TITLE

The last glaciation in Caithness, Scotland: revised till stratigraphy and ice-flow paths indicate multiple ice flow phases.

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ABSTRACT

INTRODUCTION

The importance of the glacial stratigraphy of Caithness and Orkney for reconstructions of the north-eastern sector of the British-Irish Ice sheet (BIIS) has been recognised for over 150 years (Gordon, 1993b) (Figure 1). Caithness and Orkney carry extensive deposits of shelly till, a mud-rich diamicton with fragments of marine shells that was central to debates in the early development of glacial theory over the possible roles of sea ice and glacier ice in transport and sedimentation (Cleghorn, 1850; Croll, 1870; Jamieson, 1866). The regional pattern of ice flow at the period of maximum glaciation was soon interpreted, mainly from striae orientations and directions of erratic carry, as a simple, curving flow from the inner Moray Firth across Caithness and Orkney (Peach and Horne, 1880; Peach and Horne, 1881). Curving flow paths were attributed to deflection by the presence of the Fennoscandian Ice Sheet (FIS) in the North Sea basin (Croll, 1870). During deglaciation, ice retreat back into the inner Moray Firth and the Sutherland hills was marked by sets of moraines (Croll, 1870; Peach and Horne, 1880; Peach and Horne, 1881). This early two-phase model was supported and extended in the Geological Survey Memoirs in the early 20th century (Crampton and Carruthers, 1914; Wilson et al., 1935). Over the last decade, the availability of new, detailed maps of sea bed topography (Bradwell and Stoker, 2015; Bradwell et al., 2008), combined with identification of glacial flow sets from Digital Elevation Models (DEMs) for the entire BIIS (Hughes et al., 2010) and advanced simulations of its behaviour (Boulton and Hagdorn, 2006; Hubbard et al., 2009) have led to a much improved understanding of the changing patterns of ice flow in the last BIIS through the last glacial cycle. The regional sequence of glaciation also has been refined in studies of Late Pleistocene stratigraphy in Caithness (Hall and Whittington, 1989; Omand, 1978) and Orkney (Rae, 1976), in the lowlands of Buchan on the southern flank of the MFIS (Merritt et al., Submitted; Merritt et al., 2003) and, particularly, in the central and northern North Sea (Graham et al., 2010; Sejrup et al., 2014; Sejrup et al., 2009). The timing of deglaciation in Buchan, Caithness and Orkney also has been constrained by cosmogenic isotope exposure ages (Ballantyne and Hall, 2008; Phillips et al., 2008).

Despite these significant advances, many questions remain unresolved over the last glaciation of Caithness and Orkney. Ice sheet flow sets identified onshore (Hughes et al., 2014) and offshore (Bradwell et al., 2008; Hughes et al., 2014), together with simulations of behaviour of the last BIIS (Hubbard et al., 2009) remain to be thoroughly tested against regional Late Pleistocene lithostratigraphical records. Recent simulations (Hubbard et al., 2009) and reconstructions (Clark et al., 2012) suggest the former existence of a local ice cap on Orkney, a possibility that was rejected in earlier studies (Rae, 1976; Wilson et al., 1935). Furthermore, recent work suggests that a large, independent ice cap developed on Shetland and extended at least as far south as Fair Isle during the last glacial cycle (Flinn, 1978; Hall, 2013) and so may have influenced ice flow across northern Orkney and in the northern North Sea (Sejrup et al., 2014). Recent models (Hughes et al., 2014) have also indicated previously unrecognised flow paths for ice sourced from the eastern Grampians across the inner Moray Firth and continuing over Caithness and Orkney. The recent consensus that maximum ice extent on the West Shetland Shelf occurred soon after 30 ka (Bradwell and Stoker, 2015; Sejrup et al., 2005) places this event before the global Last Glacial Maximum (LGM) from 26.5 to 19 ka (Clark et al., 2009). Finally, despite 150 years of research (Croll, 1870; Flinn, 1978; Rae, 1976), the extent of the FIS in the western North Sea and its influence over the flow of the BIIS through the last glacial cycle also remains unresolved. These questions mean that it is timely to re-examine the terrestrial evidence for the pattern, sequence and timing of glaciation across Caithness and Orkney.

This paper aims to provide a revised reconstruction of regional patterns of ice flow across Caithness, Orkney and the adjacent sea bed by bringing together existing and new data on ice sheet bedforms, till stratigraphy, striae patterns and erratic suites. New evidence is provided on pathways for long distance glacial transport using indicator glacial erratics and the first identifications of palynomorphs of Devonian-Pleistocene age contained in tills. The combined morpho- and lithostratigraphical evidence allows a new regional event

stratigraphy to be set up for Caithness and Orkney through the last glaciation. The timings of the main events are then reviewed by reference to available dating evidence. The revised model reveals a complex ice flow history in Caithness and Orkney through the last glacial cycle and has important implications for the interactions between different ice centres in northern and eastern mainland Scotland, Shetland and southern Scandinavia.

STUDY AREA

GEOLOGY

The Devonian platform of Caithness and Orkney separates the Mesozoic basins of the Moray Firth and northern North Sea from the continental shelf of the eastern North Atlantic (Figure 2). Basement rocks form the hills of the Caithness-Sutherland border and include Moine quartzite, semi-pelite, mica schist and granulite (Johnstone and Mykura, 1989). Extensive granite intrusions occur around Helmsdale and in the headwater reaches of the Berriedale and Dunbeath Waters. A small inlier of Precambrian gneiss is found at and near Stromness, Orkney. The Old Red Sandstone cover comprises basal conglomerates, and thick sandstones and flagstones, including, on eastern Orkney, the distinctive red and yellow sandstones and marls of the Eday Beds (Mykura, 1976) (Figure 2).

The inner Moray Firth basin is floored by extensive Lower Cretaceous mudstones, with Permo-Triassic sandstones and Jurassic mudstones found around its margins (Figure 2). The basin fill becomes younger eastward towards the boundary with the outer Moray Firth, where a band of Upper Cretaceous Chalk passes beneath Palaeogene sands. A wide, submerged platform, formed mainly of Devonian to Triassic sandstones, occurs at depths of <50 m off eastern Orkney (Andrews et al., 1990) bounded by a marked break of slope, the Auskerry Rise (Flett, 1920).

ICE SHEET DYNAMICS

During the Pleistocene, ice flowed into the inner Moray Firth from a catchment area covering ~20,000 km^2 of the Northern and Grampian Highlands (Figure 1). The presence of shelly tills in Buchan, Caithness and Orkney has long been understood as evidence that ice periodically escaped from the confines of the Moray Firth to flow across areas of low relief on either shore (Croll, 1870). The Moray Firth has a floor at -40 m west of Helmsdale that slopes gently to ~100 m below sea level east of Orkney (Andrews et al., 1990). The low ground of Caithness and Orkney rises to elevations of >100 m, with hills reaching 250 m a.s.l. (Figure 1). Unconstrained ice flow thus required an ice sheet that was >~250 m thick at the present eastern coastline of the Moray Firth. Thicker ice, such as that needed to scour rock surfaces at elevations of up to 470 m on Hoy (Phillips et al., 2008) must have extended far onto the North Atlantic shelf.

An important control on ice sheet flow in northern Scotland was exerted by the soft Mesozoic mud rocks and Pleistocene tills and marine sediments found on parts of the floor of the Moray Firth (Andrews et al., 1990) (Figure 2). These deformable bed materials promoted the repeated development of short-lived ice streams within ice lobes occupying all or part of the inner Moray Firth (Boulton and Hagdorn, 2006; Hubbard et al., 2009). On land and on the Palaeozoic platform east of Orkney (Figure 2), the Devonian sandstones proved extensive rigid beds, with deformable units confined to the narrow bands of Devonian and Permian marls in eastern Orkney and close offshore.

Glacial geomorphology provides useful clues about former glacier basal thermal regimes on the land areas. Glacially-eroded surfaces are largely absent from the hills of Hoy and south-east Caithness (Figure 3) and instead tor-studded summits, thick mountain-top detritus and deeply weathered bedrock become common (Ballantyne and Hall, 2008; Godard, 1965). Here ice cover remained frozen-based, slow moving and non-erosive for long periods of the Pleistocene. More widely, however, across Caithness and Orkney, bedrock surfaces have been modified and locally streamlined by erosion beneath wet-based and fast-moving ice sheets.

Detailed mapping of individual landforms using relief-shaded renditions of high-resolution elevation data and Landsat imagery has allowed successive ice sheet flow sets to be identified across the British Isles (Hughes et al., 2010). In Caithness and Orkney, the two main flow sets for drift bedforms run parallel to rock bedforms (Figure 3). Flow Set A (FS-2) relates to the former flow of the Northern Highland ice and Flow Set B (FS-1) to Moray Firth ice. These flow sets are overprinted locally by younger flow sets that relate to final deglaciation (Hughes et al., 2014). Widely-scattered fragments of former moraine systems, represented mainly by subdued, low ridges, provide important clues as to the patterns of ice retreat from Orkney and Caithness (Charlesworth, 1956; Rae, 1976) that can be added to the much-improved offshore record (Bradwell and Stoker, 2015; Bradwell et al., 2008; Clark et al., 2012) (Figure 3).

METHODS

The shelly till has long been recognised as a unifying stratigraphical marker horizon for the last glaciation in Caithness and Orkney because of its near-surface position, distinctive mud-rich, calcareous, shell-bearing diamictons and apparently regionally coherent striae patterns. Examination of the regional stratigraphy is simplified by describing sediment units found stratigraphically below, within and above and also contiguous with the shelly till (Figure 4). Shelly tills deposited by ice moving out of the Moray Firth are formally assigned to the Banffshire Coast, Caithness and Orkney Glacigenic Sub-Group (BCODG) (Table 1). This revised nomenclature combines two pre-existing Sub-Groups (the Banffshire Coast and Caithness and the Orkney Sub-Groups) (McMillan and Merritt, 2012) in recognition of the long-established use of the term "shelly till" to describe sourced from the Moray Firth (ref). Tills deposited by ice moving directly from the Northern Highlands are assigned to the Northern Highlands Glacigenic Drift Sub-Group (NHDG) (McMillan and Merritt, 2012). A detailed proposal for a revised, formal Late Pleistocene stratigraphy of Caithness and Orkney will be set out in another paper. The focus here is on examining the lithology, content and clast fabrics of the main till units and of sediments that may indicate ice-free periods to provide information on the sequence and pattern of former ice flow. Many thick diamicton sequences await detailed sedimentological study.

