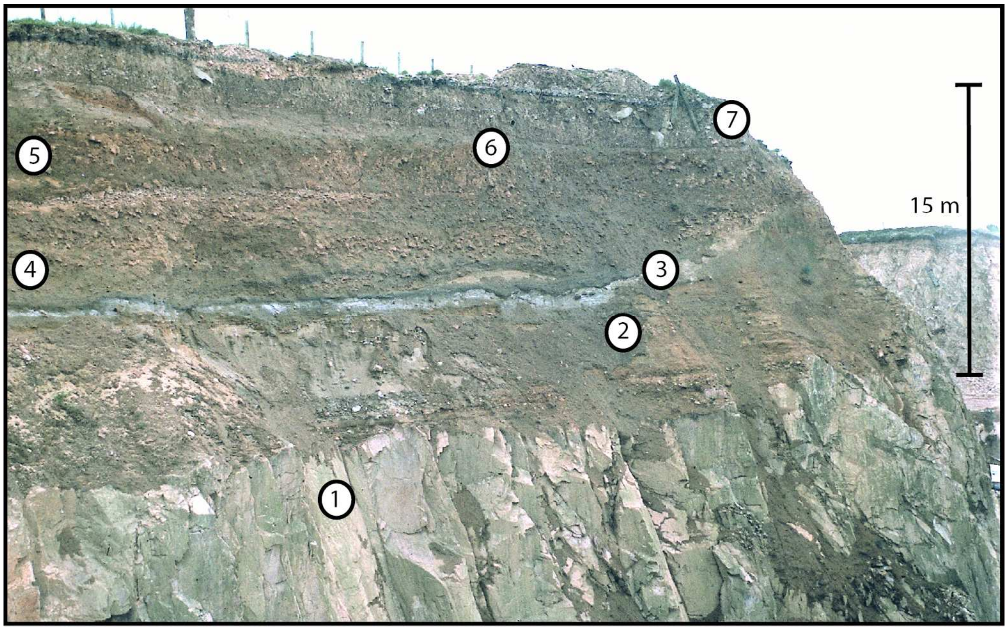

Figure 18. South Face 1 of Kirkhill Quarry in the late1970s. 1. Floor of meltwater channel cut in a felsite dyke. 2. Pitscow Sand and Gravel Formation. 3. Kirkhill Palaeosol Bed. 4. Camphill Gelifluctate Bed 5. Rottenhill Till. 6. Corsend Gelifluctate Bed. 7. Hythie Till.

170x106mm (300 x 300 DPI)

