Middle to Late Devensian glaciation of north-east Scotland: implications for the north-eastern quadrant of the last British-Irish ice sheet.

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Abstract

We present a review of over 175 years of research into the Middle to Late Devensian (Weichselian) glaciation of north-east Scotland based crucially on both its lithostratigraphic and geomorphic records. The location of the region, and surrounding seabed, makes this unusually detailed record significant for deciphering the former interactions and dynamics of Scottish and Scandinavian ice within the North Sea Basin (NSB), which continue to be controversial. A twelve-stage event stratigraphy is proposed based on a parsimonious interpretation of stratigraphic relationships, till lithology and regional clast fabrics, striae, subglacial bedforms, ice-marginal features and published geochronometry at critical sites. The record of regional glaciation supports converging evidence that the north-eastern quadrant of the last British and Irish Ice Sheet (BIIS) reached its maximum spatial extent in the late Middle- to early Late Devensian and later re-expanded following widespread internal glacial reorganisations, marine transgression and partial retreat from the central NSB. Retreat was interrupted by several glacial readvances of limited extent. Field-captured data helps identify important events that are not clearly resolved from remote sensing alone, particularly regarding growth phases of the last glaciation.

KEYWORDS: British Irish Ice Sheet; North-east Scotland; Buchan; lithostratigraphy; Devensian; North Sea; till lithology; erratics.

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Introduction

The Pleistocene stratigraphical record in the north-east of Scotland (Figure 1) includes glacigenic deposits and periglacial phenomena representing cold stages back at least to Marine Isotope Stage (MIS) 8, together with terrestrial

sediments with a biological or pedological record of interstadial and interglacial climates (Merritt *et al.*, 2003, Evans *et al.*, 2005). This unique record derived from over 175 years of published research in the region is important in understanding the history of the northern sector of the last BIIS and its interaction with ice flowing into the central NSB from Scandinavia.

In this paper we review published evidence pertaining to the last, Middle to Late Devensian/Weichselian glaciation of north-east Scotland (Figure 2). We attempt to integrate the lithostratigraphical record (Merritt *et al.*, 2003) with the subglacial bedforms mapped by Hughes *et al.* (2010) and ice-flow patterns (flowsets) interpreted from that record (Hughes *et al.*, 2014). Of particular interest are the events that occurred during build-up phases of glaciation, which have left little geomorphological footprint and are least well resolved in current reconstructions of the north-east sector of the last BIIS (Bradwell *et al.*, 2008; Scourse *et al.*, 2009; Clark *et al.*, 2012; Hughes *et al.*, 2014, 2016). Recalculated published dates are taken from a database of geochronometric information for the British Isles (Hughes *et al.*, 2011, 2016).

We offer a new event stratigraphy and conceptual glacial reconstructions based on a detailed, critical review of the literature. Sites mentioned in the text together with striae and a selection of geomorphological features identified from BGS mapping and the extensive literature are located on summary maps given in Merritt *et al.* (2003, maps 1-11), which is also available at http://earthwise.bgs.ac.uk/index.php/Cainozoic_geology_and_landscape_evolution_of_north-east_Scotland. Details of important Quaternary sites on which the stratigraphy is based are given in Table 2. A correlation chart is given in Table 3, which includes most named lithostratigraphical units. Details of the lithology, provenance and ice flow directions of key till units is given in Table 4. Compass directions have been shortened in the following text, eg. NE for north-east.

Topography

NE Scotland encompasses the eastern Grampian Highlands and the lowlands of Moray and Buchan, which rise south-westwards towards the mountains of the Cairngorms, Gaick and the Mounth, reaching over 1000 m above Ordnance Datum (OD) (Figure 3). The region is drained by two principal east-flowing rivers, the Dee and Don, which reach the North Sea at Aberdeen. The Deveron drains NE towards the Moray Firth at Banff and the Spey reaches the firth at Spey Bay. Two other major NE-trending rivers, the Findhorn and Nairn, reach the Moray Firth further to the west (Figure 4). The landscape of NE Scotland is characterised by ancient plateau surfaces eroded across a wide variety of rock types (Hall, 1991). The predominant surface is the rolling Buchan Plateau, lying between 60 and 150 m OD, which embraces Mormond Hill (234 m OD), an isolated inselberg formed of metaquartzite lying between Fraserburgh and Peterhead. The Buchan Plateau is overlooked on its south-western margin by Bennachie (528 m OD), an iconic local granite mountain.

The lithostratigraphy and bedrock geology of NE Scotland

The traditional approach of establishing lithostatigraphical relationships and correlations has been used to help decipher the particularly complex sequence of events and glacial interactions that have occurred in NE Scotland (Merritt *et al.*, 2003). The earlier informal 'series' (Sutherland, 1984; Hall and Connell, 1991) have been incorporated into a formal 'top-down' lithostratigraphical scheme that embraces all superficial deposits in Great Britain (McMillan *et al.*, 2011; McMillan and Merritt, 2012). The series are replaced by subgroups, units of which have been assigned to two groups, the *Caledonia Glacigenic Group*, of MIS 2-5e age, and the *Albion Glacigenic Group*, representing older glaciations. The use of descriptive qualifiers, such as 'glacigenic', and other issues of protocol are discussed by McMillan and Merritt (2012). An overview of the lithostratigraphical framework for Quaternary deposits on the UK continental shelf is given by Stoker *et al.* (2011).

The 'blue-grey series' of Synge (1956), renamed as the *Banffshire Coast and Caithness Glacigenic Subgroup* (BCCGS) relates to the suite of deposits laid down by ice that flowed onshore from the Moray Firth (Figure 5). The 'red series' of Jamieson (1906) has been subdivided in order to separate deposits that were laid down by ice that flowed onshore from the North Sea Basin (*Logie-Buchan Glacigenic Subgroup*) (L-BGS) from those that were derived entirely from ice flowing north-eastwards along Strathmore (*Mearns Glacigenic Subgroup*) (MGS). The 'inland series' of Hall (1984) has become the *East Grampian Glacigenic Subgroup* (EGGS). Additionally, deposits laid down by ice that arrived by circuitous routes from the western Central Highlands are assigned to the *Central Grampian Glacigenic Subgroup* (CGGS), whereas ice that flowed from the NW Highlands via the Great Glen laid down the tills of the *Inverness Glacigenic Subgroup* (IGS). Each subgroup includes formations, members and beds (abbreviated to F, M and B respectively).

All modern Superficial Deposits editions of BGS 1:50k mapping covering the region may be downloaded from http://www.bgs.ac.uk/data/maps/home.ht. Details of type sections and metadata are given in McMillan *et al.* (2011). The correlation chart given in Table 3, includes some later Middle and Late Pleistocene non-glacial, terrestrial sediments, periglacial deposits and soils that provide important biostratigraphical and geochronometric evidence and stratigraphical markers. These units are included in the Britannia Catchments Group of McMillan *et al.* (2011). Detailed descriptions of many of the sites in the region that have provided important stratigraphical information over the years are given in the Geological Conservation Review for the Quaternary of Scotland (Gordon and Sutherland, 1993), now available online at http://.jncc.gov.uk. These site descriptions and additional ones are summarized in Merritt *et al.* (2003, appendix 1). Undoubtedly the longest record has been obtained from the Kirkhill and Leys sites, in eastern Buchan (Table 2) (Connell *et al.*, 1982; Hall and Connell, 1991; Connell and Hall, 2000).

Bedrock has greatly influenced the lithology and provenance of glacigenic deposits in the region, providing valuable indicator erratics. It ranges in age

from Late Precambrian to Lower Cretaceous (Trewin, 2002; Merritt *et al.*, 2003, fig. 2). Resistant rock types such as granite and metaquartzite generally form positive topographical features, whereas gabbro and ultramafic rocks commonly form areas of negative relief. The south of the region includes the gently undulating Vale of Strathmore, underlain mainly by Old Red Sandstone (ORS) lithologies and associated Late Silurian-Devonian volcanic rocks. Although Strathmore is generally low-lying, conglomerates near the Highland Boundary Fault and the coast form higher ground. ORS lithologies also underlie the coastal lowlands between Elgin and Inverness.

Relatively soft Mesozoic and Cenozoic rocks crop out a short distance offshore beneath the Moray Firth and North Sea basins and are the source of many erratics, fossils and glacial rafts onshore. Jurassic rocks crop out only in the Moray Firth, which is of significance for mineralogical and palynological studies of the provenance of glacigenic sediments, both onshore and in the North Sea Basin. Chalk does not crop out on the mainland, but strong evidence of a former cover and post-Upper Cretaceous uplift is given by the presence of nodular flints at the base of the Buchan Gravels Formation, of Palaeocene to Eocene age (McMillan *et al.*, 2011; Hall *et al.*, 2015). These distinctive flint and quartzite gravels cap some of the highest ground in Buchan and demonstrate that topographic inversion occurred prior to the Pleistocene (Hall, 1987; Merritt *et al.*, 2003; Rea and Gemmell *et al.*, 2006)

The terrestrial glacial record

The landscape of NE Scotland has generally experienced relatively little cumulative glacial modification as it lay peripherally to the main ice-dispersion centres in the central and western Highlands of Scotland during successive glaciations (Clayton, 1974; Hall and Sugden, 1987; Hall, 1991). There is particularly significant preservation of deeply weathered regolith and residual, hill-top flint and quartzite gravel deposits in Buchan (Figure 1) (Hall, 1985, 1986, 1987), where long periods of non-erosive ice cover have allowed the preservation of an unusually detailed stratigraphical record (Merritt *et al.*, 2000, 2003) and where periglacial deposits and landforms are common (Fitzpatrick, 1987; Connell and Hall, 1987).

The coastal lowlands have been crossed at various times by ice flowing from the NW Highlands, eastern Grampian Highlands and onshore, both from the Moray Firth and North Sea basins. This has resulted in the deposition of interdigitating glacigenic units of varied provenance (Figure 5; Table 4). The eastern Grampian Highlands were mainly affected by ice that flowed outwards from, and retreated back towards centres of accumulation in the Cairngorms, Mounth and Gaick, typically depositing yellowish brown, quartzo-feldpathic diamicts with numerous boulders. The Banffshire coast was affected by ice that flowed out of the Moray Firth Basin (MFB) to lay down calcareous, fine-grained, typically dark bluish grey, shelly diamicts containing abundant erratics and rafts of Mesozoic rock and cold-water Quaternary sediments entrained from the bed of the firth (Peacock and Merritt, 1997, 2000a). The eastern coast was influenced by ice, sourced in the western Grampian Highlands, which flowed towards the North Sea through Strathmore. This ice

flowed onshore into Logie (Lower) Buchan, to the north of Aberdeen, where it disintegrated to form relatively 'fresh' hummocky topography formed by a distinctive suite of calcareous, vivid reddish brown sediments containing clasts of Permo-Triassic sandstone, dolomite, calcareous siltstone and reworked shells from the adjacent NSB in addition to material from the Old Red Sandstone (ORS) and associated Devonian volcanic rocks of Strathmore.

The terrestrial glacigenic sequence, striae, clast fabrics and distribution of indicator erratics show that the relative importance of ice dispersion centres changed during the last, and previous glaciations (Clapperton and Sugden, 1977; Sutherland, 1984; Sutherland and Gordon, 1993). For example, ice flowing from the Great Glen was forced eastwards across the coastal lowlands bordering the Moray Firth during an early phase of the last glaciation (Sissons, 1967; Fletcher *et al*., 1996) (Figure 4), possibly deflected by ice flowing south-eastwards from an ice divide stretching along the spine of the NW Highlands (Read, 1923; Bremner, 1934a, Bremner, 1943). Ice flowed from the Moray Firth across Buchan towards Aberdeen (Hall and Jarvis, 1995). The most commonly cited explanation for this onshore deflection is that Scandinavian ice had occupied the central NSB, impeding the more logical flow of Scottish ice north-eastwards out of the Moray Firth (Peach and Horne, 1893; Bremner, 1943; Synge, 1956: Sissons, 1967), but evidence for this has not been substantiated by recent research in Caithness and Orkney (Hall and Riding, 2016; Hall *et al.,* 2016).

There has been a long-standing debate whether parts of Buchan remained ice-free throughout the last glaciation (Sutherland, 1984), or became so relatively early during retreat of peripheral parts of the last ice sheet, when ice-marginal lakes (Glacial Lake Ugie) were ponded behind coastal ice lobes inland of Peterhead (Hall and Connell, 1991) (Figure 6) . There was probably a sequential south-westward 'un-zipping' down the North Sea coast of 'Strathmore' and 'East Grampian' ice during deglaciation (Simpson, 1955), possibly accompanied by a marine incursion up to about 30 m OD (Peacock, 1999). Minor readvances at Aberdeen, Dinnet and Aboyne are thought to have interrupted the general westward retreat of East Grampian ice (Jamieson, 1906; Bremner, 1931; Bremner, 1943; Synge, 1956; Sutherland and Gordon, 1993; Brown 1993, 1994; Evans *et al*., 2005). Important evidence for a minor, late-stage onshore readvance of Moray Firth ice occurs at St Fergus (Figure 6c), where raised marine deposits lying up to about 17 m OD have been deformed within a low ridge, probably a push moraine (Hall and Jarvis, 1989; Peacock, 1997). Extensive glaciofluvial and glaciolacustrine deposits were laid down along the southern margin of Moray Firth as terrestrial ice retreated inland from the coast whilst ice remained offshore (Read, 1923; Merritt *et al*., 2003) (Figure 6c). Evidence from glaciofluvial fan-deltas and glacial drainage channels indicate that a large ice-marginal lake(s) (Glacial Lake Rothes) occupied the lower reaches of Strath Spey during a minor readvance of ice within the Moray Firth known as the Elgin Oscillation (Peacock *et al*., 1968). The ice front retreated westwards into the inner Moray Firth, where a push moraine at Ardersier provides sound evidence for a subsequent glacial readvance (Merritt et al, 1995).