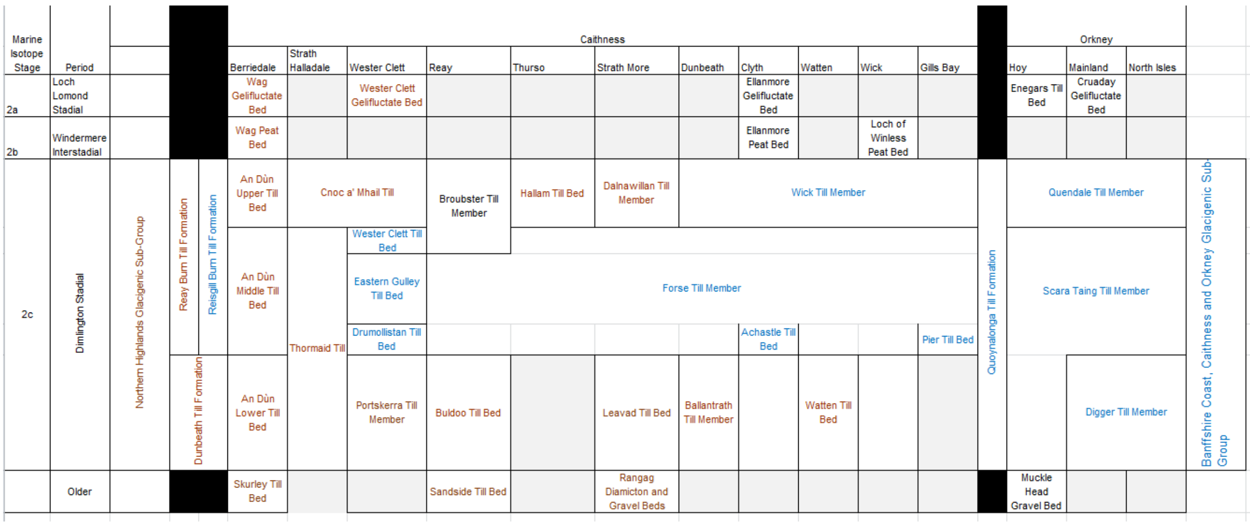
Striated bedrock surfaces are widespread on newly-exposed surfaces on the Old Red Sandstone. Although the sense of direction of some striae sets in Caithness first mapped in the 19th century (Peach and Horne, 1880; Peach and Horne, 1881) has been questioned (Flinn, 1981), more recent observations and other ice-flow directional indicators have generally confirmed striae azimuths (Hall and Whittington, 1989; Rae, 1976). Here existing and new data for striae on bedrock surfaces beneath till is matched, using striae on sub-till rock surfaces, to the main till units to indicate ice flow directions prior to till deposition (Figure 5).

New information is presented for 20 sites on the Devonian-Quaternary palynomorphs found as a component of the till matrix (Figure 6). The palynomorphs were derived directly by glacial erosion of mudrocks in the Moray Firth and indirectly through recycling from Pleistocene sediments. The palynomorphs are important in lithostratigraphical correlation and for exploring directions of long-distance glacial transport. The allochthonous palynomorph content was extracted through non-acid palynological preparation techniques (Riding and Kyffin-Hughes, 2004). ~~Three slide fractions were prepared from each residue through swirling and heavy liquid separation, representing a light, heavy and centrifuged sub-sample~~. Suggest delete The palynomorphs were grouped according to stratigraphical ranges, thus indicating their likely provenance.

Existing and new information for glacial erratics is also linked to till units (Figure 7). On the North Isles of Orkney, this information includes far-travelled erratics identified by walking storm beaches besides eroding till sections. Conventional stone counts for tills are of restricted value on Orkney because clast concentrations of non-Orcadian rocks in tills are very low (~430 ppm: Rae, 1976). Even in the cobble to boulder size fraction on beaches of Eday, concentrations of far-travelled erratics estimated from surface stone counts remain very low, with clasts from mainland Scotland found as <100 ppm and from Fennoscandia as <1 ppm. Known wreck sites were excluded from beach surveys to reduce the possibility that exotic clasts were introduced by human agency. The distribution of indicator erratics allows the ranges of erratics from different ice centres to be identified (Figure 7B).

The combined stratigraphical and flow path information is used to generate a revised event sequence for the last BIIS in Caithness and Orkney. The minimum extent of each advance is indicated by the areal and vertical distribution of individual till units and associated striae. The timing of the main events is constrained, where possible, by reference to existing dating information from radiocarbon dates and amino acid racemisation (AAR) ratios for marine shells from shelly till units (Bowen et al., 1989; Bowen and Sykes, 1988) and from cosmogenic exposure ages (Ballantyne, 2010; Phillips et al., 2008). Ice flow paths on land are shown mainly by sub-glacial bedforms, till fabrics, striae and local erratic carry. Flow paths across the floor of the Moray Firth are less clear but are loosely constrained by till palynomorphs and long distance erratic carry. The regional event sequence is then examined in the context of wider ice movements in the north of Scotland and the northern North Sea and of simulations of the behaviour of the north-eastern sector of the last BIIS. Flow path and ice extent information allow production of cartoons to show ice movements at maxima of different ice advance events. (Figure 8).

RESULTS



In Caithness, the main traps for thick glacial sediments were deep valleys and gorges along the Moray Firth coast, linear depressions in interior Caithness and rock steps and valleys at the Atlantic coast (Gordon, 1993b). Here drift thicknesses can locally exceed depths of 30 m (Crampton and Carruthers, 1914). Similar traps are absent on Orkney and exposed glacial sediments are almost everywhere <10 m thick (Rae, 1976). The Late Pleistocene stratigraphy of Caithness and Orkney consists mainly of stacked diamicton sequences with few intercalated beds of sand and gravel. No inter-till organic beds are yet known, in sharp contrast to the situation on the southern flank of the Moray Firth (Merritt et al., 2003).

NORTHERN HIGHLANDS GLACIGENIC DRIFT SUB-GROUP

Tills derived directly from ice flowing out of the Northern Highlands occur in western Caithness and in eastern Sutherland beyond the western limit of the BCODG and as units above and below the Forse Till Member east of the limit of the BCODG on the plain of Caithness (Figure 4). No shell debris or Mesozoic palynomorphs have been identified in the NHDG.

Within the zone exclusively covered by Northern Highlands ice that lies west of the shelly till limit in northern Caithness, striae orientations trend northwards (Auton, 2003) and swing progressively towards the east and south-east moving from central to southern Caithness. A radial pattern of striae left by Northern Highland ice is also found east of the shelly till limit, trending north-east towards Thurso, east towards Watten and south-east towards Dunbeath. As some of these striae occur beneath different till units (Figure 5), the striae are not coeval and relate to different phases of flow of the Northern Highlands ice sheet. Crossing striae in the Reay and Thurso areas include a south-west to north-east trending set that is abraded and partially destroyed by a second set which trends south-southeast – north-north-west (Auton, 2003; Crampton and Carruthers, 1914; Peach and Horne, 1881).

Erratics derived from granites and migmatite masses from Strath Halladale southwards are found in the Reay Burn Till Formation across northern and central Caithness. These rock types have been reworked in places into the Forse Till (Figure 7A). Migmatites and granites derived from the east also occur in glacial moraines and glacifluvial gravels that overstep the Forse Till towards Watten. Quartzite, quartz psammite and mica schist erratics derived from the hills of SE Caithness are common in the Dunbeath Till Formation, deposited prior to the Forse Till, and the Ladies' Tent Till Member, deposited after the Forse Till (Hall and Whittington, 1989).

DUNBEATH TILL FORMATION

The Dunbeath and Reay Burn Till Formations are found in southern and northern Caithness, respectively. Both Formations include multiple till units (Table 1). The oldest tills in the Dunbeath Till Formation occur as isolated units on valley floors in lower Berriedale (Hall and Whittington, 1989) and at Leavad (Tait, 1912) and may predate MIS 2 glaciations. In the valley of the Dunbeath Water, the overlying Balantrath Till Member occurs extensively. Underlying striae, stone counts, oriented boulders and till fabrics indicate deposition by ice flowing to the south east or east and into the inner Moray Firth (Hall and Whittington, 1989). In the lower part of the valley, contacts between the Balantrath Till Member and the overlying shelly Forse Till are sharp and erosive but, at Dunbeath Cemetery, interbedded brown and grey muds and diamictons occur between the two till units, indicating a possible hiatus in deposition. Till beds probably belonging to the Balantrath Till Member, with igneous and metamorphic erratics derived from the west, occur beneath the large Lower Cretaceous erratic within the Forse Till at Leavad (Tait, 1912) and also at Watten (Omand, 1973).

REAY BURN TILL FORMATION

A similar stratigraphical position below the earliest recognised shelly till unit is evident for the Portskerra Till Member, found on the north coast of Caithness between Portskerra and Reay. The abundance of migmatite and granite debris, together with fabric data, indicates deposition by Northern Highland ice moving northwards and passing beyond the present Atlantic coastline. The Portskerra Till is locally overlain by thin gravel beds, with erected pebbles at one site, indicating a break in deposition and ice-free conditions before the first advance of ice from the Moray Firth (Hall et al., 2011).

Along the northern Caithness-Sutherland border, the NHDG is represented by the Thormaid Till Member, with clasts of predominantly Caledonian igneous and Moine metamorphic rocks derived from the south (Auton, 2003). In exposures in the Smigel Burn, the Thormaid Till rests on deformed glacilacustrine sands and muds and includes multiple diamicton beds. The oldest of these units is in a similar stratigraphic position to the Portskerra Till and is probably time equivalent. Younger units of the Thormaid Till appear to be absent from the coast at Portskerra (Hall et al., 2011). Inland, however, the Thormaid Till is contiguous to the east with the Broubster Till Member. The Broubster Till incorporates clasts of Devonian sandstones, conglomerates, siltstones and mudstones, and some Caledonian igneous and Moine metamorphic rocks and was deposited by ice moving from the south or south-east (Auton, 2003). As the two tills are not seen in superposition, the lithological differences between them are gradational from west to east and the flow directions are similar, it is likely that till units from the middle part of the Thormaid Till and Broubster Till Member are of broadly similar age. The Broubster Till is replaced eastwards by the Forse Till but lies within its western limit (Hall et al., 2011).