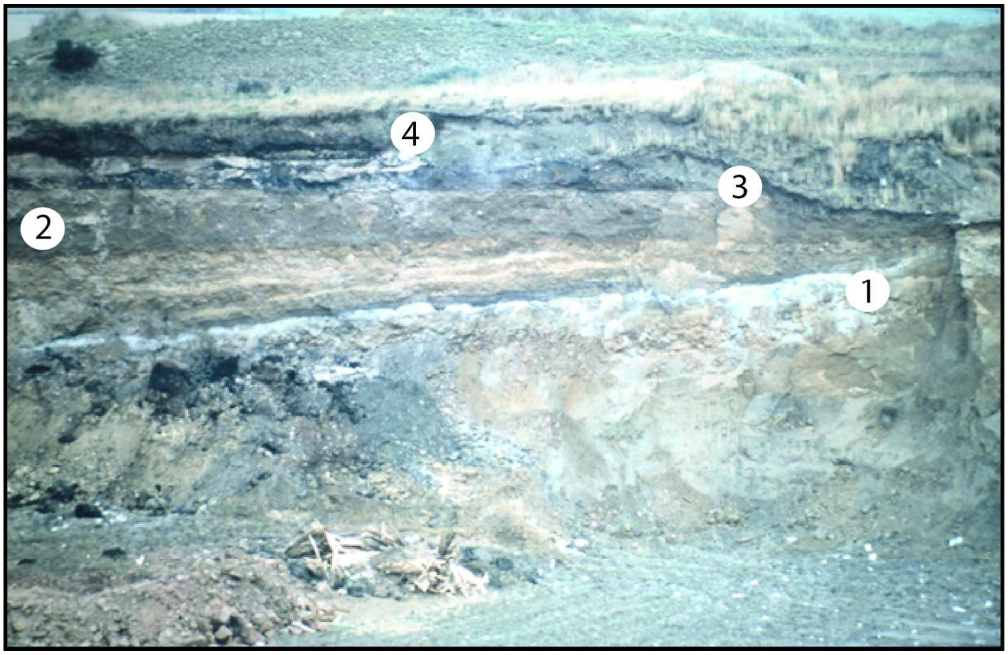

Figure 19. Kirkhill Quarry North Face in the 1980s. 1. Podzolic Kirkhill Palaeosol Bed. 2. Unconformable, sub-horizontal, base of the brown Rottenhill Till (within which the Fernieslacks Palaeosol Bed developed). 3. The black Corse Diamicton (incorporating glacitectonically-deformed pale coloured sand) overlies the Rottenhill Till. 4. Hythie Till. The section is approximately 15 m high.

175x113mm (300 x 300 DPI)

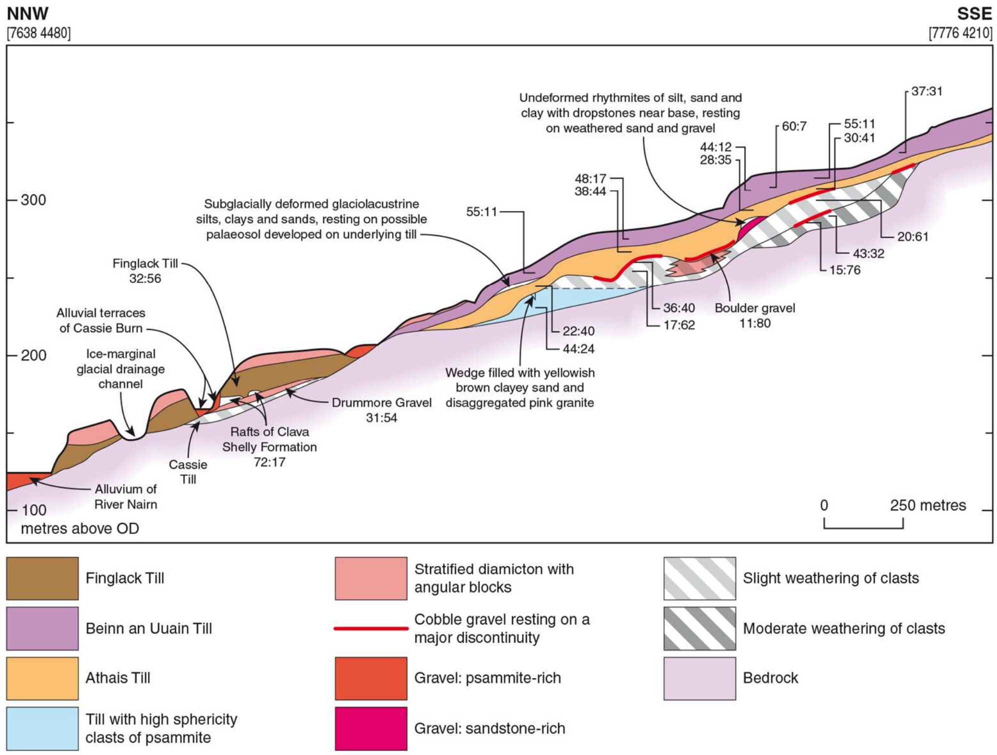

Figure 20. Longitudinal profile of the Allt Carn a'Ghranndaich valley upstream from Clava, showing multiple, buried and locally weathered Middle Pleistocene till and gravel units (after Fletcher et al. 1996).