Glacial reconstructions

Early models for the glaciation of NE Scotland are reviewed by Merritt *et al.* (2003). Although there is broad agreement on the relative sequence of events, they differ mainly regarding whether the events relate to phases of the last glaciation (eg. Clapperton and Sugden, 1977) or successive glaciations separated by interglacial or interstadial periods (eg. Jamieson, 1906; Bremner, 1943; Synge, 1956). It was believed that the British and Scandinavian ice sheets had been confluent during the last glaciation (Geikie, 1894; Jamieson, 1906; Wright, 1914; Read, 1923; Bremner, 1943; Synge, 1956; Charlesworth, 1957; Sissons, 1967; Boulton *et al.*, 1977), but exploration of the central NSB subsequently revealed thick sequences of glaciomarine material apparently containing few, if any units of Late Weichselian diamict of demonstrable subglacial origin. This supported ideas that the BIIS had been much more limited in size, both in extent and thickness (Sutherland, 1984; Boulton *et al.*, 1985, 1991; Sutherland and Gordon, 1993). For example, in Sutherland's (1984) reconstruction of an independent BIIS, ice terminates at the eastern margin of the Wee Bankie, off the eastern Scottish coast (Figure 1), and, following Synge (1956) and Flinn (1967), parts of Caithness, Buchan and northern Lewis fall beyond its limits. These non-glaciated enclaves subsequently appeared in many published reconstructions of the north-eastern sector of the last BIIS (Bowen *et al.*, 1986; Bowen, 1989; Nesje and Sejrup, 1988; Boulton *et al.*, 1991; Ehlers and Wingfield, 1991; Lambeck, 1995; Bowen *et al.*, 2002; Clark *et al.*, 2004), despite the evidence for them having been seriously questioned (Peacock, 1997; Hall and Bent, 1990; Hall, 1997; Whittington *et al.*, 1998; Whittington and Hall, 2002), or refuted (Hall *et al.*, 2003; Phillips *et al.*, 2008). Nunataks formerly identified in the NW Highlands and Outer Hebrides by Ballantyne *et al.* (1998) lent support for a thin, low-profile ice sheet, but reinterpretation of the trimline evidence now indicates that the ice exceeded 900 m and 600 m in altitude over these areas respectively and that Scotland was completely buried beneath ice during the last glaciation (Ballantyne, 2010).

Evidence now suggests that Scandinavian and Scottish ice did indeed coalesce within the NSB at least during an early stage in the last glaciation, during the local Last Glacial Maximum (LGM) (Figure 2), when the BIIS was thick (Sejrup *et al.*, 1994, 2009; Chiverrell and Thomas, 2010). This 'Atlantic Shelf Glaciation' at c. 32-25k cal a BP (Sejrup *et al.*, 2003, 2005), or 32-27k cal a BP (Sejrup, 2015), was followed by the growth of more restricted ice sheets after c. 22k cal a BP. However, doubts surround the published geochronometry (Clark, *et al.*, 2004) and it is difficult to explain why early deglaciation of the central NSB occurred during a period including the global LGM when other sectors of the BIIS were expanding (Hughes *et al.*, 2016; Sejrup *et al.*, 2016). It is generally agreed that the northern sector of the last BIIS built up towards the end of MIS 3, after c. 32k a BP, when ice extended to the continental shelf margin (Stoker and Holmes, 1991; Whittington and Hall, 2002; Wilson *et al.*, 2002; Bradwell *et al.*, 2008; Jacobi *et al.*, 2009; Chiverrell and Thomas, 2010; Gibbard and Clark, 2011; Graham *et al.*, 2011;

Clark *et al.*, 2012; Everest *et al.*, 2013; Hughes *et al.*, 2014, 2016; Hiemstra *et al.*, 2015; Bradwell and Stoker, 2015a). It is unlikely that ice-free areas existed anywhere in northern Scotland during the global LGM, when the BIIS was thick (Ballantyne, 2010; Fabel *et al.*, 2012) (Figure 2). Major readjustments occurred during later stages (Hughes *et al.*, 2014) when ice streams became established in the Moray Firth (Merritt *et al.*, 1995), the Minch (Bradwell and Stoker, 2015a) and the Firth of Tay (Golledge and Stoker, 2006), possibly as a result of switches in glacial behavoir.

The subglacial bedform record

Hughes *et al.* (2010) published a bedform map of Britain based on systematic remote interpretation from a high-resolution digital surface model (Next-Map Britain DSM; 5 m horizontal resolution). This landform record was interpreted primarily in terms of ice-flow vectors (*flowsets*) (Greenwood and Clark, 2009a) augmented with data on glacial erratic transport paths gleaned mainly from the older literature and contained within the BRITICE database (Clark *et al.*, 2004) (Figure 3 and 4). *Isochronous* flowsets, representing a single flow event, were distinguished from *time-transgressive* (TT) imprints produced by smudging of two or more flow events (Figure 7). Flowsets in NE Scotland were organised into a relative age stack following examination of superimposition relationships of the constituent bedforms (Table 1). The flowsets were subdivided into those that disregard topography and those that are topographically-constrained. The former provide a glimpse of ice-sheet geometry during maximum extent, whereas most others formed during retreat phases. The TT flowsets are divided into those reflecting generally thinning ice and those specifically associated with retreating ice lobes. Clearly a flow event can create a landform from sediments that formed in a much older event and palimpsest features (Kleman, 1994) are likely to have been preserved in central Buchan where the stratigraphical record is longest and cold-based ice was predominant (Connell and Hall, 1987).

Glacial retreat stages

The pattern of glacial retreat across NE Scotland (Figure 8) has been established by Clark *et al.* (2012) as part of a countrywide analysis of moraines, eskers, glacial drainage channels and drumlins mapped by systematic visual interpretation of Digital Elevation Models (DEMs) and satellite images, the wider literature (Evans *et al.*, 2005) and compilation of published dates (Hughes *et al.*, 2011). The retreat pattern determined by these authors is generally accepted here, but there are exceptions. Notably, their onshore limit for ice that invaded Logie-Buchan from the east or SE has been modified and replaced by the western boundary of the lithostratigraphical subgroup of that name (Figure 5). This sharp boundary has been mapped out on the ground (Merritt *et al.*, 2003, fig. 50) and the authors find no evidence that the ice encroached farther inland. Borehole information (McMillan and Aitken, 1981) shows that the Logie-Buchan ice reached northwards to beyond Peterhead (Figure 5), but any moraine features there have been obliterated by a subsequent expansion of Moray Firth ice.

The retreat pattern presented by Clark *et al.* (2012, fig. 12) has also been modified along the eastern coast, where they infer that ice retreated inland from the Wee Bankie (Figure 1), a terminal moraine according to Sutherland (1984). However, there are no diagnostic features typical of an ice-marginal moraine, morainal bank or accretionary wedge, instead mainly NE-directed channels cut into red till (Figure 8). The channels were probably eroded beneath a lateral shear margin between Scottish ice and ice occupying the central NSB (Golledge and Stoker, 2006).

The complex retreat limits formed by moraine ridges south of Bennachie (Blairdaff Moraine Formation of Merritt *et al.*, 2003) and around Durn Hill may be linked. A significant change in the character of the landscape occurs at about these limits, as noted by earlier workers. For example, periglacial phenomena, specifically ice-wedge pseudomorphs and surficial sheets of gelifractate and gelifluctate are widespread to the north-east, across central Buchan (Synge, 1956; Connell and Hall, 1987), where a network of drainage channels formed at the retreating margin of cold-based ice (Merritt and Peacock, 2000) (Figure 8a) and eskers are sparse. In contrast, relatively fresh-looking morainic and glaciofluvial deposits are more common to the SW. It is suggested that the ice-limits associated with these moraines resulted from a significant regional re-expansion of ice following prolonged very cold conditions.

The configuration of retreat limits shown in Figure 8 around Elgin are consistent with a readvance of Moray Firth ice during the Elgin Oscillation (Peacock *et al.*, 1968), when extensive lakes were ponded within lower Strath Spey and Glen Rinnes. The subsequent Ardersier Readvance is revealed by retreat limits around the inner Moray Firth (Merritt *et al.*, 1995).

A critical review of the lithostratigraphical and geomorphological records in NE Scotland and crucial parts of the offshore record

Evidence for glaciations predating the late Middle to Late Devensian.

We focus on glaciation during the late Middle and Late Devensian, but NE Scotland is unusual in northern Britain in possessing a significant number of sites documenting earlier glacial and non-glacial events (Merritt *et al.*, 2003 and references therein). Evidence for these older events will be reviewed elsewhere, but as several sites contain glacigenic units that were previously thought to be Late Devensian in age, a brief mention is given here.

Tills in NE Scotland have been attributed to earlier Devensian glaciations, as in Scandinavia (Mangerud *et al.*, 2013), but none have yet been confidently ascribed to one. If the region was glaciated then, despite it having experienced minimal glacial erosion and deposition, some tills of this age should have been preserved considering the widespread survival of regolith, units of sand and gravel, periglacial structures and sediments, and palaeosols (Table 3). This may be due partly to ‘accommodation’ for most long sequences in the region have been preserved within channels, as at Kirkhill, but once filled hollows such as these cannot accommodate more sediment.

Furthermore, many channels have a long history and tend to be re-used and flushed-out during subsequent glaciations. Those till units that have been reported to be of early Devensian age are not capped by organic deposits of certain MIS 3 age so a practical, parsimonious approach has been adopted by ascribing them to the late Middle to Late Devensian. Clearly more research is required, as for example at the Nigg Bay and Oldmill sites (Table 2), which include glaciofluvial outwash and glacideltaic deposits that have provided OSL age estimates of approximately MIS 4 age (Gemmell *et al.*, 2007).

NE Scotland has a record of erratics of Scandinavian origin (principally Oslo Graben rhomb-porphyry and larvikite) recovered from glacigenic deposits (Read *et al.*, 1923: Merritt *et al.*; 2003 and references therein) (Figure 3). Erratics of rhomb-porphyry recovered recently from till deposited by eastward flowing ice at both Kirkhill and Sandford Bay suggest that they have been recycled, having been introduced to the region prior to the Late Devensian (Merritt *et al.*, 2003). It is presently unclear if they were deposited directly by Scandinavian ice although it is a recurring theme in the older literature that such ice once lay close to the east coast deflecting Scottish ice to both north and south (Merritt *et al.*, 2003, figs 37 and 38).

Evidence for substantial east to south-east flow of ice from the Great Glen during the last glacial cycle.

East of Inverness.

Psammite-rich tills with few sandstone clasts commonly overlie diamicts containing abundant ORS lithologies (sandstone, siltstone and conglomerate) on the north-west-facing slopes overlooking the inner Moray Firth between Inverness and Forres (Horne and Hinxman, 1914; Horne, 1923). Material derived from ORS outcrops around the Loch Ness Basin was transported eastwards towards Grantown-on-Spey, onto ground up to at least 500 m OD on the Nairn-Findhorn watershed, and into the middle to lower reaches of the Nairn, Findhorn and Spey valleys (Horne, 1923; Sissons, 1967; Fletcher *et al.*, 1993) (Figure 4). The final movement of ice, however, was towards the north-east, as indicated by fs 6 (Figure 7), the orientation of glacial striae and the clast-composition of the youngest tills (Fletcher *et al.*, 1996). As the sandstone- and psammite-rich till units are now both believed to be Devensian in age (Duller *et al.*, 1995), the earlier, south-eastward flow event should be considered in reconstructions of the last BIIS.

A key locality is the Dalcharn site (Table 2, Figure 4), 200 m OD (Merritt and Auton, 1990; Auton, 1993) where the lower, sandy, *Athais Till F* (AT) (formerly Dalcharn Lower Till) rests unconformably on the *Dalcharn Palaeosol F* (DPF) (Table 3). The DPF contains compressed and disseminated organic material containing pollen of full interglacial affinity reflecting the later stages of an interglacial cycle, possibly predating MIS 5e (Walker *et al.*, 1992). The cryogenically and glacitectonically disturbed organic deposits occurred near the bleached top of a considerably weathered unit of gravel (*Craig an Daimh Gravel*) (CDG) (formerly Dalcharn Gravel). An older, weathered sandstone-rich diamict (*Dearg Till F*) underlies the gravel. Samples collected from a unit of white, clayey, cryoturbated gravel with disseminated peaty material taken

from beneath the uppermost organic part of the DPF have yielded maximal luminescence ages of 68 and 50 ka (Duller *et al.*, 1995). The ages are consistent with an infinite radiocarbon date of >41.3 ka obtained from a bulk sample of the organic unit above, but suggests that the thermophilous arboreal pollen in the DPF must be either allochthonous (Whittington, 1990) or reworked. The DPF is unlikely to be a glacial raft for it is part of a coherent weathering profile within the CDG that can be traced laterally for at least 400 m (Figure SI 14) (Bloodworth, 1990). The severity and depth of the weathering profile (over 3 m) begs comparison with the Troutbeck Palaeosol in Cumbria, England (Boardman, 1985), which like the DPF is of complex origin, but likely to be the result of a considerable period of temperate conditions including the Ipswichian and earlier interglacials.

The Athais Till overlies the *Moy Peat Bed* (MPB) at the Moy (Allt Odhar) site, some 9 km to the south, at 371 m OD (Table 2; Figure 4) (Merritt, 1990, 1993; McMillan *et al.*, 2011). This compressed bed of fibrous peat contains pollen, plant-macrofossils and coleopteran remains that reveal climatic deterioration during an Early Devensian interstadial (Walker *et al.*, 1992). Similar to the Dalcharn Palaeosol, the MPB rests on gravel, which in turn overlies an older sandstone-rich diamict (*Suidheig Till F*), but the weathering profile is far less developed. Samples collected from sand-rich lenses within the MPB have yielded luminescence ages of between 37 and 58 ka that were considered to be reliable and consistent with a finite radiocarbon age of 47.7k ^{14}C a BP obtained from the alkali insoluble component of samples of the MPB (Duller *et al.*, 1995). However, three concurrent radiocarbon age determinations were infinite (>51.1k ^{14}C a BP) (Walker *et al.*, 1992). The time span of 20 ka between the TL ages for the top and bottom of the MPB is difficult to accept, but not totally at variance with the entomological palaeoenvironmental evidence. However, the TL ages are inconsistent with an experimental U-series disequilibrium measurement of 106 ka for the MBP (Heijnis and van der Plicht, 1992). On reflection, a Middle Devensian age is possible for the Moy Peat Bed, especially as pollen grains of *Bruckenthalia spiculifolia* (Balkan heath) were not present (M.J.C.Walker pers.comm.). This species has been reported from Early Devensian interstadial deposits in Scotland (Whittington, 1994), but at much lower altitudes.