A range of till units, gravel bodies and ice-marginal landforms found as far south as Leavad record late readvances and deglaciation of the ice sheet moving from the hills of the Sutherland-Caithness border on to the plain of Caithness. West of Thurso, the thin Hallam Till Member, with many migmatite and granite erratics, rests with an erosional contact on the Forse Till (Auton, 2003). West of Reay, the boulder-rich Cnoc a' Mhail Till Member marks a final advance of Northern Highland ice beyond the north coast and its associated recessional moraines record its retreat towards the south into the main valleys (Auton, 2003). At Dirlot in central Caithness, a set of well-defined moraine ridges overstep the shelly till boundary (Peach and Horne, 1881) and may represent a readvance after an earlier, broader advance towards Watten that deposited outwash with abundant igneous and metamorphic clasts derived from the west in the Burn of Acharole (Crampton and Carruthers, 1914). West-east striae found on both sides of the shelly till limit (Figure 5) may also relate to this phase. No overstep of the Forse Till by tills derived from the hills of south-east Caithness is seen in the lower Dunbeath Water valley but the youngest till at the mouth of Berriedale is from inland and sets of recessional moraines from ice retreating inland occur on the valley floors of the Langwell and Berriedale Waters (Hall and Whittington, 1989).

BANFFSHIRE COAST, CAITHNESS AND ORKNEY GLACIGENIC SUB-GROUP

Tills deposited by ice moving out of the Moray Firth extend from the western border of Caithness to the North Isles of Orkney (Figure 4). Till colour is determined by the local Devonian geology and Devonian debris dominates the clast assemblages (Omand, 1978). The till matrix is derived at least in part from mud rocks in the Moray Firth and contains palynomorphs reworked from these mud rocks and also fragments of marine shells derived from erosion of Pleistocene marine and glaciomarine muds and sands in the Moray Firth. Traditionally, the shelly till was regarded as a single stratigraphic unit (Peach and Horne, 1881) but it is now clear that several till units exist within the BCODG and provide evidence of multiple flow events.

East of the shelly till limit, the pattern of striae is complex (Figure 5). From the coast at Lybster, striae trend SSE-NNW (Omand, 1978). Further north at Wick, striae swing round towards the north-west, a trend that is maintained to the Pentland Firth. Striae of similar orientation occur below the Forse Till. It is noteworthy however that striae occurring beneath beds of the Forse Till at Gills Bay vary in orientation from NW to NNE indicating shifting ice flow directions during deposition of different till beds. Towards Wick, striae associated with the Wick Till run parallel to the coast (Flinn, 1981). Crossing sets of striae occur around Watten (Crampton and Carruthers, 1914) in association with drumlins and moraines that also indicate shifting flow patterns (Hughes et al., 2010) in the Loch of Watten depression.

On Deerness, east Mainland, striae beneath the Digger Till show a median orientation of striae of 162˚ (Rae, 1976). The dominant set of striae patterns on Orkney, however, run SE-NW across Mainland and the eastern isles of Stronsay, Eday and Sanday, turning towards the west on Westray. Parallel striae extend to hill tops on Mainland, Westray and Rousay and indicate limited topographic control on ice flow. On the North Isles, these striae orientations conform to those found beneath the Scara Taing Till and so relate to full ice cover on Orkney. Striae orientations that deviate from this general pattern also occur widely (Figure 5). Crossing striae occur locally on Rousay and Eday (Wilson et al., 1935). Orientations that indicate topographic control over ice flow beneath thin ice cover occur on Westray, Rousay and Mainland, and include rock surfaces lying below the Quendale Till.

The Helmsdale Granite and dark grey biotite gneisses similar to Moine rocks that are common in the valleys of rivers draining Easter Ross and east Sutherland are well represented in the Forse and Wick Tills in Caithness (Jamieson, 1866) and also extend into eastern Orkney (Figure 7A). Far-travelled erratics from Ross-shire include the surface boulders of Inchbae augen gneiss and Cambrian Pipe Rock found in northern Caithness (Peach and Horne, 1881), on Stroma (Peach, 1860) and in eastern Orkney (Figure 7A).

Erratics of Late Jurassic to Early Cretaceous sedimentary rocks have been reported along both the south-eastern (Sutherland, 1915) and northern coasts of Caithness (Crampton and Carruthers, 1914) and extend into eastern Orkney (Peach and Horne, 1881). These erratics include large rafts at Leavad (Tait, 1912) and Wick (Tait, 1907). The source area for these erratics comprises much of the floor and western fringe of the inner Moray Firth (Figure 2). A number of indicator erratics however can be traced to sources on the northern edge of the inner Moray Firth basin. These include Helmsdale Granite and granite-rich Old Red Sandstone conglomerate clasts found commonly in the Forse Till at Dunbeath and also further north (Hall and Whittington, 1989).

Chalk and flint erratics first appear in tills at Wick and are abundant in the Pier Till Bed at Gills Bay and on the island of Stroma (Peach, 1860). Chalk and flint remain common on Deerness, Mainland (Rae, 1976), with chalk clasts confined to the Scara Taing Till, and are conspicuous components of the exotic clasts found in tills and on storm beaches on the north isles of Orkney and extend as far north as Fair Isle (Hall and Fraser, 2014). A few flints are found on west Mainland, Orkney, but without chalk (Rae, 1976). The sole primary source for these erratics is the Cretaceous chalk outcrop at the edge of the inner Moray Firth (Figure 2).

No erratics from the Grampian Highlands have been recognised in Caithness south of the Pentland Firth. At Gills Bay, erratics of Dalradian pelites and schist occur together with basic and ultrabasic igneous rocks of similar lithology to the Caledonian igneous and Dalradian metamorphic rocks found in the lowlands of Moray and Buchan (Figure 2). Small numbers of similar rock types are found in eastern Orkney, extending northwards to North Ronaldsay (Peach and Horne, 1893) and to Fair Isle (Hall and Fraser, 2014) (Figure 7A).

Erratic clasts on Orkney are illustrated on-line (http://www.landforms.eu/orkney/glacial erratics.htm). Erratics on North Ronaldsay include volcanic rocks that may be derived from the Forth lowlands (Peach and Horne, 1893). A few Carboniferous limestone boulders also have been identified from till at Mill Bay, Stronsay (Gordon, 1996), and on the storm beaches of the North Isles and Fair Isle (Hall and Fraser, 2014). Scandinavian erratics are confined to the North Isles of Orkney (Figure 7) and extend northwards to Fair Isle (Hall and Fraser, 2014) and the southern tip of Shetland (Hall, 2013). Most finds come from storm beaches but two Norwegian erratic clasts have been recovered from the Scara Taing Till on Westray (David Leather, pers. comm. 2006). Indicator rock types include rhomb porphyry and larvikite derived from the Oslo Graben (Smed and Ehlers, 2002) and probably also the distinctive actinolite hornblende gneiss of the Saville Boulder on Sanday (Saxton and Hopwood, 1919), although Rae (1976) makes mineralogical comparisons with Lewisian and Moine oligoclase hornblende gneisses in Sutherland. Other rocks likely derived from southern Norway or south-west Sweden include high grade, light grey gneisses, together with porphyries and granites (R. Vinx, pers. comm.2008). One granite clast from Carrick, Eday, shows pyterlite rapakivi textures and probably derives originally from Åland in the Baltic. Whilst there is a need for U-Pb dating of zircons on gneiss clasts to confirm a Palaeoproterozoic age and hence a source on the Fennoscandian shield and whilst some Scandinavian material, as with the laurdalite boulders on Flotta (Saxton and Hopwood, 1919), probably represents boat ballast (Flinn, 1978), it is now clear that Scandinavian erratics exist in very low concentrations in tills and storm beaches north of the Stronsay Firth on Orkney.

REISGILL BURN TILL FORMATION OF CAITHNESS

Sequences of till up to 25 m thick cap cliffs along the southern coast of Caithness. Exposure is generally poor and, in the general absence of detailed stratigraphic investigations, the deposits are assigned to the Forse Till Member. At the type site at Forse, a basal, brown, massive, shelly till unit, the Chruidh Till Bed, with very high proportions of grey mudstone and brown sandstone clasts, and rare Helmsdale Granite clasts, may represent an early advance of ice from the Moray Firth. The overlying Forse Till at the type site is a dark grey to dark brown diamicton, with a matrix of sandy silt, matrix-supported pebbles of diverse lithologies and scattered shell fragments.

At Leavad, in central Caithness, the Forse Till incorporates a large (250 m - long) erratic of Lower Cretaceous sandstone believed to have been transported by ice over a distance of at least 15 km from the floor of the Moray Firth (Gordon, 1993c). The raft is overlain by the Dirlot Till but old photographs also indicate that the mud-rich Forse Till has been injected into glacitectonic pull-apart structures in the upper surface of the sandstone raft (Tait, 1909). This accords with the recovery of a mixed assemblage of palynomorphs from near-surface, mud-rich diamicts above the sandstone raft. Pollen and spores are of Mesozoic aspect, with the occurrence of *Cicatricosisporites* sp. indicative of an Early Cretaceous age. Marine palynomorphs are also present with dinoflagellate cysts dominant in an assemblage of mainly Early Cretaceous character. Forms diagnostic of the Jurassic–Cretaceous transition are also present, however, and require that the Forse Till here also contains palynomorphs from the Kimmeridge Clay Formation. Boreholes have shown that the sandstone rests on green, laminated, shelly clays (Tait, 1912) of Miocene, or younger age (Gordon, 1993c) that lack a known source in the inner Moray Firth (Hall, 1991). The raft is underlain by >17 m of diamicts and gravels deposited by the Northern Highlands ice sheet and belonging to the Dunbeath Till Formation, a sequence that infills a buried channel of the Little River (Tait, 1912).