139x105mm (300 x 300 DPI)

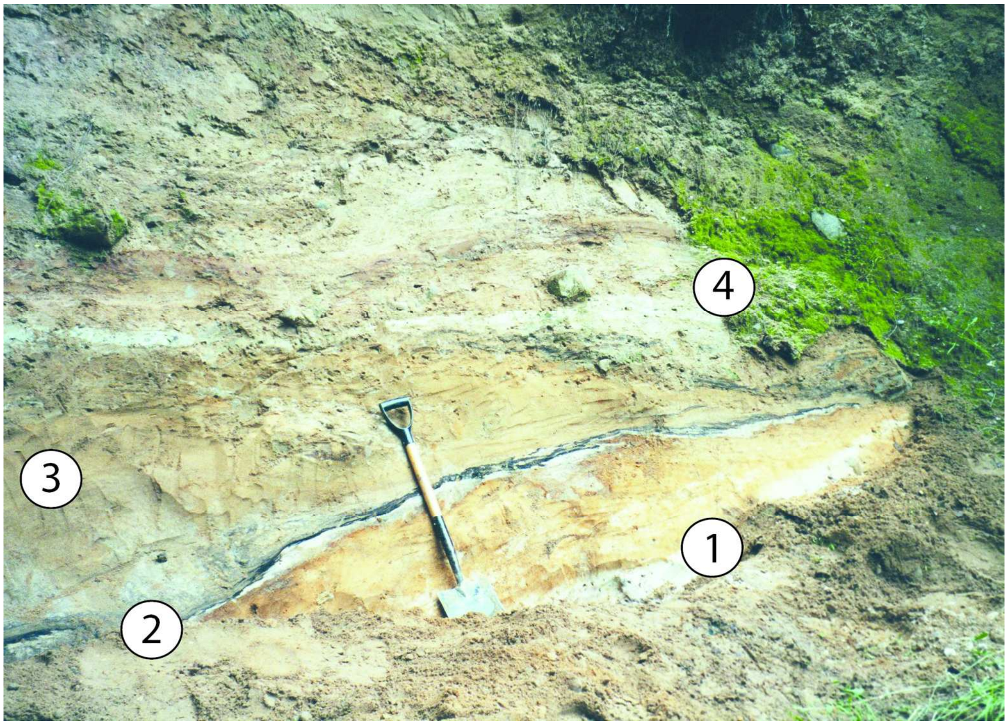

Figure 21. Teindland Quarry in 2000. 1. Teindland Lower Sand, 2. Teindland Buried Soil (MIS 5e). 3. Teindland Upper Sand. 4. Truncated and glacitectonically-sheared units beneath overlying Teindland Till.

170x121mm (300 x 300 DPI)