The Athais Till at Dalcharn has a till fabric indicating ice flow towards the south-east (Merritt and Auton, 1990; Walker *et al.*, 1992; Auton, 1993), which is compatible with the pathways of indicator erratics (Figure 4). No flowsets of this antiquity have been identified in the vicinity by Hughes *et al.* (2014), although fs. 92 in the lower Findhorn valley, south-east of Forres, does have a parallel orientation (Figure 7). It is tempting to correlate this flowset with the Athais Till, but Hughes *et al.* (2014) conclude that ice flowed in the opposite direction. Fs.92 is constrained by very few landforms and its relative age is uncertain (Table 1). Circumstantial evidence for early east to south-easterly, uphill flow has been obtained from the Clava site nearby (Table 2; Figure 4, at 150 m OD). Clava is famous for occurrences of 'arctic' shelly clay and diamict that have been interpreted either as glacial rafts or parts of an *in situ* raised cold-water marine deposit (Gordon, 1993a). The former origin is more likely (Merritt, 1992; Phillips and Merritt, 2008; Merritt *et al.*, 2014). The shelly clay

contains well preserved, high-boreal to low-arctic, shallow-water marine shells that have yielded amino acid racemerisation (AAR) ratios not younger than the mid-Devensian (Merritt, 1992). Furthermore, an associated folded raft of pebbly diamict containing fragments of *Portlandia arctica*, an indicator of shallow-marine, fully arctic conditions, yielded a radiocarbon age of > 47.1k cal a BP. Merritt (1992) concludes that the sediment forming the rafts was originally deposited in Loch Ness, a marine fjord during the early Devensian. The rafts were detached and transported eastwards upslope owing to a powerful build-up of ice to the north-west. The age estimates further constrain the maximum age of this early flow event. At Clava the rafts of shelly clay and diamict are overlain by the *Finglack Till F*, deposited by ENE directed ice in general accord with glacial striae in the vicinity (Fletcher *et al.*, 1996) and fs. 6 (Figure 7). The Athais Till is apparently absent, probably because it was eroded away beneath the Moray Firth Ice Stream during the creation of fs. 6, when it shrank and down-cut to create flights of benches, ice-marginal drainage channels and corrugations on Drummossie Muir that are possibly megagrooves (Fletcher *et al.*, 1996; BGS, 1997).

The Athais Till is well exposed in several valleys of streams draining towards the River Nairn, including the Clava site, where multiple sequences of diamict, glacitectonite, sand and gravel are exposed in river cliff sections up to 40 m high (Merritt and Auton, 1993: Fletcher *et al.*, 1996, fig. 25). These sections have good potential for luminescence dating. The AT overlies weathered sandy diamict that probably correlates with the Dearg, Suidheig and Cassie tills at Dalcharn, Moy and Clava respectively: this unit locally rests on an even older, severely weathered till (Fletcher *et al.*, 1996, fig. 25). Multiple sequences such as these may be expected in this western part of the region, which is likely to have been glaciated repeatedly during 'average' build-up of ice sheets during the Pleistocene (cf. Clapperton, 1997; Klemen, 1994).

Lower Strath Spey.

The east to south-easterly carry of ORS erratics is evident at least as far east as the Teindland site, within lower Strath Spey (Sutherland, 1993a) (Table 2; Figure 4). The *Woodside Diamicton* (formerly Teindland Till) (Table 3) overlies a truncated podzolic soil (*Teindland Palaeosol*) that contains pollen of thermophillous species and grasses assigned to the latter part of the Ipswichian Interglacial (Hall *et al.*, 1995a). Luminescence ages of around 79 and 67 ka obtained by Duller *et al.* (1995) from the *Badentinian Sand Bed* (BSB) (Table SI 2) above the main organic horizons support the age suggested and were considered to be reliable by these authors. Although the genesis of the Woodside Diamicton is unclear, the presence of an isoclinal fold and shear zones within the sand bed strongly suggest post-depositional glacitectonism (Merritt *et al.*, 2003; Connell and E.R. Phillips, unpublished). It follows that the uppermost part of the BSB may have been eroded and thus the TL dates could significantly predate the initial glaciation of lower Strath Spey during the last glacial cycle. However, a parsimonious interpretation would suggest that glaciation occurred soon after deposition of the BSB. As at Dalcharn and Moy, the palaeosol is developed on gravel that overlies an older diamict (*Red Burn Till*).

A condensed sequence occurs at the original Teindland site, but three younger till units have been identified above the stratigraphic level of the palaeosol in the vicinity (Hall *et al.*, 1995a) (Table 3). The oldest is the dark grey *Altonside Till*, which is exposed in a river cliff section of the River Spey at Tofthead (Table 2). It includes pebbles of Mesozoic mudstone and sandstone from the Moray Firth Basin and both the provenance and fabric of the till indicate former ice flow towards the south-east (Table 4). The Altonside Till, together with other dark grey diamicts (some shelly) recorded from boreholes drilled in lower Strath Spey (Aitken *et al.*, 1979), thus probably correlates with the sandy Athais Till farther west (Table 3). If correct, the differences in colour, clast composition and matrix between the till facies simply reflects the bedrock over which the ice flowed during a regional south-easterly flow event(s) of ice from the Moray Firth.

Evidence for south-east flow of ice from the Moray Firth across the Banffshire coast and Buchan.

The isolated masses of dark grey, shelly diamict that occur beneath younger tills from Strath Spey south-eastwards to Aberdeen have been assigned to one allostratigraphical unit, the *Whitehills Glacigenic Formation* (WGF), within the Banffshire Coast and Caithness Glacigenic Subgroup (Peacock and Merritt, 1997; 2000a) (Figure 5, Table 3, 3). The shelly deposits are generally capped by till containing clasts derived from the west or west-north-west, as at the Boyne Quarry, Castlehill of Gardenstown and King Edward sites (Jamieson, 1906; Read, 1923; Peacock *et al.*, 1968; Hall *et al.*, 1995a; Merritt *et al.*, 2003) (Table 2; Figure 8). The tills incorporate ice-worn Pleistocene shell fragments in addition to abundant reworked, predominantly, Early Jurassic to Early Cretaceous fossils and palynomorphs (Riding, 2003). Blocks and large glacial rafts of Permo-Triassic and Lower Jurassic to Upper Cretaceous rocks are commonly enclosed within the shelly diamict. For example, mudstone rafts within the WGF were large enough to support brick and tile works at Whitehills, west of Banff, Tochieneal, south of Cullen and Plaidy , north of Turriff (Read, 1923). Large Jurassic erratics were formerly exposed at Atherb and Brucklay Castle , to the SW of Strichen (Jamieson, 1906), rafts of Late Jurassic black lignitic clay are described at Ardglassie , SSE of Fraserburgh (Merritt and Connell, 2000b) and ammonite-bearing black mudstone at the Oldmill site (Table 2) (Merritt and Connell, 2000a: Riding 2003).

Amino acid (AAR) ratios and radiocarbon dates on shell fragments collected from the WGF, mostly at the King Edward site (Table 2), suggest that the shelly components of the formation are derived from cold-water marine muds of Early to Middle Devensian age (Miller *et al.*, 1987; Peacock and Merritt, 1997; Hall and Peacock, 2000; Peacock, 2000a; Bowen *et al.* (2002). More specifically, the ratios correlate with the Bø Interstadial of Norway (Mangerud *et al.*, 1981), for which ages from 40 to 80 ka have been proposed by Miller *et al.* (1983), the higher estimates being favoured by Sejrup *et al.* (2000). No material dating to the younger Ålesund Interstadial of the Norwegian sequence has been reported in the WGF, suggesting that the last BIIS first expanded across the Moray Firth in the later part of the Middle Devensian. However, younger AAR ratios have been derived from shelly till at Dunbeath, in Caithness (Hall *et al.*, 2011). It is not possible to fully establish the age of

the WGF owing to poor exposure and some rafts and shelly deposits may have been deposited during pre-Devensian glaciations (Merritt *et al.*, 2003).

Probable correlatives of the Whitehills Glacigenic Formation have been reported at several sites north of Aberdeen. For example, at Kirkhill and Leys, where large masses of dark grey clay (*Corse Diamicton Member*) consisting mainly of crushed mudstone bearing dinoflagellate cyst assemblages of Late Jurassic to Early Cretaceous age lie above a cryoturbate *(Corsend Gelifluctate Bed)* (CGB) deposited on the truncated *Fernieslack Palaeosol Bed* (Connell et al, 1982: Connell, 1984, p.69, Hall and Jarvis, 1993a), of likely Ipswichian age (Duller *et al.*, 1995) (SI Table 2). The period of time represented by the CGB is unknown and hence the age of emplacement of the Corse Diamicton. At the Bellscamphie site (Table 2), near Ellon, the 'indigo' till of Jamieson 1906 and/or Pitlurg Till of Hall and Jarvis (1993b; 1995) underlies red diamict. The igneous and metamorphic clasts in these dark grey tills are likely to have been derived from the gneisses, gabbros and norites that crop out to the NW of Ellon (Figure 3), but the ammonite recorded by Jamieson (1906) and dinoflagellate cysts recovered by Hall and Jarvis (1995) and Riding (2003) both indicate derivation ultimately from the Moray Firth Basin west of Fraserburgh. However, although a weak north-south clast fabric has been detected in the Pitlurg Till by Hall and Jarvis (1995), direct transport from the north-west through to the north-east is difficult to accept because the till contains few, if any, pebbles of flint and quartzite from the Buchan Ridge Gravels, to the north (Merritt *et al.*, 2003, fig. 2). Shell fragments of mixed populations in the Pitlurg Till have yielded AAR ratios of MIS 7 and MIS 5e age (Bowen and Sykes, 1988) suggesting, but not proving that the till correlates with the WGF. The *Anderson Drive Diamicton* found near the Bridge of Dee, in Aberdeen, is also shelly (Bremner, 1934a, 1943; Hart, 1941). It is no longer exposed, but at Nigg Bay (Table 2), some 4 km to the ENE, the *Nigg Bay Till Member* contains a rich palynoflora with a conspicuous Jurassic component (Riding, 2003) believed to have been entrained from the outcrop of Anderson Drive Diamicton. The Nigg Bay Till is otherwise a typical westerly-derived, sandy till with metamorphic and igneous erratics from inland (Table 4).

The scarcity of distinctive flint and quartzite clasts in the Pitlurg Till suggests that the ice was cold-based as it flowed across Buchan. This would explain the general absence of south-east orientated subglacial landforms there (Hughes *et al.*, 2010). Furthermore, a large raft of ammonite-bearing Jurassic mudstone set into the base of the Whitehills Glacigenic Formation was observed to rest directly on undisturbed, weathered, cross-stratified, glaciofluvial sand and gravel with possible ice-wedge casts at the Oldmill site (Merritt and Connell, 2000a, fig. 32), to the north of the Buchan Ridge, indicating that minimal subglacial deposition of till accompanied the initial flow of ice from the Moray Firth. The emplacement of the Corse Diamicton directly upon the Corsend Gelifluctate (hosting at least one ice wedge cast) at Kirkhill and Leys (Table 3) reinforces the conclusion that the ice advanced across frozen ground.

The Jurassic material in the Whitehills Glacigenic Formation and its correlatives is derived either from the northern shores of the Moray Firth, around Brora, or from strata cropping out beneath the firth (Jamieson 1906; Read 1923; Bremner, 1928, 1934a). Quantitative palynology of samples taken from the thickly developed WGF at Oldmill quarry indicate the main age diagnostic component of the palynofloras are of Jurassic origin, with little contribution from younger Mesozoic rocks (Riding, 2003). This assemblage suggests that ice flowed eastwards along the southern coast of the Moray Firth, crossing Jurassic outcrops offshore, before turning SE and E across Buchan.

Further evidence of an 'early' SE ice flow comes from the work of Synge (1963), Murdoch (1977) and McLean (1977) to the west and north of Aberdeen, on BGS Sheet 77. All three authors recorded tills with SE directed clast fabrics and associated striae on bedrock. Murdoch and McLean both recorded an older till in gas pipeline trenches with SE orientated fabrics and NW derived erratics, though the unit was generally thin and restricted to bedrock depressions. In all cases this older till was overlain by a till unit with westerly derived clasts and a generally ENE clast fabric. At the more recently studied site at Kingwells, west of Aberdeen city, these two till units have been named the *Denburn* and *Kingswells members* respectively (Merritt *et al.*, 2003; Table 4). The two till units have been recorded over a distance of some 15 km and are now considered to date to the late Middle to Late Devensian, although Sutherland (1984) speculated that the lower till may be older. At the Kingswells site, and in the boreholes drilled for the outer Aberdeen ring road, there is no evidence of a significant discontinuity between these two till units.

The western limit of material derived from the floor of the Moray Firth is shown in Figure 5. SE-directed striae reported to the west of this limit suggest that Grampian ice was deflected parallel to this boundary. For example, Bremner (1920b) recorded SE and SSE-directed striae on the interfluve lying between Banchory-Devenick and Cove Bay, south of the River Dee, and found erratics of Binn Hill gabbro on the coast south of Aberdeen (Figure 3). Furthermore, Francis Synge (pers. comm. to ERC in 1980) recorded SE-orientated striae on the NE flank of Bennachie at c. 335 m OD (Figure 7), which demonstrates that the ice was thick.

Evidence for the south-eastward flow event comes mainly from till-provenance, till-fabric and SE-directed striae recorded around Elgin (Merritt *et al.*, 2003, map 1) and Banff (Merritt *et al.*, 2003, map 3). It is possible that some components of fs.72, in eastern Buchan, together with some ice-moulded rock features associated with fs. 92, SE of Forres, may have formed contemporaneously (Figure 7; Table 1). The south-easterly directed flowset identified by Hughes *et al.* (2014) in Angus (Figure 7, fs. 7) certainly invites correlation with this stage (Table 1). It requires thick cover over the eastern Grampians to drive ice across the Vale of Strathmore and over the Sidlaw Hills, at up to 455 m OD. However, the antiquity of fs. 7 is unclear (Hughes *et al.*, 2014) and older units of grey diamict containing Mesozoic erratics do occur in NE Scotland (Hall and Connell, 1991; Merritt *et al.*, 2003) (SI Table 2) indicating that south-eastward flow of ice from the Moray Firth occurred during more than one glaciation.

Evidence for an abrupt switch in ice flow direction following the early south-easterly flow event.

East of Inverness.

Based on thorough, systematic logging of natural sections on geological sheet 84W (BGS, 1997), east of Inverness, Merritt and Auton (1993) found that the contact between the sandstone-rich and overlying psammite-rich tills was generally represented by a sharp change in colour and commonly by a planar, sub-horizontal discontinuity. No major unconformities, distinct weathering profiles, palaeosols or organic deposits were found that could be linked with a complete deglaciation, but the common presence of wedge-shaped pull-apart structures, truncated gravel-filled channels, seams of glacitectonite and rip-up clasts of diamict suggest that ice-bed boundary conditions changed during the switch in flow (Fletcher *et al.*, 1996; Walker *et al.*, 1992), the ice-sheet possibly becoming more wet based. The sandy tills generally appear to be more weathered, but this may reflect their greater permeability or inclusion of previously weathered material.