On the Caithness-Sutherland boundary at Wester Clett, three till units derived from the Moray Firth are recognised: the Drumhollistan, Eastern Gulley and Wester Clett Till Members. The Drumhollistan Till is a stiff grey, muddy diamicton unit with very sparse, small shell fragments and a clast assemblage dominated by grey flagstones (Hall et al., 2011). Allochthonous palynomorphs, plant tissues and wood fragments are present in the till matrix and include abundant Middle Jurassic to Early Cretaceous dinoflagellate cysts, but no material of post Hauterivian age (Riding, 2007, 2010). The Drumhollistan Till passes up into and is overlain by bedded diamictons, with intercalations of gravel and massive, locally deformed beds of sand, that probably represent debris flow deposits. The bedded diamictons are covered by bedded and cemented gravel and sand, up to 15 m thick, deposited by meltwater flowing from the south to form alluvial fans in ponds dammed by ice against the coastal cliffs. The Eastern Gulley Till is an overlying brown diamicton, up to 17 m thick, that shows features typical of subglacial till deposition, with striated and bevelled clasts, boulder pavements and matrix-supported clasts. Clast composition is dominated by Devonian sandstone and grey flagstone and this unit can be correlated with the Broubster Till (Hall et al., 2011). Till fabric indicates deposition by ice flowing from the south-east. The till has a calcareous matrix which has yielded abundant Lower Cretaceous dinoflagellate cysts and sparse Carboniferous spores, indicating erosion of Late Tithonian to Berriasian/Early Valanginian (latest Jurassic– Early Cretaceous) rocks in the inner Moray Firth which are known to incorporate reworked Carboniferous palynomorphs (Windle, 1979). The base of the overlying Wester Clett Till Member locally rests on deformed sand and gravel, marking a possible break in sedimentation, and is elsewhere marked by boulder lags. The Wester Clett Till is up to 6 m thick and comprises a dark yellowish brown muddy diamicton, weathered to a reddish brown colour beneath the present landsurface. The colour contrast between the Eastern Gulley and Wester Clett Tills is accompanied by an increase in brown sandstone, red granite and migmatite clasts in the upper unit, indicating a more southerly component of flow (Hall et al., 2011). Allochthonous palynomorphs include sparse Lower Cretaceous dinoflagellate cysts. The Wester Clett is interpreted as a mixed unit contiguous with upper units of the Forse Till.

Dark grey shelly till of the Forse Till can be followed up valleys including the Dunbeath Water (Hall & Whittington 1989) and Strath More (Peach & Horne 1881) until it is replaced abruptly by the Dunbeath Till Formation. No ice-marginal sediments or landforms are known and so the drift limit of the Forse Till clearly is not an ice margin (Hall & Whittington 1989), contrary to other interpretations (Bowen et al., 2002). West of the shelly till limit near Dunbeath, striae run south to north, parallel to striae found below the Forse Till. The western limit of the Forse Till relates to a flow phase when ice from the Northern Highlands was diverted to flow north alongside the MFIS.

On the coast of northern Caithness, the Forse Till attains thicknesses of >10 m at Forss and >30 m at Scrabster (Crampton and Carruthers, 1914). Till palynomorphs at these two latter localities belong to assemblages with forms typical of the Jurassic-Cretaceous transition and the Early Cretaceous. At Scorriclett, south of Watten, Jurassic–Cretaceous pollen and spores are again present in abundance. Of particular interest are the low levels of Palaeogene material that was also entrained into this till, as shown by the presence of rare *Wetzeliella* sp. and *Achomosphaera andalousiensis*. Further east, at Gills Bay, the Forse Till is up to 10 m thick and shows high proportions of chalk and flint clasts, in addition to basic and ultrabasic igneous clasts and Dalradian schists derived from north-east Scotland. At its base lies the Pier Till Bed, a 20 cm thick unit with many chalk and flint clasts that may represent a source for Late Cretaceous clasts found higher in the till sequence. Striae on the underlying sandstone surface are oriented to 20˚ whereas striae on adjacent bedrock surfaces beneath the Forse Till are oriented to 320˚. The till sequence at Gills Bay includes a relatively rich palynoflora entirely dominated by Middle Jurassic-Early Cretaceous palynomorphs, with sparse Eocene input due to the rare occurrence of *Homotryblium tenuicostatum*, and also extremely rare Carboniferous spores (*Densosporites* spp.).

Shell debris is widely present in the Forse Till in Caithness and the Scara Taing Till on Orkney. The shells occur as fragments and many are abraded and striated. The number and size of shells fragments generally decreases from south to north in Caithness and from south-east to northeast in Orkney, consistent with comminution during glacial transport from the floor of the inner Moray Firth. The 19th century controversy over the origins of the shelly till in Caithness led to the careful identification of molluscs and ostracods found as fragments in tills in Caithness (Peach, 1858, 1859, 1863a; Peach, 1863b). The species lists for Caithness include mainly fauna found presently in the North Sea (Saxon, 1973), together with a few cold water indicators (Peach, 1863b). Few littoral or shallow water forms are represented (Peach, 1863b). No faunal lists of marine mollusca exist for Orkney to compare to Caithness. Recorded species include *Arctica islandica*, *Astarte* sp., *Saxicava arctica*, *Mya truncata*, *Mytilus edulis* (Peach and Horne, 1880; Wilson et al., 1935), with *Dentalium* on North Rona (Peach and Horne, 1893). Aside from *Mytilus*, the records also include few littoral species. The species also have mainly cool temperate to boreal affinities. It can be concluded that the source sediments for the marine shells now found in the Forse and Scara Taing Tills were marine muds mostly deposited beyond the littoral zone under sea surface temperatures similar to or colder than the present. Based on published interpretations of amino acid racemisation ratios, the marine sediments from which the shells were derived covered a wide age range between MIS 7 to MIS 3 in Caithness and MIS9 to MIS3 on Orkney (Bowen et al., 2002; Bowen and Sykes, 1988), indicating that the source marine sediments spanned a similar age range. Shells from Latheronwheel have yielded D/L amino acid ratios of 0.085 that support a Late Devensian age for the Forse Till (Bowen and Sykes, 1988). *Turritella* at Gills Bay have provided infinite radiocarbon ages of >34,700 B.P. for the inner fraction (Birmingham 179b) and >40,800 B.P for the outer fraction (Birmingham 179a). An unidentified bivalve mollusc shell from Forss also has an infinite AMS ^{14}C age of >47, 970 ^{14}C years BP (Beta-175903). An abraded fragment of unidentified mollusc shell from Forse Till near Scrabster has an finite AMS ^{14}C age of 46,160 ± 860 ^{14}C years BP (Beta-175902) (Auton, 2003). Marine shells from till have also yielded three infinite dates of >43450, >43450; and >36170 ^{14}C years BP (SRR-487-489) from borehole 74/17 close to the Caithness coast (Figure 1) (Harkness and Wilson, 1979).

Along the coast from Dunbeath northwards and in the Watten depression, the Forse Till is locally overlain by a thin, near-surface till, termed the Wick Till Member. This unit was first described from Wick Harbour (Jamieson, 1866), where it rests with a merging contact on the Forse Till, but has a higher stone and boulder content, with conspicuous erratics up to boulder size of Helmsdale Granite, and a lower shell content. The Wick Till has a poorly-defined northern limit and the set of NW-SE oriented meltwater channels, cut into gravels with metamorphic and granite clasts that extends towards Watten indicates that ice moving out of the Moray Firth may have been in contact with Northern Highland ice. Sections at Scorriclett and in the Burn of Haster (Peach, 1864) show glacitectonically-deformed masses of sand, gravel and diamicton incorporated within the Wick Till, consistent with deformation during a readvance. At Watten, the Wick Till is overlain by moraine mounds developed in block-rich, bedrock-derived tills. Striae (Flinn, 1981), meltwater channel orientation, erratic carry and the pattern of linear deeps on the floor of the inner Moray Firth (Andrews et al., 1990) indicates ice movement sub-parallel to the present coastline.

QUOYNALONGA TILL FORMATION OF ORKNEY

Scara Taing on the west coast of Rousay (Figure 4) is the type site for the till stratigraphy of Orkney. Here, three till units are superimposed, forming the Quoynalonga Till Formation, each resting locally on striated flagstone surfaces and with no observed intercalated sediments (Hall, 1996). The lower, brown Digger Till Member is dominated by clasts of Rousay Flagstone. Underlying rock surfaces carry sets of crossing striae of which the youngest trends 292˚ (n=19) and older trend 330˚. The overlying Scara Taing Till Member has a red-brown, silty sand matrix derived from the incorporation of relatively large amounts of debris from the red Eday Marls. Only at one point was the Scara Taing Till observed to rest on bedrock and here striae run to 309˚ (n=21). The upper Quendal Till Member is a blocky diamicton in which large striated boulders are oriented to 300˚ that passes upwards into a matrix- and clast-supported boulder diamicton, with beds and lenses of bedded diamicton and gravel, forming N-S trending ridges and mounds. The Quendal Till rests on rock surfaces carrying striae trending 308˚ (n=8) and 329˚ (n=6). The upper 1.5 m of the Quendal Till has been strongly cryoturbated and displays erected and frost-shattered clasts. Comparable tripartite till sequences occur on Eday at Bay of Newark and Carrick.

Detailed, unpublished litho-stratigraphic analyses completed by Rae (1976) provide a firm basis for characterising the Quoynalonga Till Formation in the rest of Orkney. Only a few tripartite till sequences were recognised from Eday southwards to South Ronaldsay but bipartite sequences are more widespread (Figure 4). Multi-till sites generally occur where the till was sheltered from subsequent glacial erosion on north or west-facing slopes (Rae, 1976). Typically, the lower till units have fewer far-travelled erratics, less shell debris and a darker hue than the overlying reddish Scara Taing Till. Although all lower till beds may not all be of equivalent age, these tills are grouped within the Digger Till Member. At Den Wick, East Mainland, striae, clast fabrics and a high content of Lower Eday Sandstones indicate deposition of the Digger Till by ice moving from between south and east (Gordon, 1993a; Rae, 1976). Palynomorphs are extremely sparse in this till unit but include the Carboniferous spores *Lycospora pusilla* and *Densoisporites*, indicating some Carboniferous input, together with saccate pollen derived from the Permian. Dinoflagellate cyst specimens include *Apteodinium* sp. of Davey (1982), which is indicative of the Jurassic-Cretaceous transition. Whilst the Digger Till may locally represent a basal, bedrock-derived facies of overlying till units, it is also clear from fabrics, underlying striae, matrix colour and erratic suites that, at numerous sites, this lower till was deposited by ice moving from a more southerly direction to the overlying tills (Rae, 1976).