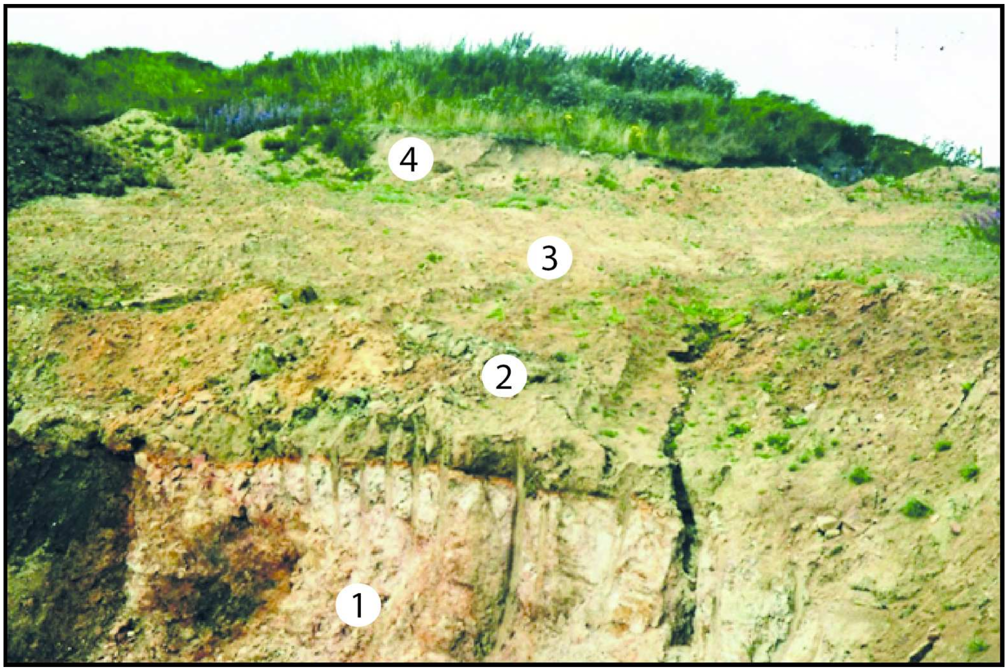

Figure 22. Toddlehills Quarry, N face. Weathered bedrock (1) is overlain by a till unit (2) correlated with the MIS 6 (191-123 ka) Rottenhill Till Formation at Kirkhill. OSL dated (mean 85 ka) sands are obscured by made ground in mid-section (3). Late Devensian Hythie Till Formation can be seen higher in the section beneath vegetated made ground (4).

171x113mm (300 x 300 DPI)

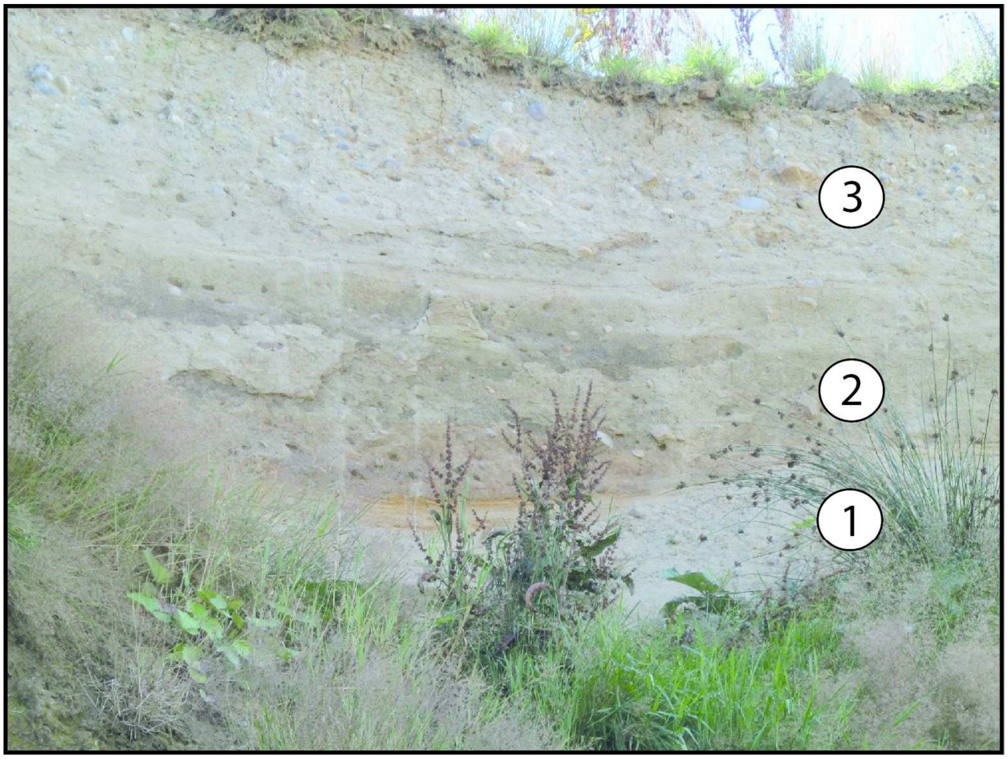

Figure 23. Savock Quarry in 2014. Section ~5m high. 1. Middle Pleistocene sand and gravel channel fill. 2. Brown, possibly weathered till correlated with the MIS 6 Rottenhill Till Formation at Toddlehills, Leys and Kirkhill. 3. Upper clast-rich till correlated with the MIS 3-2 Hythie Till.

159x120mm (300 x 300 DPI)

Fig 24 Benholm (high res)

176x129mm (300 x 300 DPI)