At Dalcharn the sandy Athais Till is overlain by two members of the *Beinn an Uain Till Formation* (Table 3) that contain an increasing proportion of psammite upwards and fabrics that indicate a switch in flow first towards the east and then NNE (Walker *et al.*, 1992). Both the fabric and provenance of the upper, *Ruallan Till M* supports correlation with fs.34 (Figure 7). This TT flow line is associated with ice that flowed from a centre in the western Highlands via upper Strath Spey to the vicinity of Grantown-on Spey. Flow was then concentrated across a gap in the Spey-Findhorn divide at Beum a' Chlaidheimh (Figure 4), at c. 360 m OD, as ice flowed northwards towards the Moray Firth via Lochindorb (Merritt *et al.*, 2013). Considering the elevation of the gap and surrounding mountains, fs.34 must have shut down soon after deglaciation of the Cairngorm tops commenced at c. 21.3ka (Phillips *et al.*, 2006) and an outlet glacier became established in upper Strath Spey creating fs.47 (Figure 7). Cosmogenic ages of c. 17.1ka on a rock glacier in Strathnethy (Phillips *et al.*, 2006; Ballantyne, 2010) therefore provide only a minimum age for fs.34.

Banffshire and Buchan.

Like the Athais Till, the Whitehills Glacigenic Formation generally has a gradational upper contact with tills of contrasting provenance indicating a switch in ice flow direction unrelated to any deglacial event. For example, at Boyne Quarry there is corroborative structural evidence and striae indicating that the WGF was deposited by ice flowing southwards yet the overlying diamict (*Old Hythe Till F*) contains clasts of westerly provenance except for boulders of troctolite recycled or brought by a circuitous route from the south (Gordon, 1993b; Peacock and Merritt, 2000a; Peacock and Merritt, 2000b; Merritt *et al.*, 2003). At the Castlehill site (Table 2 and 2) the sheared and ice-thrusted WGF is locally overlain by a thin unit of diamict (*Crovie Till F*) containing well-rounded pebbles most likely derived from ORS conglomerate cropping out to the south-west. At both sites the tills overlying the WGF can

therefore be correlated tentatively with fs. 36, indicating that an abrupt switch in ice flow occurred.

Important evidence comes from the Kirkhill and Leys sites where the mudstone-rich Corse Diamicton underlies the *Hythie Till Formation* (HTF) (Table 3 and 3). Based on its relative age and provenance, the Corse Diamicton invites correlation with fs. 72. Although Hughes *et al.* (2014) suggest that fs. 72 cuts fs. 36 (Figure 7; Table 1), the latter set could be older because it has a much less clear geomorphological signature and no cross-cutting landforms have been identified. Fs. 36 is confidently correlated with the Hythie Till (EGGS), which contains clasts derived mainly from the west and south-west. The former quarry at Kirkhill is situated within a rock-cored drumlinoid ridge trending WSW-ENE and other ice-moulded features in the area are similarly orientated (Merritt *et al.*, 2003, map. 6). As a note of caution, however, felsite dykes like that which was formerly quarried at Kirkhill lie in the same orientation.

At Oldmill , the WGF and its included rafts are overlain gradationally by a thin unit of diamict that is correlated with the *Hythie Till* as it contains erratics from the west and a weak 'west to east' fabric (Merritt and Connell, 2000b). Farther south, in the Aberdeen area, the Den Burn Till is overlain by a range of younger till facies that occur at the surface, or beneath glaciofluvial sediments over a significant area. These younger tills, the *Kingswells* and *Nigg Till members* of the *Banchory Till Formation* (Table 4) were generally deposited by ENE flowing ice with no major discontinuities between the older and younger units. Both striae and clast fabric measurements suggest flow fluctuated between E and ENE, which is compatible with fs 64 (Figure 7).

Evidence for ice flow from Strathmore up the eastern coast of Buchan

It is generally accepted that ice formerly flowed north-eastwards along the coast from Strathmore (Jamieson, 1906; Bremner, 1916; Synge, 1956; Clapperton and Sugden, 1977; Merritt, 1981; Hall, 1984; Munro, 1986; Hall and Connell, 1991). Glacial striae locally provide evidence of NNE-directed ice flow (Jamieson, 1882a, 1906; Bremner, 1916), notably near Nigg Bay (Merritt *et al.*, 2003, map. 9) and high on the hillside overlooking Boddam, south of Peterhead (Jamieson, 1882a, 1906; Merritt *et al.*, 2003, map. 7). Red sandy textured tills of the Mearns Glacigenic Subgroup (MGS) (Table 4) were laid down by ice flowing in this direction (Bremner, 1920a), but possibly on more than one occasion. We have identified silty clay-rich red till as far north as Netherhill Farm, c. 7 km NNW of Peterhead, where it is capped by grey diamict belonging to the BCCGS. At Nigg Bay, Cove (Jamieson, 1882a and Findon (Synge, 1963) (Merritt *et al.*, 2003, map 9 and 11) red till locally rests on grey till of western provenance indicating that East Grampian ice formerly flowed offshore before being replaced by Strathmore ice. Gradational contacts between the tills suggest that they were laid down during the same (Middle-Late Devensian) glaciation. This flow event is correlated with fs. 51 (Figure 7), which Hughes *et al.* (2014) conclude is isochronous.

The direction of ice flow subsequently changed from NNE to ENE as the Strathmore ice stream became dominant, creating fs. 56 (Figure 7). The presence of red tills of the MGS in the mouths of most valleys draining the southern flank of the eastern Grampian Highlands, such as Glen Clova and Glen Esk (Bremner, 1934b, 1936; Synge, 1956), and at Balnakettle (Table 2), 4 km NW of Fettercairn, indicate that Strathmore ice either forcibly pushed back ice occupying the valleys to the north, or that the ice within them had already begun to thin and retreat, enabling Strathmore ice to advance towards the mountains (Figure 5). The sequence of events at Balnakettle may be more complex, because East Grampian ice subsequently expanded back towards Strathmore (Merritt *et al.*, 2003) and Hughes *et al.* (2014) recognise a NNE-directed flowset in the area (fs. 93), which is cut by, and is therefore older than fs. 51 (Table 1).

Evidence for an onshore re-advance of ice into Logie-Buchan

Ice sourced in Strathmore encroached onshore between Aberdeen and to the north of Peterhead following the creation of fs. 51 and the aforementioned NNE striae near Boddam. It laid down a distinctive suite of deposits in Logie-Buchan (Figure 5) (Jamieson, 1906; Bremner, 1916; Synge, 1956; Clapperton and Sugden, 1977; Merritt, 1981; Hall, 1984; Munro, 1986; Hall and Connell, 1991; Merritt *et al.*, 2003, fig. 50) with clast fabrics in diamicts of the *Hatton Till Formation* indicating flow towards the NNW. The onshore movement is confirmed by the clay mineralogy of the L-BGS (Glentworth *et al.*, 1964) likely derived from Triassic mudstones (Figure SI 12) together with glacial erratics derived from the floor of the North Sea Basin immediately to the east, including Permian dolomite, Mesozoic limestone and calcareous siltstone, shelly sandstone (Crag) (Jamieson, 1882b) and shell fragments of early Pleistocene and younger age derived from the Aberdeen Ground Formation offshore (Merritt *et al.*, 2003: Stoker *et al.*, 2011).). Quantitative palynological analyses of samples from this unit contain rich assemblages dominated by Jurassic forms with less common Permian pollen and sparse Carboniferous and Cretaceous/Palaeogene forms (Riding and Stephenson, 2001). This enigmatic onshore flow direction led to the deposition of a swathe of relatively ‘fresh’ hummocky topography formed of vivid reddish brown, interbedded diamict, clay, micaceous silt, sand and gravel. Topography bears little relationship to the sub-drift surface and laminated silts and clays overlying buff-coloured, pebbly sands with shell fragments commonly occur at the base of the sequence within hollows (Merritt, 1981). This complex landform-sediment assemblage typical of ice disintegration either relates to a local glacial reorganisation during the decay of the ice stream responsible for fs 51 after the ice sheet had thinned considerably, or to a subsequent readvance (Clark *et al.*, 2012). For convenience the event is named here as the *Logie-Buchan Readvance*. The Kippet Hills Esker (Figure 8; Table 2) (Gordon, 1993c) was deposited by water flowing NNW (Merritt *et al.*, 2003), most likely in the general direction of ice flow during stagnation and decay of this coastal ice lobe.

Recent interpretation of the glacial deposits exposed in Sandford Bay (Table 2) (Hall and Connell, 1991; Merritt *et al.*, 2003), south of Peterhead, broadly

confirms Jamieson's (1906) final conclusion that early expansion of ice from inland to, if not beyond the present coastline was succeeded by the deposition of a glaciolacustrine sequence (*Ugie Clay Formation*) (UCF) that received sediment both from the westward-retreating East Grampian ice sheet and northward-advancing Logie-Buchan ice. Subsequently the latter advanced onshore and deposited a thick till complex including rafts of dark grey, shelly, clayey diamict. The ice advanced over 5 km inland into the lower Ugie valley, west of Peterhead, damming meltwater to create an extensive proglacial lake (Glacial Lake Ugie) (Figure 8). Reddish brown silt and clay of the UCF widely underlie the floodplains and glaciofluvial terraces associated with the North and South Ugie waters (McMillan and Aitken, 1981) and at Baluss Bridge (Table 2) the UCF includes thinly interbedded reddish brown and dark grey plastic clay, the latter yielding rich Palaeozoic and Mesozoic palynomorph assemblages (Hall, 1984; Hall and Connell, 1991). Similar laminated organic deposits occur at Errollston (Peacock, 1984; Connell *et al.*, 1985; Merritt et al, 2003) (Table 2), near Cruden Bay.

A lobe of ice advanced onshore up the valley of the River Ythan, where it laid down red diamict (*Hatton Till F*) on till of inland provenance at Bellscamphie (Table 2), north-east of Ellon, and at a number of other nearby sites (Hall and Jarvis, 1995). The advance terminated close to the Cross-Stone site, south of Ellon (Table 2; Figure 8), where a pair of crescentic, asymmetrical end moraines were formed (Merritt *et al.*, 2003). As in the Ugie catchment, East Grampian ice had retreated sufficiently to allow a substantial glacial lake to form in the Ythan valley upstream of Ellon (Merritt, 1981; Hall, 1984) (Figure 8). In the Aberdeen area, however, masses of red diamict locally occur within a grey-brown till of western provenance and vice versa (Bremner, 1916; Munro, 1986; McLean, 1977; Auton and Crofts, 1986; Merritt *et al.*, 2003), which led Clapperton and Sugden (1977) to conclude wrongly that the ice responsible for laying down the L-BGS was wholly in contact with East Grampian ice.

The inland margin of the L-BGS can be traced north-eastwards from the Ythan valley towards the Den of Boddam (Figure 8), at about 80 m OD, before descending to about 50 m OD to the west of Peterhead. The Den has a long history but finally carried meltwater north-eastwards towards Sandford Bay. Red tills overlie yellowish brown and grey tills of western provenance between Ellon and Peterhead (Wilson, 1886; Jamieson, 1906; McMillan and Aitken, 1981) and at Downiehills (Merritt *et al.*, 2003, map 7) Jamieson (1858) recorded large blocks of Peterhead Granite in reddish brown till together with shell fragments. He noted dark blue clay 'intermingled' with red deposits in a former claypit at Ednie (Jamieson, 1906) (Merritt *et al.*, 2003, map 7), whereas the red till had been observed to enclose irregular masses of 'dark grey till' and 'dark blue clay and sand' by Wilson (1886). These observations have caused confusion for on one hand they have been taken to support the view that deposits of Moray Firth and North Sea derivation are intermingled and of approximately the same age (Jamieson, 1906; Hall and Connell, 1991). The alternative view is that older blue-grey sediments have been incorporated into the red glaciotectonically by a later, northward movement of ice (Sutherland, 1984). This view is supported by evidence reported from

temporary exposures at Invernettie, near Sandford Bay, that revealed very dark grey, calcareous, shelly, clast-poor, clayey diamict forming rafts up to 2.0 m thick and over 50 m in length (Merritt *et al.*, 2003). The rafts were disrupted by south dipping, low-angle, thrust faults. Darker colours predominated close to the rafts, passing outward into the vivid reddish brown colours of the host diamict suggesting that the rafts were in the process of being 'digested'. Analysis of the diamict forming the rafts showed it to be rich in Late Jurassic to early Cretaceous palynomorphs (Riding, 2003). Though thrust from south to north, the grey diamict had an original provenance to the north or NW of the site in the Moray Firth.

The precise sequence of events is difficult to establish for the stratigraphic record in eastern Buchan is complex. For example, a small ice-free enclave possibly opened up in eastern Buchan late in the previous stage during ice-sheet thinning, occupied by Glacial Lake Ugie at its 80 m level, in the lee of the confluence of Strathmore and Moray Firth-sourced ice (Peacock and Connell, 2000) (Figure 8). Evidence for the 80 m lake is restricted to the valley of the North Ugie Water, where Moray Firth ice formed a narrow, ESE-trending morainic ridge adjacent to the 80 m lake near Strathstodley, east of Mormond Hill (Peacock, 1997; Merritt *et al.*, 2003, map 7). Glaciolacustrine deposits of the UCF were overlain by glaciodeltaic and glaciofluvial terrace gravels as lake levels fell from 80 to 50 m OD. The gravels subsequently became permanently frozen with the formation of tundra polygons (Gemmell and Ralston, 1984; Ballantyne and Harris, 1994). No exits have been identified for the 80 m and 50 m glacial lakes in the lower Ugie catchment, and since the ground lies below 50 m OD towards both the north and east coasts, the lakes must have been dammed by coastal ice sourced both in the Moray Firth and North Sea basins.

The Ugie terrace gravels have yielded OSL ages in the range of 76 to 108 ka (Gemmell *et al.*, 2007). These dates are anomalously old as the gravel terraces partly overlie laminated silt and clay laid down in Glacial Lake Ugie (*Ugie Clay F*) and several till units (McMillan and Aitken, 1981). Puzzlingly, the samples appeared to be well bleached. Furthermore, at Toddlehills (Table 2, Figure 8) glaciofluvial sand related to northward flow of water into Glacial Lake Ugie has yielded an OSL age of 31 +/-2 ka (Gemmell *et al.*, 2007). This age is more in keeping with the stratigraphical evidence at the site, but may still be too old.