Red brown, shelly, massive, matrix-supported diamictons correlated with the Scara Taing Till occur widely on low ground in eastern Orkney but gradually change to a brown colour in western areas (Wilson et al., 1935) with increasing distance from outcrops of the red Eday Marls which have been considered the main source of the red coloration (Rae, 1976). At Den Wick, Mainland, the Scara Taing Till is separated from the Digger Till by a 10-15 cm thick layer of massive but sorted red sand and gravel. Elsewhere basal contacts of the Scara Taing Till are sharp and marked by stone layers or seepage lines (Rae, 1976). At numerous sites, masses of Digger Till have been partly incorporated within the Scara Taing Till (Rae, 1976). Clast fabrics and stone content indicate deposition of the Scara Taing Till by north-westward moving ice (Gordon, 1993a; Rae, 1976). On east Mainland, the median orientation for sub-till striae is 320˚, with flow vectors from 315-345˚ (Rae, 1976). On the north isles, striae swing round towards 300˚ (Peach and Horne, 1880). Erratic trains at Stromness and on Shapinsay indicate ice flow to the west and north-west (Figure 7A).

The Scara Taing Till is decalcified in its upper 2 m but the till often includes conspicuous fragments of marine shell at depth, especially in eastern Orkney (Rae, 1976). An infinite radiocarbon age exists for a marine shell from Mill Bay, Stronsay (Gordon, 1996). Published amino acid ratios for the Scara Taing Till indicate that the bulk of the shells date from OIS 5 or older stages (Bowen et al., 1986; Bowen and Sykes, 1988) but include, at Suckquoy Ness and other sites, younger faunal elements from OIS 4 and 3 (Sutherland, 1991). The youngest ages indicate that the Scara Taing Till was deposited by the last ice sheet (Hall et al., 2003).

The Scara Taing Till at Den Wick has yielded an abundant palynoflora in which the Carboniferous input is most prevalent and is dominated by the long-ranging species *Lycospora pusilla*. Other taxa include *Endosporites globiformis*, *Endosporites zonalis*, *Densoisporites* spp., *Florinites mediapudens*, Florinites spp. and *Tripartites* sp. The presence of *Endosporites globiformis* and *Endosporites zonalis*, together with Florinites spp., is indicative of extensive input from Coal Measures material of the Late Carboniferous (Smith et al., 1967). In contrast, at Mirkady on Deerness and at Garth on Shapinsay, the Scara Taing Till matrix contains mainly saccate pollen of Permian aspect. Permian saccate palynomorphs also dominate the assemblage at Sands of Mussetter, Eday, where a single chorate (spine-bearing) dinoflagellate cyst was observed which may indicate minor derivation from the Palaeogene.

The Quendale Till Member is found on low ground across Orkney (Figure 4). The Till is generally dominated by large clasts of local Devonian rocks and lacks shell debris. The Quendale Till locally incorporates masses of glacitectonized bedrock and forms sheets, mounds and ridges produced during ice retreat (Wilson et al., 1935) (Figure 3). At Bay of Newark, Eday, the Scara Taing Till is overlain by a further two till units, separated by horizontally-bedded sandy diamicton (Rae, 1976). Till fabrics, erratic carry and associated striae indicate flow to the north-west in the North Isles and the west on east Mainland, with deflection of ice flow around hills. At Scara Taing, Rousay, moraine ridges line the coastal cliffs and contain debris transported from adjacent hill tops, marking a final phase of ice flow along the Sound of Rousay. Around Finstown, striae indicate formation of ridges and deposition of till by ice flowing to the west out of Wide Firth (Wilson et al., 1935).

Large moraines in the valleys of west Hoy have been related previously to a period of valley glaciation that post-dated the decay of the last ice sheet (Wilson et al, 1935). Temporary exposures however in one of the pair of moraine ridges at the north end of Ford of Hoy revealed that the ridges are largely composed of glacilacustrine sands disturbed by ice moving from the east (Sutherland, 1996). Coastal exposures at the south end of Rackwick reveal clast-supported diamictons containing large blocks of sandstone also derived from the east that form a moraine ridge that slopes westward towards a large kame terrace in the Rackwick valley. Hence the assemblage of landforms and sediments in the valleys of western Hoy appears to relate not to valley glaciation but rather to a late phase of deglaciation when ice remained in the Pentland Firth and Scapa Flow, trapping glacial meltwater in lakes formed in the valleys of west Hoy.

EVENT STRATIGRAPHY

Multi-proxy evidence summarised above from glacial landforms, till stratigraphy, striae patterns, erratic distribution and till matrix palynomorphs allows a new event stratigraphy for Orkney and Caithness to be proposed that spans at least the last glacial cycle. Emphasis is placed below on identifying the main periods of ice advance, with recognition that isolated, thin sediments intercalated between till layers probably indicate phases of ice retreat.

EVENT 1: EARLY EXPANSION OF NORTHERN HIGHLANDS ICE INTO CAITHNESS AND MORAY FIRTH ICE ACROSS ORKNEY

Tills of the Dunbeath Formation occur at depth in Caithness as far east as Watten (Omand, 1973) but are unknown on Orkney. Along Berriedale and in the Langwell valley, bedrock lineaments in Flow Sets 26b and 26c of Hughes et al. (2014) indicate flow to the south-east, consistent with directions of ice flow indicated by striae, till fabrics and erratic carry in tills of the Dunbeath Formation. West of Reay, the Portskerra Till is spatially associated with and partly time equivalent to Flow Set A of Hall et al. (2011) and elements of Flow Set 2 of Hughes et al. (2014). As recognised by Sutherland (1984), these erratics, tills, flow set elements and associated striae record a phase of radial expansion of Northern Highland ice from the hills of the Caithness-Sutherland border to beyond the present Atlantic and inner Moray Firth coasts and onto the plain of Caithness.

The Digger Till on Orkney also rests on bedrock. This till and its associated striae record one or more phases of extensive ice cover, with ice flowing to the north and northwest across Orkney. Although low ground on Orkney was covered at this stage, the lack of chalk erratics and the low content of Jurassic and Cretaceous palynomorphs does not indicate a major input of debris from the inner Moray Firth. Instead the presence of Permian and Carboniferous palynomorphs in the Digger Till implies ice movement over the platform east of Orkney. Limited topographic control on striae patterns suggests that ice over Orkney was thin, with a margin not far north and west of Orkney (Figure 8).

EVENT 2: EARLY EXPANSION OF MORAY FIRTH ICE INTO NORTHERN CAITHNESS

Gravels resting on the Portskerra Till indicate subsequent withdrawal of Northern Highland ice from the present north coast. The Drumhollistan Till, probably the oldest unit in the Forse Till, records the first arrival of Moray Firth ice at the Atlantic coast. The restricted thickness and distribution of the Drumhollistan Till make it unlikely that Moray Firth ice extended far onto the Atlantic shelf at this time. Younger gravels at Wester Clett indicate subsequent withdrawal of the Moray Firth ice from the present north coast.

EVENT 3: LGM IN ORKNEY AND CAITHNESS

The Scara Taing Till of Orkney and the Forse Till of Caithness have been regarded as correlative deposits on the basis of stratigraphic position and regionally consistent patterns of striations and erratic carry, including the widespread incorporation of marine shell debris (Hall, 1996; Rae, 1976; Sutherland, 1991; Sutherland and Gordon, 1993). A significant difference emerges from this study however in till lithology. Whereas the grey to black Forse Till contains abundant material derived from the inner Moray Firth, including erratics and Late Jurassic-Early Cretaceous fossils and palynomorphs, the brown to red Scara Taing Till contains fewer erratics and palynomorphs derived from this source and significant proportions of Permian and Carboniferous palynomorphs derived from east of Orkney.

Collectively, the various indicators of ice flow demonstrate flow towards the north and northwest across Caithness and an increasing westward component of flow further north across Orkney. In northern Caithness, the pattern of flow conforms to that indicated by the subglacial bedforms of Flow Set B of Hall et al., (2011), a flow set that oversteps the Forse Till drift limit on the Caithness-Sutherland border and includes the area covered by the Broubster Till of the NHDG. More widely, the pattern of flow corresponds to Flow Set 1 of Hughes et al. (2014). The presence of glacially-stripped surfaces at 467 m a.s.l. on the highest hills of Hoy is consistent with the whole of the Orkney and Caithness being under ice cover at this time. Along the western margin of the MFIS, the flow of Northern Highland ice was turned north at this stage, surmounting hills up to 350 m high. The extent, elevation and pattern of glacial features at this stage indicate that Event 4 included the Last Glacial Maximum.

EVENT 4: LATE READVANCE ACROSS ORKNEY AND DEGLACIATION

The Quendale Till found on the west coast of Mainland and Rousay marks a final period of ice cover over the low ground of Orkney and extending onto the adjacent shelf . The absence of chalk from the Quendale Till again suggests that ice moved across the Palaeozoic platform east of Orkney, with flow to the west and northwest. Hill summits on Hoy were first deglaciated at 17.2 ± 1.6 ka cal. k yr yet other cosmogenic exposure ages indicate that low ground on west Mainland only became ice-free at 15-14 ka (Ballantyne, 2010; Phillips et al., 2008). These dates probably bracket the period of deposition of the Quendale Till. The final retreat of ice across Orkney was marked by isolated moraine systems on west Rousay and central Mainland and by moraines and glacilacustrine sediments in the valleys of western Hoy. The ice filling the major valleys, now occupied by the sea in Eynhallow Sound, Wide Firth, Scapa Flow and the Pentland Firth, retreated towards the east and southeast and into the Moray Firth (Rae, 1976)(Figure 8).

EVENT 5: LATE READVANCES IN CAITHNESS AND DEGLACIATION

Several till units and associated moraine systems record late ice advances on to the plain of Caithness. After Moray Firth ice withdrew, inland ice appears to have pushed forward into the Forss area (Auton, 2003). Subsequently, ice spread out from Strath Halladale towards Reay (Hall et al., 2011) and then retreated, leaving moraine systems in the major valleys of western Caithness (Auton, 2003). Further south, meltwater draining from an ice-front to the south-west deposited outwash gravels towards Watten and subglacial bedforms belonging to Flow Set 26c of Hughes et al. (2014) indicate an ice movement towards Wick, again after withdrawal of Moray Firth ice. The Dirlot moraines record a later minor readvance when Moray Firth ice had retreated south of Ben a' Chielt to allow ice from inland to advance a short distance down Strathmore. The Wick Till and its associated striae and moraines record, however, a final incursion of the Moray Firth glacier to a limit north of the Wick River. Cosmogenic exposure ages from Dunnet Head suggest that ice had retreated from this ground by 14.7-15.6 cal. k yr (Ballantyne, 2010; Phillips et al., 2008) but deglaciation of the Moray Firth coastal slope at Mid Clyth was only completed after retreat of the ice lobe that deposited the Wick Till by 13.0 ± 1.4 cal. k yr (Ballantyne, 2010; Phillips et al., 2008).

LINKS TO FLOW SETS

Regional flow sets have been identified for Caithness and Orkney from DEMs within a wider study of the last BIIS (Hughes et al., 2010; Hughes et al., 2014). Whilst these regional sets generally conform well to patterns of ice flow recognised from other proxies and summarised here, there are important differences. Firstly, Event 1 recognises a radial flow of Northern Highland ice in the west of the study area (Figure 8), unlike Flow Set 2 of Hughes et al. (2014) that recognises only a northward flow (Figure 3). Secondly, some events inferred from the till stratigraphy are not represented by flow sets, such as the movements of Northern Highland ice towards Watten before and after deposition of the Forse Till and the movement or movements of ice across Orkney that deposited the Digger Till. Thirdly, flow sets often appear to relate to more than more event in the regional event stratigraphy. Examples include (i). the earliest Flow Set 2 that matches Flow Set A of Hall et al. (2011) in northern Caithness and so represents Events 1 and 5 and perhaps locally also Event 3 when Northern Highland ice flow followed a similar northward pathway; (ii) Flow Set 1 includes flow paths that recurred during Events 2-5 in different parts of Caithness and Orkney and (iii) the late flow Sets 26b and 26c in the valleys of southern Caithness that represent flow during the late Event 5 but that extend beyond the Forse Till limit to the Moray Firth coast and so include streamlining during Event 1. From the above, it is clear that the flow sets are not only time-transgressive, as recognised by Hughes et al. (2014), but also developed during different flow events, making recognition of spatial and age relationships problematic when based on cross-cutting flow sets alone. This difficulty is greatest where glacially-streamlined bedforms are cut in rock. In northern Caithness, valley floors retain MIS 2 and older glacial sediments, most notably at Leavad (Gordon, 1993c). Glacial streamlining of this terrain has been cumulative, developing as ice has moved along similar pathways during multiple glacial phases. Such inheritance is consistent with the widespread survival in Caithness and Orkney of coastal landforms cut in rock, including cliffs, geos and shore platforms, that are covered locally by glacial deposits (Steers, 1973) and so must pre-date MIS 2 glaciation.

FAR-TRAVELLED TILL COMPONENTS AND ICE FLOW DIRECTIONS AT THE LGM

Tills deposited during unconstrained ice flow in Event 4 at the LGM are associated with far-travelled erratics and palynomorphs. Distinctive indicator erratics can be assigned with confidence to sources in the Northern Highlands, the inner Moray Firth, the Grampian Highlands and southern Scandinavia. These indicator erratics have different but often overlapping ranges in the study area (Figure 7B). Erratics from the Northern Highlands, including Cambrian Pipe Rock derived from outcrops close to the main Atlantic-North Sea ice shed, are found across Caithness (Peach and Horne, 1881) and, more sparsely, across Orkney (Peach and Horne, 1880). Mesozoic erratics derived from the inner Moray Firth have a similar range (Peach and Horne, 1880). Chalk or flint are both present between Wick and the Pentland Firth (Peach, 1860) and again in northern Orkney, but only flint is distributed, sparsely, on Hoy and west Mainland (Rae, 1976). This distribution requires transport of chalk erratics west along the Pentland Firth and northwest into the North Isles, but with only brief, if any, flow of ice across the Chalk outcrop and then across Mainland in the last glaciation. Chalk was also carried east into the Witch Ground by the last BIIS (Graham et al., 2010). Grampian Highland erratics are confined to the shores of the Pentland Firth, to the North Isles of Orkney (Peach and Horne, 1893) and also extend to Fair Isle (Hall and Fraser, 2014). Small numbers of Carboniferous sedimentary and volcanic rocks are recorded from the North Isles of Orkney (Peach and Horne, 1893) and from Fair Isle (Hall and Fraser, 2014). Shetland erratics probably extend south only as far as Fair Isle (Flinn, 1978; Hall and Fraser, 2014), although a record exists of an epidote-bearing granite, similar to the Spiggie Granite of south Shetland, in a field wall on North Ronaldsay (Rae, 1976). Scandinavian erratics, including rock types sourced from the Oslo Graben, occur in very low concentrations from the Sound of Stronsay on Orkney northwards to the southern tip of Shetland.

Till palynomorphs in Caithness are dominated by Late Jurassic and Early Cretaceous forms derived from the inner Moray Firth. The sparse Palaeogene material at Scorriclett and Gills Bay however must have been transported from outcrops that lie 60-110 km to the east. On Orkney, the till palynomorph assemblages are more diverse. Late Jurassic and Early Cretaceous palynomorphs remain a significant component, requiring at least one phase of transport by ice moving out of the inner Moray Firth. The dominance of Permian saccate pollen in red tills at several sites however indicates erosion of Permian rocks that lie immediately east of Orkney (Figure 2). The unexpectedly strong presence of Carboniferous palynomorphs in tills on Shapinsay and Deerness is intriguing. Carboniferous rocks probably occur at depth in the Wick Sub-Basin (Glennie, 2009), 50-60 km south-east of the till sites. Other flow indicators in this part of Orkney indicate derivation of till material from the south-east and so the palynomorph data may indicate that Carboniferous strata, including the Coal Measures, crop out on the sea bed against the Wick Fault at the eastern edge of this basin. The source may be more proximal, as plant-bearing boulders of unknown age are reported from storm beaches on Auskerry (Wilson et al., 1935)(Figure 7). Alternatively, the Carboniferous palynomorphs may be derived from the Witch Ground Basin, >150 km to the east, where Carboniferous coal-bearing strata occur at depth (Leeder et al., 1990) and Carboniferous palynomorphs are also known to be abundant in glacial deposits (Davies et al., 2011). Direct glacial transport from Carboniferous outcrops 400 km away in the Forth Approaches is unlikely, given the apparently localised distribution of Carboniferous palynomorphs on Orkney.

There is little evidence for former ice flow northwards across the inner Moray Firth from the eastern Grampians, Moray and Buchan, as proposed in several ice flow models (Bradwell et al., 2008; Bremner, 1934; Hughes et al., 2014). No shelly till or glacial rafts have been reported south of Berriedale, as would be expected if ice had crossed the Jurassic and Cretaceous mud rocks and marine deposits of the innermost Moray Firth and moved into Ross-shire. Moreover, no erratics of Dalradian metamorphic and Caledonian igneous rocks from Moray and Buchan have been recorded in Caithness, except along the southern shore of the Pentland Firth. The northward to westward ice flow recorded by different flow indicators across Caithness and Orkney must therefore either relate to abrupt curving of ice flow out of the inner Moray Firth or to flow from ice sheds that lay at or to the south-east of the present coastline.

There is evidence to support both scenarios. Along the western limit of the Forse Till, the presence of Kimmeridgian palynomorphs, Late Jurassic fossils and Helmsdale Granite boulders shows that ice moved along the northern shore of the innermost Moray Firth before turning north in the vicinity of Dunbeath. Striae also indicate that a marked change from northward to north-westward flow direction also occurs within 5 km of the coast south of Wick (Omand, 1973)(Figure 5). Similar changes in flow direction occur in northern Caithness, where the distribution and striae patterns associated with the Drumhollistan and Eastern Gulley Till indicate curving of ice flow towards the west. Coast-parallel flow off the north coast of Scotland is also indicated by sea bed moraine ridge orientations (Bradwell and Stoker, 2015). These directional changes may relate to part to the movement of ice from deformable to rigid beds (Hall and Bent, 1990). The westward transport of chalk debris and Palaeogene palynomorphs into the Pentland Firth also requires however that the ice shed at some stage lay >60-110 m east of Orkney. The curving flow out of the Moray Firth depicted in early models of glaciation (Peach and Horne, 1881), as with Flow Sets 1 and 2 (Hughes et al., 2014), probably represents a composite flow signature from multiple ice flow events.

For both till palynomorphs and glacial erratics, it is important to recognise the likelihood of reworking. Erosion and transport by the Moray Firth ice sheet of pre-existing marine and glaciomarine muds and sands of MIS9 to MIS3 age in the inner Moray Firth led to incorporation of these materials as rafts and lenses in tills and allowed reworking of shells, clasts and palynomorphs into MIS2 tills. The Witch Ground Basin also held pre-MIS 2 marine, glaciomarine and glacial sediments. Saalian shelly diamicton in borehole 81/26 in the Witch Ground contains erratics of Old Red Sandstone, chalk, as well as clasts and heavy minerals from the Grampian Highlands and abundant Carboniferous spores (Davies et al., 2011; Sejrup et al., 1987). Chalk and flint clasts also were moved north-eastward and eastward into the Witch Ground Graben during the Elsterian and Saalian (Davies et al., 2011) glaciations. A wide range of erratic material derived from the Scottish mainland was thus already available in the Moray Firth and Witch Ground Basin to be reworked by ice sheets during the last glaciation. It is likely also that glacial and glaciomarine sediments in the Witch Ground Basin included erratics from southern Scandinavia. Although only a single rhomb porphyry from the Oslo Graben is recorded from borehole samples, FIS reconstructions show ice margins in the vicinity of the Witch Ground during MIS 2 and earlier (Graham et al., 2011; Sejrup et al., 2014). This raises the possibility that the low numbers of Scandinavian erratics recorded from southern Shetland to northern Orkney are not a product of single phase transport but instead relate to reworking of older deposits in the Witch Ground by the BIIS. Such reworking is consistent with the lack of support from provenance studies for direct incursion of the FIS into eastern England during the last glacial cycle (Davies et al., 2011).