Further problems surround a curious suite of hummocky sandy deposits, the *Auchleuchries Sand and Gravel Formation* (ASGF) (Table 3), that straddles the boundary between the L-BGS and EGGS to the south of the 'Buchan Ridge' (Merritt *et al.*, 2003). At the Hill of Auchleuchries (Merritt *et al.*, 2003, fig. 50), where Jamieson (1882, p.172) recovered a rich shell fauna, the sands are capped by yellowish brown till of probable western derivation, whereas to the north and west of Hatton they are capped by red till of the L-BGS (Merritt, 1981). The sands contain conspicuous amounts of pink (Peterhead) granite, but surprisingly little flint and quartzite from adjacent outcrops of the Buchan Gravels Formation (Merritt *et al.*, 2003). The sands overlie dark grey till with shell fragments correlated with the Pitlurg Till at Bellscamphie (Table 2), deposited by ice flowing from the ENE (Bremner, 1928; Hall and Jarvis,

1995). The pink granite clasts in the pebbly sands together with of seams of fissile, chocolate brown to olive grey clay (Merritt, 1981) either also suggest derivation from this direction, or reworking of older material. It may be concluded that there was complex interplay between ice sourced from the Moray Firth and the North Sea basins following retreat of East Grampian ice across eastern Buchan.

At the Burn of Benholm site, between Stonehaven and Montrose (Table 2), shelly diamict of the *Benholm Clay Formation* (BCF) was laid down by ice flowing onshore from the North Sea Basin, probably during MIS 6 (Merritt *et al.*, 2003) (Table 3). A lens of peat embedded in the base of the overlying red *Mill of Forest Till Formation* has been assigned to MIS 5a or 5c (Campbell, 1934; Auton *et al.*, 2000), thus providing a maximum age both for the till and fs. 51 with which it is correlated.

Evidence surrounding the retreat of Strathmore ice from the Aberdeenshire coast and marine incursion.

It is generally believed that the Logie-Buchan Readvance was followed by sequential 'un-zipping' down the North Sea coast of 'Strathmore' ice, and ice sourced more locally in the East Grampians (Simpson, 1955). There was certainly widespread ponding between East Grampian and Logie-Buchan ice to the north of Aberdeen, where subaqueous fan and glaciofluvial deltaic deposits abound (Aitken, 1995), for example at the Strabathie (Thomas, 1984: Thomas and Connell, 1985) and Mill of Dyce sites (Aitken, 1998) (Table 2) (Merritt *et al.*, 2003, map 9). That this ponding was closely followed by a marine incursion is suggested by various reported finds of the bones of whales, seals and birds in isolated, locally fossiliferous deposits of red and brown silt and clay overlying glaciofluvial deposits up to about 30 m OD (Peacock, 1999; Merritt *et al.*, 2003). In the Aberdeen area these deposits, assigned to the *Tullos Clay Member* (Table 3), were exploited in former clay pits at Tipperty (Bremner, 1943; Munro, 1986), Blackdog (Jamieson, 1906; Bremner, 1916; Peacock, 1975), between Torry and Tullos Hill (Simpson, 1948), and at Nigg Bay (Table 2) (Merritt *et al.*, 2003, map 9). As similar clays described at the Errolston site (Peacock, 1984) (Table 2) (Merritt *et al.*, 2003, map7), near Cruden Bay, contain numerous reworked microfossils and other materials, further work is required to confirm the marine invasion. However, presence of roughly E-W orientated linear ridges lying closely offshore (Figure 8) and interpreted as De Geer moraines (Bradwell *et al.*, 2008, fig. 5) suggests that the 'Strathmore' ice calved into a marine embayment that had opened up from the north. These features, with average wavelengths of 200 m and heights up to 17 m, have been interpreted as giant sand waves by Gatliff *et al.* (1994), but others lying 50 km to the east are anomalously large at least for present hydraulic conditions. Those ridges lying offshore from Ellon (Figure 8c) are matched by similarly orientated linear features immediately onshore (Hughes *et al.*, 2010).

The 'unzipping' of the ice masses probably continued down the coast to the vicinity of Montrose, where Strathmore ice was able to flow directly seawards to create isochronous flow-set 56 (Figure 7). Strathmore ice apparently then

retreated inland sufficiently to allow the accumulation of red marine clay to an elevation of c. 22 m OD at Lunan Bay. This *Lunan Bay Clay Member* of the Errol Clay Formation is capped locally by glacial outwash that includes thin beds of till (Rice, 1959). Controversially, McCabe *et al.* (2007) report AMS dates of 20,097 ± 87 and 20,881 ± 102 cal a BP (Hughes et al., 2016) on hand-picked, monospecific foraminiferids from the clay, providing a date for marine incursion, but the basis of their investigation has been questioned by Peacock *et al.* (2007) and Sejrup *et al.* (2009), who comment on how the dates are incompatible with youngest ages of c. 17.5ka for deglaciation of ground above 200 m on Mormond Hill and Pitfichie provided by cosmogenic techniques (Phillips *et al.*, 2008). Although McCabe *et al.* (2007) incorrectly correlate the glaciofluvial deposit overlying the Lunan Bay Clay with the supposed Perth Readvance at Perth, there are insufficient grounds to discard their age determinations, which are at least 1000 radiocarbon years older than the oldest dates for late-glacial marine deposits obtained so far in the Firth of Tay (Peacock *et al.*, 2007). Considering the importance of these dates further detailed stratigraphical work and sampling is required to resolve these issues.

Evidence for late incursions of ice across Buchan from the Moray Firth Basin.

There has been little consensus concerning how many times ice flowed onshore into Buchan from the Moray Firth Basin, but the last encroachment probably formed fs. 100 (Figure 7). This TT flowline probably correlates with calcareous blue-grey tills assigned to the *Essie Till Formation* (ETF) (Table 3), which crop out along the coast between Rosehearty and Peterhead, where most glacial striae, ice moulded features and erratics also indicate that the last movement of ice was towards the ESE or SE (Peacock, 2000b; Merritt *et al.*, 2003, map 4). At St Fergus (Table 2) (Figure 8) the ETF overlies reddish brown diamict that was deposited by Logie-Buchan ice (Hall and Connell, 1991), whereas at Lumbs (Merritt *et al.*, 2003, fig.10) a trial pit dug revealed 3.8 m of stiff, dark grey pebbly clay with lenses of reddish brown diamict, small masses of red clay, clasts of marl and red sandstone, and very sparse fragments of shell and chalk. The underlying red diamict contained granules of red sandstone and mudstone. The trial pit was dug into an isolated, drumlinoid hill trending NW-SE and both the glacial streamlining of the feature and the composition of the ETF indicate ice flow towards the SE, which accords with fs. 100. The ETF is possibly the 'blue oolite clay' with striated stones that was formerly worked at Lumbs (Milne, 1892). The red materials, black mudstones and chalk probably have been derived from the juxtaposed outcrops of Permo-Triassic and Cretaceous strata lying within the Moray Firth Basin to the north of Fraserburgh. This direction of transport is supported by the presence of boulders of an uncommon set of Lower Cretaceous siliceous malmstones, sponge-chert and fossiliferous glauconitic sandstone that have been collected from morainic deposits south of Fraserburgh (Cumming and Bate, 1933).

Several boreholes to the north of the River Ugie proved dark shelly diamicts that probably correlate with the ETF (McMillan and Aitken, 1981). For example, one 4 km NW of Peterhead proved 5.4 m of dark bluish grey clayey

diamict overlying 3.2 m of dark reddish brown diamict, both units containing clasts of red granite most probably derived from a small outcrop of coarse-grained pink granite to the north-west of Crimond or beneath part of the gas terminal at St Fergus (Merritt *et al.*, 2003, map 7). The diamicts overlay 9.8 m of crudely laminated, red, reddish brown and yellowish-brown, micaceous silt assigned to the Ugie Clay Formation (see above). Both the red and grey diamict units therefore result from readvances of coastal ice across Glacial Lake Ugie after East Grampian ice had retreated westwards. Near Kirkhill the Essie Till locally truncates gravel containing erect pebbles suggesting that Moray Firth ice readvanced over frozen ground that had been deglaciated previously (Merritt *et al.*, 2003, plate 8d).

The ESF probably correlates, at least in part, with grey-black till, over 23 m thick, proved beneath a veneer of shelly pebbly sand in BGS offshore borehole 72/31 (Owens and Marshall 1978; Evans *et al.*, 1981), 13 km east of Peterhead. The diamict yielded Quaternary miospores and microplankton accompanied by a rich assemblage of reworked late Jurassic and early Cretaceous palynomorphs indicating a likely NW provenance for the deposit.

Evidence regarding the East Grampian ice sheet: correlation with flowsets 33, 36, 64 and 72.

The cumulative amount of glacial erosion decreases rapidly northwards into central Buchan (Hall and Sugden, 1987) where the sandiness and common relatively pale colour of the tills suggest that they are significantly weathered (Fitzpatrick, 1958, 1972) and hence may been laid down either during an early-Devensian glaciation (Sutherland, 1984; Hall and Connell, 1991), or an older one (Charlesworth, 1957; Synge, 1956). However, the sandiness and colour are more likely to result from the incorporation of significant proportions of deeply weathered bedrock unless biotite-bearing clasts are weathered too. Furthermore, pedological studies of till (correlated with the Hythie Till) near Mintlaw suggest that soil forming processes occurred solely during the Holocene though developed on a previously periglacially disrupted fabric (Van Amerongen, 1976). Where tills and subglacial landforms are poorly developed the last direction of ice flow across central Buchan may be inferred from the widespread, reticulate pattern of glacial drainage channels formed at the westward retreating margin of a cold-based ice sheet (Merritt and Peacock, 2000; Merritt *et al.*, 2003, map 6; Clark *et al.*, 2012). The identification of flowsets 36 and 72 only in the east of Buchan suggests that they are relatively older, as concluded by Hughes *et al.* (2014) (Table 1); they formed beneath the ice sheet when it was thicker and possibly became locally warm-based during a 'purge' event.

Ice-moulded bedrock features are mainly restricted to the valleys of the Don and Dee, which focussed ice flowing eastwards from the Cairngorms and created fs.64. The *Banchory Till Formation* (BTF) (Merritt *et al.*, 2003) correlates with this TT-thinning flowset (Figure 7) as it contains clasts of westerly provenance (psammite, pelite, semipelite, granite and gabbro). Subglacial scouring is most pronounced towards the North Sea Basin, between the Ythan Estuary and Aberdeen (Hall, 1986; Hall and Sugden,

1987), where roche moutonees, crescent-shaped erosional depressions ('moats') at the stoss-ends of crag-and-tail features and striae are relatively common (Merritt *et al.*, 2003, map 8 and 9). The eastward flow of ice represented by fs. 64 became increasingly influenced by topography as the ice sheet margin retreated westwards, as indicated by the varying orientations of subglacial features and drainage channels and the fan-shaped distribution of striae and clasts fabrics (Merritt *et al.*, 2003, map 8).

Four members of the Banchory Till Formation have been recognised in the Aberdeen area, notably around Nigg Bay (Table 3 and 3) and to the west and north-west of the city (Merritt *et al.*, 2003). Ice advanced from the north (*Anderson Drive Diamicton*) and north-west (*Den Burn Till*) before a strong ice flow from the west and south-west deposited the extensive *Nigg* and *Kingswell* members. These last two tills are lateral equivalents and locally grade up into, or are interbedded with tills of the Mearns Glacigenic Subgroup in the coastal zone, indicating some contemporaneous deposition associated with flowsets 51 and 64. Fs. 64 cuts fs 51 to the south of Aberdeen (Figure 7), which is consistent with ideas of an 'Aberdeen Readvance'. Recent work in the north cliff of Nigg Bay, Aberdeen (Connell and Gemmell unpublished) has identified a thin (~1 m) till of inland provenance overlying coarse gravels of the Drumlithie Sand and Gravel Formation and itself overlain by more coarse gravels and sands. It is likely that this thin till unit represents a minor eastward readvance of the East Grampian ice sheet that created moraines and other ice contact landforms to the north and south of the city (Bremner, 1917; Merritt *et al.*, 2003, map 9). This event followed at least a partial retreat of Logie-Buchan/Mearns ice.

Evidence for a minor readvance of ice from the Moray Firth and the creation of the St Fergus Push Moraine.

The late-glacial sea invaded the eastern coast of Buchan following the creation of fs. 100, deposition of the Essie Till Formation and the draining of 50 m Glacial Lake Ugie (Merritt *et al.*, 2003). Glaciomarine deposits of the *St Fergus Silts Formation* (SFSF) were laid down around the Loch of Strathbeg and in the vicinity of the St.Fergus gas terminal (Hall and Jarvis, 1989; Peacock and Connell, 2000) (Table 2; Merritt *et al.*, 2003, map 4 and 7). The SFSF comprises dark grey to dark greyish brown, laminated, calcareous mud with sand laminae and shell fragments (Peacock, 1999). The presence of dropstones of gneiss, chalk and red sandstone suggests a proximal glaciomarine environment adjacent to ice flowing across the Moray Firth Basin since Upper Cretaceous strata crop out on the sea floor only to the north or north-east of Fraserburgh. The SFSF generally rests on reddish brown diamict, but on the south-eastern side of the gas terminal it rests on dark shelly till with chalk erratics (Hall and Jarvis 1989).

The surface elevation of the SFSF and associated raised beaches imply a marine transgression to at least 12 m and possibly 15 m above OD (Peacock, 1997; Peacock *et al.*, 2000). Radiocarbon dates on marine bivalves provide ages of 17,652 ± 250 cal a BP (Hall and Jarvis, 1989; Hughes et al., 2016) and 17,490 ± 101 and 18,147 ± 232 cal a BP (Peacock, 1999; Hughes et al., 2016), adjusted using a marine reservoir age of 400a. These dates have been questioned as being too young by Peacock *et al.* (2007) on the grounds that the shells were possibly chalky, but this is

incorrect as they retained their original sheen. The SFSF poses a problem, however, because late-glacial raised beaches and marine deposits generally have been assumed to be absent in peripheral areas of eastern Scotland on theoretical grounds that the contemporary sea level was below OD (Sissons, 1976; Lambeck, 1995). Much more ice must have been present in the region than thought hitherto to cause the required glacio-isostatic depression at about 17-18 ka (Peacock, 1997). The additional ice load was probably mainly offshore in the Moray Firth Basin and to the north. The dates certainly suggest that ice remained active within the outer Moray Firth several thousand years after the initial marine incursion.