DISCUSSION

The event sequence proposed above is significantly more complex than the long-established two- or three-stage models of the last glaciation of Caithness (Crampton and Carruthers, 1914; Peach and Horne, 1881) and Orkney (Rae, 1976; Wilson et al., 1935). Recognition of multiple ice advances rests on the interpretation of thin and widely-scattered inter-till sediments as representing significant breaks in glacial deposition. This splitting of the till sequence receives some support from the widespread development of stacked sequences of multiple tills with erosive basal contacts and from the differences in ice flow directions between successive till units. The revised event stratigraphy indicates that the plain of Caithness experienced at least two separate ice advances from the Northern Highlands and at least four separate ice advances from the inner Moray Firth. At least three separate ice advances onto Orkney are also recognised. Recently-identified till beds also point to additional events around the time of the LGM. New information from erratic carry and till palynomorph content indicate pathways for long distance glacial transport and thereby allows testing of existing models and simulations of the behaviour of the north-eastern quadrant of the BIIS.

CORRELATIONS WITH ICE MOVEMENTS IN NORTH-EAST SCOTLAND

The event stratigraphy proposed for Caithness and Orkney can be compared with the stages of the last glaciation identified along the southern shore of the inner Moray Firth (Merritt et al., Submitted). Correlations should be straightforward as both regions have members of the BCCODG derived from the inner Moray Firth and reconstructions and simulations of ice sheet configurations towards the close of the last glaciation indicate that ice cover extending beyond the Buchan coast requires also full cover in Caithness and Orkney (Hubbard et al., 2009). Yet weak dating controls on the timing of events during the last glaciation in both areas bring uncertainties in correlation.

In Moray, an early advance of ice from the North-West Highlands (Stage 1)(Merritt et al., Submitted) crossed the innermost Firth and moved upslope to reach elevations of ~500 m. Further east, ice flowed south-eastward over the lowlands of Buchan to reach beyond Aberdeen. This phase is likely contemporaneous with expansion of Northern Highland ice onto the plain of Caithness and northward flow out of the Moray Firth across Orkney during Event 1. Subsequent (Stage 2) west to east movement of ice across the North Sea coast at Peterhead indicates establishment of a powerful and parallel ice flow in the inner Moray Firth. Ice subsequently flowed from Strath Spey into the Moray Firth (Stage 3). Stages 2 and 3 relate to the period of the LGM (Merritt et al., Submitted) and were broadly contemporaneous with Event 3 in Caithness and Orkney. Stages 4-10 in north-east Scotland relate to early deglaciation (Merritt et al., Submitted) and link to the late readvance and phased retreat of ice across Orkney and Buchan during Events 4 and 5.

LINKS TO THE LAST GLACIAL CYCLE IN THE NORTH SEA AND ON THE ATLANTIC SHELF

Ice discharging from the Moray Firth fed into the western North Sea and interacted there with ice moving from ice centres on Shetland, in eastern Scotland and in southern Scandinavia. The Witch Ground was ice free until after 34.7-32.4 k cal. yr (Sejrup et al., 2014) or 36.1-33.7 k cal yr (Graham et al., 2010). Thereafter the northern sector of the BIIS expanded rapidly, covering north Lewis after 32.0 k cal yr (Whittington and Hall, 2002) and with a peak in IRD flux at the Rosemary Bank and on the Barra–Donegal Fan indicating extension on to the shelf by ~29 ka (Scourse et al., 2009). The FIS also reaches a maximum extent in Denmark at 29-27 ka (Houmark-Nielsen and Kjaer, 2003).

The sequence and timing of events in the western North Sea over the next ~9 kyr remains unclear. Whereas IRD fluxes indicate that the BIIS remained at the shelf edge (Wilson et al., 2002), cave sediments in western

Norway indicate ice retreat to the present coast at 29.7 ka (Mangerud et al., 2010; Valen et al., 1996) and inter-till sediments in Denmark indicate ice recession from maximum limits there at 27 and 24 ka (Houmark-Nielsen and Kjaer, 2003). Combined with the IRD flux increases initiated at 27 ka on the western Irish margin and at 25 ka on the Goban Spur (Scourse et al., 2009), this timing suggests the BIIS and FIS were not fixed at LGM limits but fluctuated markedly, consistent with the behaviour of the last BIIS in simulations (Hubbard et al., 2009). Peak IRD flux coincident with Heinrich Event 2 at 24 ka is a feature of all records of the BIIS on its western margin (Scourse et al., 2009). The FIS margin was also close to its southernmost limits in Europe from 24.3 to 23.4 ka, 22.5 to 21.3 ka and again from 20.3-18.7 ka (Toucanne et al., 2015). This LGM timing is difficult to reconcile with radiocarbon dates on marine shells from the Witch Ground Basin that indicate the establishment of ice free conditions after 25 k cal. yr in the north-east quadrant of the BIIS (Holmes, 1997; Sejrup et al., 1994). The key radiocarbon dates in boreholes BGS 97-7 and 77/2 however span ~9 ka (Sejrup et al., 2014) and may represent reworking at a fluctuating ice margin of shells from more than one brief marine interval, with final deglaciation constrained only by the youngest age of 17.7 k cal. yr. This timing is more consistent with cosmogenic isotope exposure ages on deglaciation of high ground (217-530 m a.s.l.) in Orkney, Caithness and Buchan as late as 18.2 ± 2.6 ka (Ballantyne, 2010). A consequence of such a reassessment is that the major erosional unconformity at the top of the Coal Pit Formation may relate to a glacial phase after, rather than before 25 ka. The Tampen moraine on the western flank of the Norwegian Channel marks a readvance of the FIS after 22.4 k cal. yr, prior to final shut down of the NCIS at 20 to 19 k cal. yr (Svendsen et al., 2015). Subsequent advance of Moray Firth ice into the Witch Ground is indicated by chalk-bearing Swatchway Formation sediments (Carr et al., 2006; Graham et al., 2010), an event recently more firmly dated to c. 17.5 k cal. yr BP and 16.2 k cal. yr BP (Sejrup et al., 2014). Although available chronometric control remains weak for the period between 30 and 18 ka and allows several interpretations of the history of the last glaciation of the central North Sea, a tripartite model of glaciation is plausible, with extensive ice cover from 32-28 ka, 25-18.5 ka and 17.5-16.2 ka. The event stratigraphy of Caithness and Orkney can be fitted to this model, with Events 1 and 2 falling within the 32-28 ka interval, Event 3 in the 25-18.5 ka interval and Events 4 and 5 in the final interval but only the later events have chronological control.

The major unconformity on the upper surface of the Coal Pit Formation in the Witch Ground Basin carries mega-scale glacial lineations (MSGL) formed by erosion at the base of fast-flowing ice streams (Graham et al., 2007). Two sets of streamlined lineations, oriented at approximately 90˚ to each other occur within the MSGL package in the Witch Ground basin. An older, Late Saalian or Early Weichselian MGSL set, trending SW-NE and formed by the BIIS (Graham et al., 2011), is over-printed by widely-distributed, streamlined lineations trending SE-NW or NW-SE. Radiocarbon dates from the base of the overlying Swatchway Formation include the sequence in borehole 77/02 with a youngest age of 17.7 k cal. yr. (Sejrup et al., 1987, 1994) and marine sediments in borehole BH04/01 with an age of 16.2 ^{14}C ka BP (Graham et al., 2010). The younger MGSL set has been interpreted as a product of a zone of fast north-westward flow in the FIS (Graham et al., 2010) when flow extended from the western flank of the Norwegian Channel to the North Atlantic shelf edge (Bradwell et al., 2008). The Coal Pit Formation that underlies this MGSL set however includes chalk debris, as does the overlying Swatchway Formation (Graham et al., 2009), implying that erosion of the MGSLs was bracketed by phases of ice flow from the Moray Firth. Alternatively, and as originally recognised (Graham et al., 2007), the MGSLs may have been cut by the BIIS flowing south-eastwards. The likelihood that the ice divide at 19-20 ka lay south of the Witch Ground also allows the alternative possibility that the young MGSLs were cut by ice moving north-westwards in the north-east quadrant of the BIIS. The low concentrations of Scandinavian erratics on Orkney would also indicate no direct link between the young set of MGSLs and the flow of the FIS across the North Sea.

The pattern of deglaciation across the shelf is now much clearer due to recent advances in mapping moraines on the sea bed. Combining this data with the pattern of deglaciation indicated by moraines in Orkney and

Caithness shows the main stages in the retreat from an extended ice margin at 17.5 k cal. yr BP (Sejrup et al., 2014) back towards Orkney, into the Pentland Firth (Bradwell and Stoker, 2015) and subsequently into the inner Moray Firth. The Bosies Bank Moraine, previously regarded as a possible LGM limit (Hall and Bent, 1990) is now recognised as a composite ridge produced early in this recession (Sejrup et al., 2014). The pattern of meltwater channels in the Witch Ground and of ice flow associated with the Quoynalonga Till on Orkney indicate that the ice divide sat east of the topographic divide (Figure 8). The Moray Firth glacier remained active during its retreat and advanced to deform glaciomarine deposits dated at 15, 320 ± 200 ^{14}C years BP (Hall and Jarvis, 1989) at St Fergus, near Peterhead (Peacock, 1997) and subsequent minor advances occurred at Elgin, possibly at about 14 ka BP (Merritt, 2000) and at Ardersier at about 13 ka BP (Merritt et al., 1995).

VERIFYING ICE SHEET SIMULATIONS

Recent simulations of the BIIS during the last glacial cycle have provided valuable visualisations of its likely behaviour (Hubbard et al., 2009). For the north-eastern sector of the BIIS, the simulation E109b4 has the following main features that can be tested against the regional lithostratigraphical record:

1. Full ice cover in Caithness from 35.5-15.5 ka and much of Orkney from 32.5-17.0 ka, apart from brief ice-free intervals at 33, 31, 27.2 and 17.0 ka. The timing of the onset of the last glaciation is consistent with available dating evidence for the northern BIIS (Sejrup et al., 2009). Ice-free intervals at the north coast of Caithness are consistent with stratigraphic evidence at Wester Clett (Hall et al., 2011).

2. The Moray Firth ice stream remained restricted in extent and topographically-constrained for most of the period 33-24 ka and after 17 ka, with discharge mainly via streaming through the inner Moray Firth. This scenario is largely consistent with ice extent and flow patterns during Events 1, 2 and 5.

3. A modelled LGM between 24 and 18 ka, with extension of the BIIS into the Witch Ground, a phase that included the main phases of warm-based, fast ice flow. An ice shed developed over the topographic high of the Orkney-Shetland Platform and migrated at 20-19 ka to a position east of the Witch Ground. Ice streams developed for short intervals during the modelled LGM, with flow S-N along the western border of Caithness, E-W along the Pentland Firth, SE-NW in the firths of Stronsay and North Ronaldsay and S-N to the east of Orkney and towards the shelf edge W of Shetland.

   Extensive warm-based ice sheet flow at the LGM is marked by Flow Set 2, formed in part during Event 3. The development of an ice shed close to the present coasts of Caithness and Orkney is consistent with north-westward flow across Caithness and westward flow over Orkney and also with its later displacement towards the south-east. An ice shed location over or east of the Witch Ground is also compatible with carry of chalk erratics into the Pentland Firth and the reworking of Scandinavian erratics from the Witch Ground Basin. The shallow, linear depressions of the Pentland Firth, the Sound of Stronsay and the Orkney-Shetland Channel acted have long been recognised as likely outlets for ice streams (Godard, 1956).

4. Deglaciation of much of Orkney and Caithness by 17.0 ka with readvances at 16.5 and 15.6 ka. Early deglaciation as modelled is not compatible with extensive glaciation of lowland Caithness and Orkney in Event 4 and also of Shetland (Hall, 2013), extending into the northern North Sea at 17.5 k cal. yr BP and 16.2 k cal. yr BP (Sejrup et al., 2014). The later simulated readvances however may correlate with moraines formed in Event 5 and found on the shores of the innermost Moray Firth (Merritt et al., 2003).

5. Repeated development of an independent ice cap on Orkney centred on the high ground of Hoy and west Mainland. No till unit, striae or erratic train has been recognised however that might relate to

eastward or north-eastward expansion of the simulated local ice cap. Instead the patterns of striae, erratic carry, glacial bedforms all point to flow across the islands from an ice shed that lay at least as far east as the Auskerry Rise. During deglaciation and again in the Loch Lomond Stadial (Ballantyne et al., 2007), glaciers on Hoy remained of restricted extent. The very limited presence of far-travelled erratics, including marine shells, in Hoy and west Mainland and the absence or weak development of subglacial bedforms on the hills of Hoy is consistent however with the build-up of a dome of cold-based ice of sufficient thickness to prevent incursion of Moray Firth ice into this part of Orkney for long periods.

Interaction between the BIIS and the FIS has been simulated independently by Boulton and Hagdorn (2006). Confluence only occurs after 25 ka. By 20 ka, an ice divide is established across the central North Sea, with north- to north-westward ice flow over Orkney and the Witch Ground. Several elements of this simulation match the regional event stratigraphy. Late confluence is supported by the absence of Scandinavian erratics from the Digger Till. Migration of the ice shed during the LGM to the south would allow transport of mixed assemblages of erratics into Orkney associated with deposition of the Scara Taing Till. This ice shed position is also compatible with formation of MGSLs in the Witch Ground, without requiring the FIS to cross the North Sea bed. In Events 3 and 4, ice from the inner Moray Firth flows across Caithness but the main flow across Orkney is from the south-east and east across the platform east of Orkney, with only brief streaming events bringing in erratic material from the south, and so accounts for the lithological differences between the Forse and Scara Taing Tills.

INFLUENCE OF THE FIS

The long-held and often repeated assertion that the flow of ice across Caithness and Orkney required deflection by the blocking presence of the FIS can now be evaluated. It is clear from Event 4 that north-westward flow over Orkney does not require a blocking FIS as the FIS was not in contact with the BIIS at this time (Sejrup et al., 2014). The north- to north-westward ice flow that deposited the Digger Till in Event 1 also occurred without confluence of the BIIS and FIS. Westward flow that carried chalk and Palaeogene palynomorphs through the Pentland Firth in Event 4 is also not associated with Scandinavian erratics and so records an ice stream within the BIIS. Simulations for an unrestricted BIIS show that short bursts of north-westward and westward flow across Caithness and Orkney may have occurred repeatedly under conditions of both constrained and unconstrained flow during the last glacial cycle as zones of fast ice flow propagated headwards from the Atlantic shelf (Hubbard et al., 2009). Several lines of evidence indicate that the observed pattern of flow during the last glaciation did not require deflection by the FIS.

No till unit on Orkney can be attributed with confidence to deposition by the FIS. Whilst the presence of Scandinavian erratics on northern Orkney and Fair Isle is confirmed, concentrations in the Scara Taing Till are very low. Moreover these erratics occur in association with other far-travelled clasts from northern, north-eastern and eastern Scotland (Figure 7). This mixed erratic assemblage is consistent with reworking of older Pleistocene deposits in the Witch Ground that are known to include this clast assemblage. Long distance glacial transport from the Witch Ground is confirmed by the presence of Palaeogene palynomorphs in tills in northern Caithness and Orkney. As in other parts of the western North Sea (Davies et al., 2011), it is likely that Scandinavian erratics were introduced by glacial and iceberg transport prior to the last glaciation and reworked into tills.

CONCLUSIONS

Combined evidence from till stratigraphy, glacial lineaments, striae, palynomorphs, erratic content and moraines identifies and constrains the pattern and sequence of flow of the last British Ice Sheet over Caithness and Orkney.

- The terrestrial stratigraphic record is more complex than previously thought. The plain of Caithness experienced at least two separate ice advances from the Northern Highlands and at least four separate ice advances from the inner Moray Firth. At least three separate ice advances onto Orkney are also recognised. Whilst some older events may predate the last glaciation, newly-recognised till beds also point to additional events during the Last Glacial Maximum.

- Glacial lineaments in bedrock belong mainly to two cross-cutting flow sets developed through erosion by Northern Highland and Moray Firth ice through multiple phases of ice flow before and during the last glaciation.

- Glacial erratics have overlapping ranges and derive originally from many sources: the Northern and Grampian Highlands, the Moray Firth, the Forth lowlands and southern Scandinavia. Erratic distribution does not support northward movement of ice across the inner Moray Firth south of Wick. The carry of chalk into the Pentland Firth, eastern Orkney and the Witch Ground requires complex ice flow patterns that probably included periods of ice stream development. The mixed assemblages of Scottish and Scandinavian erratics from found in very low concentrations in northern Orkney probably indicate reworking of older deposits from the Witch Ground Basin.

- Palynomorphs found in tills in Caithness are largely derived from Late Jurassic to Early Cretaceous mud rocks in the inner Moray Firth. North of Wick, Palaeogene forms appear, sourced from the east. In eastern Orkney, Permian and Carboniferous palynomorphs are dominant, occurring alongside smaller amounts of Mesozoic palynomorphs. The apparent confinement of Carboniferous palynomorphs to Deerness and Shapinsay indicate a previously unrecognised proximal source off eastern Orkney.

The event stratigraphy of Caithness and Orkney indicates the following sequence:

During **Event 1**, ice centres in the North-West and Northern Highlands were dominant. The topographic control on flow indicated by the Digger Till and its associated striae suggests that the BIIS did not reach the shelf edge. Ice covered all of Caithness and Orkney, probably with full ice cover in Buchan and extension of ice into the Witch Ground. The Shetland ice cap and the FIS were also extensive at this time.

Event 2 represents an early, limited expansion of the Moray Firth ice lobe when Northern Highland ice is unable to restrain its flow to the north coast of Caithness. Parts of Buchan, NE Caithness and Orkney were probably ice-free at this time.

Event 3 includes the LGM and involved radial flow into the inner Moray Firth. Topographically-unconstrained flow escaped north-westwards over Caithness to the Atlantic shelf edge. A shifting south-west to north-east to west-east oriented ice shed developed in the central North Sea, giving generally westward flow over Orkney. Short-lived, linear zones of fast flow carried erratics northwards and westwards. Moray Firth ice was in contact with ice from the Northern Highlands and Shetland. The BIIS and FIS were also likely confluent in the central North Sea during this time, although short-lived marine embayments probably developed during periods of minor ice front withdrawal. The FIS was prevented from flowing across the northern North Sea by an extensive elongate ice dome that built up in the north-eastern quadrant of the BIIS to the south-east of Orkney and Shetland.

During **Event 4** after 18.2 ± 2.6 ka ice again extended onto the Atlantic shelf, into the Witch Ground and off the Buchan coast as part of an elongate ice dome that again developed south-east of the Orkney-Shetland Platform (Sejrup et al., 2014), allowing transport of Devonian erratics westwards across southernmost Shetland (Hall, 2013). The fluctuating ice margin built large moraines in the Fladen area at 17.5 and 16.2 ka (Sejrup et al., 2014).

Events 4 and 5 together also represent the phased retreat from this extended position and reconfiguration of the ice sheet to a smaller, lobate form in the inner Moray Firth. Retreat was interrupted by significant readvances of Northern Highland and Moray Firth ice.

The pattern and timing of these events are generally consistent with mathematical simulations that indicate that the last British Ice sheet in northern Scotland was highly dynamic. There is no clear lihtostratigraphical evidence for the development of an independent ice cap on Orkney. There remains no clear evidence for the passage of the FIS across Orkney and Shetland during the last glaciation. There is however a pressing need for more detailed study of till lithology, erratic distributions and heavy mineralogy to improve understanding the provenance of tills in northern Scotland and for more dating to better constrain the age of the till sequence.

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FIGURE LIST

Figure 1. Location

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Figure 2. Geology

In hand.

Figure 3. Glacial geomorphology and flow sets

Figure 4. Regional litho-stratigraphy.

Figure 5. Striae patterns

Figure 6. Palynomorphs.

Figure 7. Glacial erratics

7A. Distribution of indicator erratics across Caithness and Orkney.

7B. Ranges of indicator erratics.

Figure 8. Reconstructed ice flow paths and main events

TABLE LIST

Table 1. Regional lithostratigraphy

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