The surface level of the SFSF locally reaches 16 m OD within a low ridge that extends 5 km along the coast from Annachie towards Rattray Head (Merritt *et al.*, 2003, map 4 and 7). Exposures of faulted, tilted and deformed masses of bedded silt and sand in the ridge led Hall and Jarvis (1989) to interpret the feature as a push moraine formed by a readvance of ice from the east or north-east. This conclusion is supported by borehole evidence that indicates that the SFSF passes under, and is therefore mainly older than the moraine feature. A cutting through the cliffline backing the Holocene raised beach also revealed faulted, tilted and sheared masses of bedded sand and black clay (Merritt *et al.*, 2003). This *St Fergus Push Moraine* may be linked with arcuate ridge features offshore (Clark *et al.*, 2012) (Figure 7).

There is related evidence of a significant readvance of ice from the north and east that affected a narrow coastal zone between Cairnbulg Point and St Combs, between Fraserburgh and St Fergus, where discrete NNW-SSE striations cross earlier WNW-ESE striations and glacial grooves (Peacock, 1997). Importantly, a sheet of glaciofluvial outwash descends to the Holocene raised beach at c 5 m OD (and possibly below this level). This suggests that ice was delivering meltwater south-eastwards towards St Fergus after relative sea level had fallen by at least 7 m from the time that the SFSF was deposited.

Deglaciation of the northern coast of Banff and Buchan.

Read (1923) provides convincing evidence for a sluggish, northerly 'encroachment' of ice that laid down his 'Northerly Drift'. It transported numerous boulders and blocks towards the coast, notably troctolite gabbro from outcrops to the west of Huntly (Figure 3). Such boulders are found in the *Old Hythe Till* at Boyne Quarry (Peacock and Merritt, 2000b), and are particularly common on Durn Hill, SW of the site, where he reports that some have been pushed from the south. Arcuate recessional moraine ridges occur to the south of Durn Hill together with northerly-orientated eskers (Figure 8), clearly recording retreat of this ice mass back towards the south, as deduced by Read (1923). This direction of ice retreat suggests correlation with a suite of subdued subglacial bedforms of NNW orientation that occur around Durn Hill and to the south of Boyne Quarry (Figure 8). These bedforms belong to fs.35, but they were deduced to have been formed by ice flowing in the opposite direction by Hughes *et al.* (2014) (Figure 7). This would reopen a long-standing debate regarding evidence for a final onshore readvance of Moray Firth ice (Read, 1923; Bremner, 1943; Peacock and Merritt, 2000a). However, although some crag and tail features suggest that ice flowed from

the Moray Firth there are others that indicate it flowed in the opposite direction, which on balance is now considered more likely.

Read (1923) also describes a belt of glaciofluvial and glaciolacustrine deposits extending inland for no more than about 10 km between Portknockie and New Aberdour (Merritt *et al.*, 2003, maps 2, 3 and 4). The suite is associated with several ice-marginal glacial drainage channels orientated parallel to the coast, clearly suggesting that ice lay closely offshore (Figure 8). These 'Coastal Deposits' (Read,1923) originally included dark grey shelly tills and clays now assigned to the Whitehills Glacigenic Formation (Peacock, 1971; Peacock and Merritt, 1997). The fluvioglacial deposits are now assigned to the *Blackhills Sand and Gravel Formation* (BSGF) (Peacock and Merritt, 2000d) and glaciolacustrine silts and clays to the *Kirk Burn Silt Formation* (KBSF) (Table 3).

At Castle Hill of Gardenstown (Figure 8; Table 2) the KBSF consists mainly of ochreous to dark olive brown, laminated to thin-bedded silts and clays up to about 10 m in thickness (Peacock and Merritt, 1997). Bands of ferruginous or calcareous nodules occur locally. The sediments show signs of settlement and minor slumping, but there is no evidence that they have been affected by a significant post-depositional glacial advance from inland as deduced by Read (1923), or that they are widely covered by solifluction deposits as described by Synge (1956). However, similar deposits have been deformed by ice pushing from seawards at Troup Head (Peacock and Merritt, 2000c). The KBSF was laid down during deglaciation, when East Grampian ice had retreated inland, but active ice remained in the Moray Firth Basin, forming a barrier along the present coastline beyond which lakes were ponded to the south (Figure 8). It seems that lakes first formed to the north of New Aberdour, draining eastwards along the coast. A larger lake then formed between Gardenstown and Pennan, draining via the Afforsk Spillway eventually into the valley of the Deveron (Figure 8). Much larger lakes formed subsequently between Portknockie and Macduff.

There are several localities along the coast where the Blackhills Sand and Gravel has been disturbed by a late-stage push of ice from the Moray Firth (Peacock and Merritt, 2000d), locally laying down thin beds of gravelly diamict named as the *Arnhash Till Member* (Table 3), as at New Aberdour (Merritt *et al.*, 2003, map 4). Other sites include Gallows Hill, near Cullen (Merritt *et al.*, 2003, map 2) (Bremner, 1928), Troup Head (Merritt *et al.*, 2003, map 9) (Peacock, 1971) and Broomhead, SSW of Fraserburgh (Merritt *et al.*, 2003, map 4). At Arnhash and Broomhead deltaic deposits have been pushed by ice nudging inland from the NW and NNE respectively (Peacock and Merritt, 2000d; fig. 26).

A crucial site for determining the glacial history of the coastal region is at the Howe of Byth, south of Pennan (Table 2, Figure 8), where quarry sections in a large gravel fan fed from glacial drainage channels to the north have been described by Hall *et al.* (1995b) and Hall and Connell (2000). The *Auchmedden Gravel* (AG) forms the upper part of the fan, resting on the Byth Till of western provenance. This generally thin reddish brown till rests on a lower unit of fan gravel, the *Howe of Byth Gravel* (HBG), from which Duller *et*

al. (1995) obtained luminescence ages of c. 45.4 and 37.8 ka. Hall *et al.* (1995b) concluded that the gravels were ice-proximal, fed from ice lying along the coast to the north, although they are composed almost wholly of local, well rounded cobbles of ORS conglomerate. Both units of gravel have southerly directed palaeocurrents and it is clear from NextMap imagery (Figure 8) that at least the AG was deposited from water flowing eastwards via interconnected glacial drainage channels typical of those associated with westward retreating ice (Merritt and Peacock, 2000). The generally dense, matrix-rich, ferruginous HBG includes laterally discontinuous beds of diamict interpreted as debris flows, and several horizons of erect clasts, one immediately beneath the Byth Till (Hall and Connell, 2000). The HBG has the attributes of an alluvial fan that accumulated over a period of time including several periglacial episodes. However, the large size of the fan and the presence of ice-scratched pebbles suggest that it formed in close proximity to an ice front for a significant period of time.

Duller *et al.* (1995) judged that the grains sampled from the Howe of Byth Gravel for TL dating were completely bleached and thus yielded a reliable Middle Devensian age estimation. The deposit certainly looks old because it is ferruginous, but the iron may have been liberated by acid waters from ferruginous ORS conglomerate in the vicinity. Gemmell *et al.* (2007) attempted to date the upper gravel and sand unit (AG), obtaining an OSL age estimate of c. 61 ka, which is older than dates on the HBG below. This OSL age determination is probably spurious, reiterating the problems of dating ice proximal sediments expressed by Duller *et al.* (1995). The true age of the HBG remains enigmatic and awaits further research, but on present evidence the TL ages obtained from it support a Middle Devensian glaciation that affected at least the southern coast of the Moray Firth (Hall *et al.*, 1995b; Hall and Connell, 2000; Merritt *et al.*, 2003), as predicted by Hubbard *et al.* (2009).

A reticulate network of S to N /W to E orientated glacial drainage channels are well displayed around the Tore of Troup and to the west of the Howe of Byth site (Figure 7) (Merritt and Peacock, 2000; fig. 22). These features formed mainly during the general westward retreat of combined Moray Firth and East Grampian ice (Bremner, 1934a) and locally cut into elongate ridges aligned with fs. 33, which are mainly controlled by the similarly orientated strike of the bedrock. Some channels probably have a long history. For example, in central Buchan, the bedrock cut channels that preserve sequences dating back possibly to MIS 8 at Kirkhill and Leys quarries have focussed meltwaters on a number of occasions, but which remain unfilled.

Lower Strath Spey and the Elgin Oscillation.

Surficial tills around Elgin and in lower Strath Spey are sandy and dominated by well-rounded clasts derived from ORS conglomerates cropping out to the west (Peacock *et al.*, 1968; Aitken *et al.*, 1979). The widespread upper diamict, the *Tofthead Till* of Hall *et al.* (1995a), has a strong WNW-ENE fabric (Table 4). These authors identified a younger sandy diamict locally, the *Waterworks Till*, which correlates with a local glacial readvance from the W or NW, possibly the Elgin Oscillation (EO) of Peacock *et al.* (1968). Neither of the above-mentioned tills were identified above the interglacial palaeosol at

Teindland (Table 2 and 2) where another sandy diamict with complex glaciotectonic structures (Connell and Phillips, unpublished), the *Woodside Diamicton*, was formerly assigned to an Early Devensian glaciation (Hall, 2000).

None of the till units identified in lower Strath Spey can be correlated easily with fs.34, but they can be linked with glacial striae and other features described by Peacock *et al.* (1968) (Merritt *et al.*, 2003, map 1). Most glacial drainage channels lying to the south of Elgin swing around towards the NE, suggesting that meltwater was flowing around a retreating ice lobe occupying the Moray Firth. This lobe was responsible for ponding the Spey Valley upstream of Fochabers, where laminated silts and clays were laid down in *Glacial Lake Rothes (Fochabers)* (GLR) (Bremner, 1934a), as at the Tofthead site (Table 2) (Connell, 2000a). Splendid southward-directed, deltaic foresets exposed in Glen Rothes were clearly deposited by meltwaters flowing from the margin of the lobe into the lake, whereas similarly well-preserved, northward dipping foresets were observed in Glen Rinnes, some 25 km to the south, where a delta formed at the margin of East Grampian ice.

Glacial Lake Rothes occupied ground that had been previously vacated by East Grampian ice, but the deltaic deposits preserved in Glen Rinnes show that ice flowing from the eastern Cairngorms remained to the south of the lake, possibly sufficiently active to have formed fs. 95. Flowset 94 may also have formed at this time in the middle reaches of Strath Spey, although Hughes *et al.* (2014) speculate that it was created earlier (Table 1). West Highland-sourced ice (fs. 47) terminated in the vicinity of Grantown-on-Spey whilst the middle reaches of the Findhorn Valley remained blocked by ice (Merritt *et al.* (2013).

No definitive end-moraine has been assigned to the Elgin Oscillation, but Peacock *et al.* (1968) present evidence that GLR was still in existence during the EO, which they linked with the late S or SSE orientated scratches of two sets of cross-cutting striae recorded between Elgin and the coast (Merritt *et al.*, 2003, map 1). The age of the EO may be estimated from the presence of glaciomarine muds of the *Spynie Clay Formation* (SCF), which underlies kettled, raised marine flats up to about 20 m OD between Elgin and Lossiemouth (Peacock *et al.*, 1968; Peacock, 1999; Merritt *et al.*, 2003). The muddy SCF has a low-diversity, high-arctic fauna similar to that in the *Errol Clay Formation* of eastern Scotland, which has yielded radiocarbon ages between 12.8 and 14.3k ^{14}C a BP (c. 14-16k cal.BP) (Peacock, 1999; Hughes *et al.*, 2016)). The SCF includes large dropstones and lenses of diamict indicating the presence of an ice front nearby (Peacock, 1999). Peacock *et al.* (1968) describe several sets of N-S orientated till ridges around Elgin formed at a westward retreating ice margin following the EO (Merritt *et al.*, 2003, map 1). These ridges, together with others on the Black Isle, have been identified as de Geer moraines (Finlayson *et al.*, 2007). Such features have not been recorded to the east of the Spey so their presence within the EO limits suggests that glaciological conditions may have changed following that event, associated with relatively high sea level. The Moray Firth ice stream probably became established at this time too, represented by fs. 6 (Hughes *et al.*, 2014) (Figure 7). Finlayson *et al.* (2007) speculate that the de Geer moraines they identified around Elgin and on Tarbat Ness formed in the sea when it

stood at c. 55 m OD, which is considerably higher than established by detailed sea level studies in the region (Merritt *et al.*, 1995; Shennan *et al.*, 2006). It is perhaps more likely that fresh water was ponded up to this level by NW Highland-sourced ice pinning against the coast to the east of the Spey.

A review of critical parts of the offshore record

In order to examine the event stratigraphy for NE Scotland in a wider context some critical parts of the offshore record must be considered, particularly the Norwegian Channel (NC) and the Witch Ground Basin (WGB) (Figure 1). Although firmly-based time-slice reconstructions of the last BIIS and SIS have been presented recently by Clark *et al.* (2012) and Hughes *et al.* (2015), these researchers found it difficult on present evidence to reconstruct the build-up and break-up of ice in the North Sea Basin, presenting alternative maximum and minimum scenarios. There was either complete disintegration in the North Sea Basin by 25 ka BP (more likely 22 ka BP), or two-stage deglaciation involving partial break-up of North Sea ice from the north, leaving a more persistent, low-profile ice dome over the central North Sea Basin.

The offshore record around NE Scotland and in the North Sea Basin has been reviewed by Holmes (1997), Merritt *et al.* (2003), Carr (2004), Stoker *et al.* (2011), Davies *et al.* (2011) and Graham *et al.* 2011). Thin-section micromorphology of borehole cores reveals that shell-bearing glaciomarine deposits in the central North Sea Basin have been glacially over-ridden on at least three occasions during the Devensian/Weichselian, but the episodes are poorly dated and the micromorphology of few borehole cores have been examined (Carr *et al.*, 2006). Two advances (Ferder and Cape Shore) demonstrate confluence between the British and Scandinavian ice sheets during the early Weichselian and the Skjonghelleren Stadial (c.40 ka) respectively, whereas the final Bolders Bank episode (Late Weichselian) was regarded as more restricted with an ice-free corridor separating the two ice sheets (Sejrup *et al.*, 2000; Carr, 2004).

Ice-rafted debris sourced from British volcanic rocks recovered from the Donegal/Barra Fan, off NW Scotland and Ireland, suggest that extensive regional glaciation with tidewater termini began at c. 45 ka BP (Knutz *et al.*, 2001; Peck *et al.*, 2007). A broadly similar record was obtained from a core obtained from the adjacent Rockall Trough in which a continuous IRD flux is seen throughout MIS 2 and 3, with a pulse at c. 41 ka (Hibbert *et al.,* 2010). These authors conclude that NW Britain was also extensively glaciated during MIS 4 from c. 70 ka onwards, with peaks in IRD at c.70.2 and 61.7 ka.

Southern Norway became extensively glaciated during MIS 3, but there is no firm evidence for glaciation of the North Sea Basin (Sejrup *et al.*, 2009). Periods of ameliorated climate (including the Ålesund, Sandnes and Tolsta Interstadials) occurred between c. 39 ka and 29 ka, alternating with limited glacial advances in western Norway (Sejrup *et al.*, 2009). The northern part of the last BIIS built up towards the end of MIS 3, after c. 32k a BP (Whittington and Hall, 2002; Jacobi *et al.*, 2009) at a time when Central Scotland remained largely ice free, judging from dates of 34.5k to 28.1k cal a BP obtained on

glacially over-ridden organic deposits at Sourlie (Bos *et al.*, 2004) and Balglass (Brown, 2007) (Figure 1). Ice expanded westwards to the shelf break shortly after 30k cal a BP (Wilson *et al.*, 2002; Scourse *et al.*, 2009; Bradwell and Stoker, 2015a; Bradwell and Stoker, 2015b *et al.*), it had reached at least as far as North Rona at 25-27 ka (Everest *et al.*, 2013) and probably over-ran St Kilda, north-west of the Western Isles (Figure 1) at this time (Hiemstra *et al.*, 2015). The Fennoscandian Ice Sheet (FIS) first expanded southwards into Denmark through the Kattegat, between 29 and 26k cal a (Houmark-Nielsen and Kjaer, 2003). The peak in clastic sedimentation on the Barra Fan occurred at c. 27 ka (Knutz *et al.*, 2001), in agreement with a step-change increase in IRD flux at c. 27.4 ka recorded from the adjacent Rockall Trough (Hibbert *et al.,* 2010). These dates coincide with the maximum extent of the north-eastern quadrant of the last BIIS deduced by Sejrup *et al.* (2009), Bradwell *et al.* (2008) and Hughes *et al.* (2016). The BIIS was confluent with Scandinavian ice in the central North Sea basin prior to 22k ^{14}C a BP (Graham *et al.*, 2011) or possibly as early as 27k cal a BP (Sejrup *et al.*, 1994, 2014) when a major shelf-edge-parallel ice sheet became established from Cape Wrath to Norway (Sejrup *et al.*, 2005). Ice appears to have been most extensive and thickest early in the development of the last BIIS, during the local LGM (Sejrup *et al.*, 2009; Chiverrell and Thomas, 2010; Clark *et al.*, 2012; Hughes *et al.*, 2014, 2016) (Figure 1). Importantly, Scourse *et al.* (2009) report that the deep-sea ice-rafted detritus record from the continental slope adjacent to the last BIIS indicates that the ice sheet reached its maximum extent at Heinrich Event H2 (24 ka) (cf. Bond *et al.*, 1993; Peck *et al.*, 2007). Rapid retreat, initially characterised by peak ice-rafted debris (IRD) flux during Greenland Interstadial (GI) 2 at 23 ka was followed by readvance between 22 and 16 ka, embracing the global LGM. Major readjustments occurred during later stages (Hughes *et al.*, 2014) when ice streams were established in the Moray Firth (Merritt *et al.*, 1995), the Minch (Bradwell and Stoker, 2015) and the Firth of Tay (Golledge and Stoker, 2006).

Evidence for stages during the local LGM

Important new findings and dates have been published recently for the Norwegian Channel (NC) and the Witch Ground Basin (WGB). The Norwegian Channel Ice Stream (NCIS) may have operated within the Norwegian Channel throughout the last glacial cycle (Sejrup *et al.*, 1995, 1998; Rise *et al.*, 2004; Ottesen *et al.*, 2005). However, pertinent information has been obtained from borehole MD99-2283 drilled on the western flank of the North Sea Fan (Lekens *et al.*, 2009) (Figure 1). Based on bulk accumulation rate and concentration of ice-IRD it shows that glacial activity increased around 42k cal a BP at the time when the SIS expanded beyond the coast of Norway. Accumulation rates increased between 34k and 29.7k cal a BP and were highest between 25k and 19k cal a BP when the NCIS was particularly active and re-advanced on three occasions. A corollary is that the NCIS appears to have shut down between about 30k and 25k cal a BP, possibly because an ice divide became established across it between Shetland and Norway at this time. Indeed, a major shelf-edge-parallel ice divide lying across the Norwegian Channel was modelled numerically by Boulton *et al.* (1985) (Figure 9.1), constrained by these authors regional mapping of glacial features using satellite imagery. This period embraces the

global sea-level minimum at 26k cal.a BP established by Peltier and Fairbanks (2006). Ordered layered expandable minerals (OLEM) identified in the core, probably derived from mudstones of Mesozoic age beneath the Moray Firth, were delivered to the fan between 24 and 22k cal a BP, during GI 2, following collapse of any such divide (Figure 9.3).

Although the positioning of an ice divide across the NC is difficult to reconcile with the role of the deep trough in concentrating flow along the west coast of Norway towards the shelf edge, its presence may explain some issues concerning the glacial records within the central and southern North Sea Basin. For example, several units of glacigenic sediment have palynological and minerogenic signatures suggesting that ice sourced in the Moray Firth flowed along the eastern coast of England and into the southern North Sea Basin during early stages of the last glaciation (Davies *et al.*, 2011). Specifically, heavy mineral assemblages diagnostic of the Grampian Highlands and the north-east coast of Scotland, together with Late Jurassic palynomorphs sourced from the Moray Firth Basin or from northern England, have been identified in the Swarte Bank, Fisher and Bolders Bank formations of MIS 12, 6 and 2 respectively. A broadly similar suite has also been identified in the Horden Till of the Durham coast and the Skipsea Till of eastern Yorkshire, which were deposited by the North Sea Ice Lobe of the last BIIS during the Dimlington Stadial (Davies *et al.*, 2009, 2012). It has been difficult to reconcile this recurring south-eastward trajectory from the Moray Firth with ice sheet reconstructions placing low ice divides stretching across the central North Sea Basin between Scotland and Norway (Davies *et al.*, 2011, fig.11; Busfield *et al.*, 2015, fig.7). It is compatible, however, with the early south-east phase of flow of our event stratigraphy, which may have transported material from NE Scotland into the path of later ice streams flowing out of the Firth of Forth.

The Witch Ground Basin (WGB) (Figure 1) undoubtedly contains crucial evidence for understanding the glacial history of the north-eastern quadrant of the last BIIS and SIS (Sejrup *et al.*, 1987, 1994, 2009; Hall *et al.*, 2003; Graham *et al.*, 2007, 2010). High-resolution seismic data, bathymetric records and dates on shells taken from sediment cores suggest that the basin was glaciated early in the last glaciation, between c.33k and 27k cal a BP (Sejrup *et al.*, 2015) after which it became a shallow marine embayment with connections to the Atlantic Ocean east of Shetland and possibly the Norwegian Channel (Bradwell *et al.*, 2008). We note, however, that the radiocarbon dates for shells in borehole 77/2 in the WGB span 9,000 years (Sejrup *et al.*, 2015) and that reworking of shells from multiple ice-free periods would allow intervening periods of ice cover between 26.6k and 17.7k cal a BP (Sejrup et al., 2016).

Mega-scale glacial lineations (MSGL) imaged on 3D seismic datasets at the unconformable top of the uppermost glacigenic unit represent the signature of fast-flow within a grounded ice sheet (Graham *et al.*, 2007; Graham *et al.*, 2009; Graham *et al.*, 2010). Their presence and general SE-NW orientation are compatible with a major ice stream (Witch Ground Ice Stream; WGIS) draining the northern North Sea Basin fed by coalescent British and

Scandinavian ice sheets. Bradwell *et al.* (2008) interpret the former zone of confluence between the BIIS and FIS was positioned across the northern Orkney Islands with fast-flowing ice in the Orkney-Shetland Channel focusing sediment delivery north-westwards to the continental shelf edge. Flow towards the NW is supported by streamlined features, the Egersundbanken (Figure 9.6), lying some 50 km west of the Norwegian Channel, which reveal that grounded ice flowed north-westwards from the Baltic towards the WGB (Stalsberg *et al.*, 2003). These glacial lineations indicate that the western margin of the NCIS was not always confined by the Norwegian Channel, especially if the northern sector of the trough becomes filled by ice flowing directly from inland (Figure 9.2). Furthermore, the Egersundbanken were not necessarily formed contemporaneously with the MSGL imaged in the WGB and could have formed during a subsequent event. An alternative scenario is illustrated in Figure 9.3 in which an ice stream flowing through the Orkney-Shetland Channel scavenges ice that had previously built-up in the central North Sea Basin, creating the MSGL in the WGB during a purge event following the local LGM (see below). Bradwell *et al.* (2008) conclude that the WGIS operated earlier, between 31and 25k cal a BP, but there are other difficulties with this scenario as Hall (2013) finds little or no support for the Shetland archipelago having been over-run by Scandinavian ice in the last glaciation. Moreover the WGB lineaments are also compatible with flow from the north-west (Graham *et al.*, 2007).

Evidence for stages during and following the global LGM (23-21 ka)

Bradwell *et al.* (2008) speculate that a major glacial reorganisation was triggered by rapidly rising sea levels associated with H2, at c. 24 ka that resulted in a marine calving bay opening up between the BIIS and FIS along a north-south axis east of Shetland, followed by much of the northern North Sea Basin (Figure 9.4 and 9.5). Indeed, peak IRD flux coincident with this event is a feature of all records of the BIIS on its western margin (Scourse *et al.*, 2009) and there is a convergence of evidence suggesting that the BIIS underwent a period of large-scale re-organization and overall reduction in ice volume of about 80 % at about this time (Bowen *et al.*, 2002; Chiverrell and Thomas, 2010; Finlayson *et al.*, 2010; Clark *et al.*, 2012; Hughes *et al.*, 2014. Rising sea level alone may not have been the trigger as ice retreated from the shelf edge during warmer periods coinciding with influxes of Atlantic Water towards the Norwegian Sea (Brendryen *et al.*, 2015)), such as during GI 2 at c. 23 ka. A warmer period is claimed to have occurred between 25 ka and 20 ka ('Trofors Interstadial') associated with significant glacial retreat in western Norway (Johnsen *et al.*, 2012), but the geochronology is seriously questioned by Hughes *et al.* (2016).

Early deglaciation of the WGB is difficult to reconcile with peak sedimentation on the North Sea Fan by the NCIS at 25-19k cal a BP (Lekens *et al.*, 2009) and with extension of the BIIS to maximum limits in Wales at 25.2 ka to 21.2 ka, and in the Vale of York between 24.8 ka and 21.8 ka (Gibbard and Clark, 2011). Simulations indicate instead that this was a phase in which the BIIS extended to the North Atlantic shelf and was at intervals confluent with the FIS in the North Sea (Boulton and Hagdorn, 2006). Moray Firth ice was also simulated as confluent with Shetland ice after 23.7 ka (Hubbard *et al.*, 2009).

Although a scenario of a second maximum to the last ice sheet on northern Scotland appears to be in conflict with the onset of ice-free conditions in the WGB, Sejrup et al. (2016) now suggest that reworked marine shells in glaciomarine deposits may relate to periods of ice withdrawal from the WGB at 27-25.5 ka, after 18 ka, and during intervening periods.

Simulated solar-shaded renditions of the Olex bathymetric database now provide an unprecedented view of seafloor geomorphology from the continental shelf around the northern United Kingdom (www.olex.no) (Bradwell *et al.*, 2008). In particular, the dataset reveals multiple ridges of distinct lobate moraines around Shetland and including the Bosies Bank, in the outer Moray Firth (Figure 1). The pattern of ice-marginal sea-bed features show unambiguously that a significant re-expansion of ice occurred over Orkney and Shetland (Bradwell *et al.*, 2008; Clark *et al.*, 2012; Bradwell and Stoker, 2015a) (Figure 1), when Scandinavian and Scottish ice possibly coalesced again in the northern North Sea Basin and adjusted to new quasi-stable marginal positions. The BIIS had readvanced off western Scotland by 19k cal a BP (Knutz *et al.*, 2001) and the re-expansion peaked between c. 18.4 and 15.4k cal a BP (Brendryen *et al.*, 2015). Sejrup *et al.* (2008) suggest that a shelf-edge parallel ice sheet was re-established from Shetland to Northern Ireland and Bradwell and Stoker (2015b) demonstrate that there was subsequent asymmetric retreat towards Orkney.

There is good geomorphological, stratigraphical and chronological evidence for three distinct ice-marginal positions (readvances) in the WGB. The oldest includes a glacial-fed debris wedge in the eastern part of the Basin that probably links with the Tampen Ridge (Figure 1), a lateral morainic feature formed at the western flank of the NCIS after c. 21k cal a BP (Sejrup *et al.*, 1994, 2000, 2014). There were subsequently two glacial readvances of the BIIS from the north-west, Fladen 1 and Fladen 2 at c. 17.5k and 16.2k cal a BP respectively (Sejrup *et al.*, 2015) (Figure 1 and 9.6 stages 8 and 9). The two Fladen readvances post-date the collapse of the NCIS, which occurred at between 19.5k to 18.5k cal a BP, based on radiocarbon age determinations on foraminifera and molluscs (Mangerud *et al.*, 2013), or as early as 20.8 to 20.2 ka, based on cosmogenic ^{10} Be exposure ages on glacial erratics on the island of Utsira (Figure 9.6) (Svendsen *et al.*, 2015).

Uncertainty remains concerning the extent of the BIIS at the time the Tampen Ridge was formed. Was it formed at the marine-based margin of the NCIS, implying non-coalescence of the BIIS and FIS, or at a lateral shear margin between the ice stream and ice radiating out from a centre situated over Shetland (Hall 2013). Sejrup *et al.* (2000) conclude that the ridge resulted from re-advance of the NCIS during the Tampen Stadial (22-19k cal a BP), the time-span of the global LGM (Mix *et al.*, 2001), when the adjacent Viking Bank area (Figure 1) was partially shallow high-arctic sea and dry land based on faunal palaeoenvironmental reconstruction and a recalibrated age of c.18.7k cal a BP on a mussel shell (Peacock, 1995; Hughes *et al.*, 2016). However, this date would become at least 500 years younger if a more realistic marine reservoir age adjustment were made (JD Peacock, personal communication). Glacio-eustatic sea level is estimated to have been below -

140 m on the Viking Bank during the global LGM, suggesting that there was a forebulge of some 20 m (Peacock, 1995). The FIS also readvanced southwards into Denmark through the Kattegat, between 23k and 18k cal a BP (Houmark-Nielsen and Kjaer, 2003).

A new event stratigraphy for NE Scotland

Twelve stages in the evolution of the last BIIS in NE Scotland are recognised based on a parsimonious (ie. that no more causes or forces should be assumed than are necessary to account for the facts) interpretation of stratigraphic relationships, the subglacial bedform record and published dates at a number of critical sites, both onshore and offshore. The stages represent a likely minimum sequence of events. Stages 1 to 5 are established mainly from the lithostratigraphical record at a few key sites and are not yet securely dated. They probably include short-lived events that occurred during relatively long periods of maximum glaciation that left relatively little reported evidence in the region. Stages 6 to 12 may be linked more securely to retreat stages established from the terrestrial geomorphological record and sea-bed features by Clarke *et al.* (2012) (Figure 8). They are better age-constrained, but difficulties with the published geochronometry remain to be resolved.

Stage 1 [Middle Devensian]. Evidence from several sites indicates that ice advanced from the north-west across ground bordering the southern shore of the Moray Firth during the Middle Devensian. Luminescence ages from a gravel fan at Howe of Byth site suggest that ice reached the northern coast of Buchan between c. 45.4 and 37.8 ka (Duller *et al.*, 1995). A considerable accumulation of ice to the NW of the region resulted in a powerful, ESE-directed flow across ground rising to at least 500 m OD to the east of Inverness. Ice sourced from the Great Glen and NW Highlands laid down thick units of till against north-facing slopes of the Moray Firth and in the middle to lower reaches of the Nairn, Findhorn and Spey valleys. Published evidence from the Dalcharn, Moy, Clava, and Teindland localities (Figure 4) concludes that these sandy tills could have been deposited when ice advanced into NE Scotland after 37 ka if the youngest TL age at Moy is accepted (Duller *et al.*, 1995). However, an earlier Middle or Early Devensian age for at least some sandy till units remains probable on present evidence.

Stage 2. [c. 32-24 ka]. SE flow of ice from the Moray Firth also laid down dark grey, shelly tills across the coastal lowlands of Moray and Buchan. These tills with a rich Jurassic to early Cretaceous palynoflora (Riding, 1998; Riding, 2003; Riding and Stephenson, 2001) become thinner and patchy inland, where isolated glacial rafts commonly lie directly on bedrock or older glacigenic deposits. This suggests that subglacial boundary conditions changed from warm to cold-based as ice penetrated inland across central and eastern Buchan. Ice probably flowed both directly across and around the north of the Buchan peninsula, laying down dark shelly till in Logie-Buchan. AAR ratios (Miller *et al.*, 1987) on derived shell fragments in glacigenic sediments, mostly from the King Edward site (SI Table 1, Figure 8c), indicate

that the last BIIS advanced across Buchan in the latter part of the Middle Devensian (Peacock and Merritt, 2000a).

Although the evidence for SE flow is mainly based on till-provenance, till-fabric, erratic transport paths (Figure 3) and some SE-directed striae, it is likely that some elements assigned to fs.72, in eastern Buchan and possibly some ice-moulded rock features associated with fs. 92, SE of Forres, may have formed contemporaneously (Table 1). Ice was sufficiently thick to create SE-orientated striae on the NE flank of Bennachie at c. 335 m OD (Figure 7) and the SE-orientated flowset in Angus (Figure 7, fs. 7) invites correlation with this stage. It requires very thick ice cover over the eastern Grampians to drive ice across Strathmore and over the Sidlaw Hills, at up to 455 m OD.

We propose that a substantial shelf-edge parallel ice sheet became established during this stage, the local LGM. It covered Caithness (Hall and Riding, 2016), Orkney (Hall et al., 2016), Shetland (Hall 2013) and possibly linked with the SIS across the Norwegian Channel rather as modelled by Boulton *et al.* (1985) (Figure 9.1. Further expansion of ice flowing from a centre positioned over the Orkney-Shetland Platform and Scandinavia possibly buttressed ice flowing from the Moray Firth and the eastern Grampians, steering it south-eastwards across Buchan towards the southern NSB (Figure 9.2).

Stage 3 [c. 24 ka]. A major glacial reorganisation followed associated with dramatic thinning, but apparently not with widespread glacial retreat across NE Scotland. In eastern Buchan the direct superimposition of tills suggests that ice flow swung around to the ENE, towards the central NSB, creating fs. 36. Evidence is less secure to the west, but till provenance suggests that ice flow also generally swung around to the E or NE along the coast of the Moray Firth. There is no stratigraphical evidence for the hierarchical position of the northward trending fs.33 deduced by Hughes *et al.* (2014) (Table 1). It is suggested that some of the bedforms of fs. 33 are indeed cut by fs. 36 in eastern Buchan, but were created in an earlier glaciation. The bedforms of fs. 33 in western Buchan are relatively sparse, poorly developed and are generally aligned parallel to the northward strike of the bedrock, which forms most of these features. However, evidence of northward flow towards Orkney has been deduced by Hall et al. (2016), apparently following a significant period of ice sheet thinning and recession. The ice shed positioned across Caithness and Orkney during Stage 2 possibly migrated southwards towards Buchan and north-eastwards towards Shetland as a result of the establishment of an ice stream centred on the Orkney-Shetland Channel (Figure 9.3.1).

Stage 4 [c. 23 ka]. Thinning continued. At numerous localities on the high ground overlooking the inner Moray Firth sandy till laid down by the early ESE-directed flow of ice is directly overlain by till deposited by ice flowing NNE in general alignment with fs.34 (Merritt and Auton, 1993; Fletcher *et al.*, 1996). Although contacts between the tills are generally sharp, no major unconformities, weathering profiles, palaeosols or organic deposits have been found that could be linked with a complete deglaciation. However, wedge-

shaped pull-apart structures, hydrofractures, truncated gravel-filled channels, seams of glacitectonite and rip-up clasts of diamict suggest that ice-bed boundary conditions may have changed during the switch in flow direction.

Flowset 34 represents an extensive flowline directly towards the MFB from the Cairngorms and western Highlands via upper Strath Spey. A thick ice sheet is required to drive ice across the Spey-Findhorn divide at over 360 m OD (Figure 4) and it follows that the Cairngorm tops remained fully glaciated at this time, as suggested by a limiting cosmogenic age of c. 21.3 ka (Phillips et al., 2008). Hughes *et al.* (2014) link fs.34 with fs. 1 (Figure 7), concluding that ice flowed across the inner Moray Firth towards the NW Highlands. Hall and Riding (2016) and Hall et al. (2016) find no supporting evidence for this flow path. Instead, once ice reached the coast it was more likely to have been deflected sharply eastwards by ice flowing from the western and north-western Highlands (Figure 9.3), as indicated at Dalcharn (Figure 4, SI Table 1) where ice first swung around to the east before flowing NNE (Walker et al., 1992).

The sparse, poorly developed bedforms of fs. 33 in western Buchan were possibly created after fs. 36 (Table 1), during northward drawdown of ice towards the MFB from an ice divide stretching from the Cairngorms towards Buchan (Figure 9.3). This hierarchy is supported by crossing striae recorded at two localities SSE of Banff, where eastward-directed striae are cut by northward or NNE-directed ones (Read, 1923; Merritt *et al.*, 2003, map 3). It follows that eastern Buchan was protected beneath cold-based ice for there is no evidence there for contemporaneous northward flow.

The ice shed positioned between Buchan and Shetland possibly migrated farther to the east by the end of this stage, drawing ice north-westwards across the Witch Ground Basin (WGB) in accord with the flowsets identified there by Graham et al. (2007) and Bradwell et al. 2008 (Figure 9.3.2), but other scenarios are possible (Sejrup et al., 2016). The stage probably equates with the widespread dramatic thinning and drawdown of ice that affected at least the SW sector of the last BIIS during Greenland Interstadial (GI) 2 at c.23 ka (Scourse *et al.* 2009). Shetland retained an independent ice cap (Hall, 2013). Ice was drawn northwards from Strathmore towards Orkney at about this time, carrying chalk eroded from beneath the outer Moray Firth (Hall and Riding, submitted b).

Stage 5 [c. 22-19 ka]. Ice flowing through the MFB and Strathmore thickened and coalesced at the angle of Buchan, much as envisaged by Clapperton and Sugden (1977) (Figure 6a, 9.4). Ice flowed NNE along the coast from Strathmore as evidenced by red tills, glacial striae and subglacial landforms of flowset 51. The former inland boundary of Strathmore ice can be traced NNE from the Ythan valley towards the mouth of the Den of Boddam, at about 80 m OD (Figure 6a), suggesting that there was ice occupying the central NSB at this time, preventing Strathmore ice from flowing directly offshore. The Wee Bankie Formation was laid down offshore (Stoker *et al.*, 2011). Ice flowed towards, but probably did not reach the WGB. Central Buchan was mostly protected beneath cold-based ice. This stage is probably contemporaneous

with the creation of the Tampen Ridge, at the western margin of the Norwegian Channel (Figure 1), during the Tampen Stadial of Sejrup *et al*. (2000) and the global LGM of Mix *et al*. (2001) between c. 22 and 19k cal a BP. The BIIS and SIS probably eventually re-coalesced when a shelf-edge parallel ice sheet regrew across Orkney and Shetland (Sejrup *et al.*, 2014; Sejrup et al., 2016; Hall *et al*., 2016) (Figure 9.4). If so, the central NSB either became reoccupied by ice or an ice-locked, seasonally frozen lake.

Stage 6 [c. 22-19 ka]. A small ice-free enclave first opened up in eastern Buchan, occupied by Glacial Lake Ugie (GLU) at its 80 m level, in a window at the confluence of Strathmore, East Grampian and Moray Firth-sourced ice (Figure 6a). East Grampian ice slowly retreated westwards across Buchan, leaving a reticulate network of ice-marginal channels typical of cold-based ice margins (cf. Benn and Evans, 2010, fig. 8.38) (Figure 8b). A local glacial reorganisation followed general thinning of ice involving a further encroachment of Strathmore ice onshore between Aberdeen and Peterhead, up the valley of the River Ythan to the vicinity of Ellon, where it dammed a proglacial lake and formed arcuate end-moraines at the Cross-Stone site (SI Table 1, Figure 6b). The ice also advanced into the lower Ugie valley during this *Logie-Buchan Readvance* (LBR) damming the 50 m level of GLU in which thick sequences of laminated muds were deposited. The Logie-Buchan ice lobe subsequently decayed to form hummocky topography typical of ice stagnation. The distinctive suite of glacial erratics derived from the floor of the North Sea in the Kippet Hills Esker (Figure 6b, SI Table 1) suggests that ice still occupied the NSB to the east (Figure 9.4).

The 50 m GLU was dammed by a combination of Logie-Buchan and Moray Firth-sourced ice as no exits have been identified in the lower Ugie catchment and since the ground lies below 50 m OD towards both the north and east coasts. Deltas and glaciofluvial terrace gravels were laid down by meltwaters entering the lake from the west and south. These deposits experienced intense periglacial conditions during subsequent stages, testified by widespread preservation of tundra polygons and other cryogenic phenomena in the Ugie Valley, but attempts at OSL dating have proved inconclusive.

The valleys of the Don and Dee steered ice flowing eastwards from the Cairngorms parallel with fs.64. Flow became increasingly influenced by topography as the ice sheet thinned and its margin retreated westwards. Although East Grampian ice had retreated from at least the lower reaches of the Ythan and Ugie valleys during the LBR, the two ice masses abutted in the vicinity of Aberdeen where there is both stratigraphical and geomorphological evidence for limited eastward readvance, but no confining dates (see SI).

Stage 7 [c. 19 ka]. Strathmore and East Grampian ice continued to ‘unzip’ down the eastern coast. At first ponding occurred between the ice masses as they parted to the north of Aberdeen, where there was widespread glaciofluvial deposition as deltas and subaqueous fans (Figure 6c). Marine conditions apparently then ensued along the coast with relative sea level standing at about 30 m OD (Peacock, 1999). The presence of roughly E-W orientated linear ridges lying closely offshore (Figure 8c), tentatively

interpreted as de Geer moraines (Bradwell *et al.*, 2008, fig. 5), suggest that the North Sea/Strathmore ice lobe calved into the sea that had entered from the NE (Figure 9.4). We deduce that ice must still have occupied the NSB to the east, buttressing the coastal ice lobe and stopping it from calving directly eastwards.

The 'unzipping' continued down the coast to Montrose, where Strathmore ice flowed directly seawards to create fs. 56, now unconstrained by ice lying offshore (Figure 9.5). Red marine clay was laid down at Lunan Bay (Figure 8) in open waters at c. 20.1 -20.9k cal a BP when relative sea level stood at least 22 m OD following a possible minor readvance of Strathmore ice. However, these dates would become at least 500 years younger if a more realistic marine reservoir age adjustment were made (JD Peacock, personal communication). Shennan *et al.* (2006) suggest that the area only became ice-free after c.17 ka. The Lunan Bay Clay (LBC) clay is capped by glacial outwash that includes thin beds of till (Rice, 1959), suggesting that Strathmore ice did not readvance far beyond the present coastline, where there is another cluster of possible de Geer moraines (Figure 8d). The recessional retreat limits shown in Figure 8 support Peacock *et al.* (2007) in that the LBC cannot be correlated with any glacial readvance at Perth as suggested by McCabe *et al.* (2007). The LBC probably correlates with the St Abbs Formation offshore (Gatliff *et al.*, 1994), which should drape over, and not underlie the ridge features if they are correctly re-interpreted as de Geer moraines.

Stage 8 [18-17.5 ka]. This stage is correlated with the Fladen 1 Readvance (17.5k cal. a BP) identified in the WGB (Clark *et al.,* 2012; Sejrup *et al.*, 2015) (Figure 9.6.8). The BIIS and Fennoscandian Ice Sheet (FIS) had separated by this time as the Viking Bank (Figure 1) had become ice-free by c. 18.3 ka (Peacock, 1995; Hughes et al., 2016). The contemporaneous position of ice within the Norwegian Channel is unclear, but had possibly retreated to the south of Utsira (Svendsen *et al.*, 2015) (Figure 9.6).

Stage 9 [17.5-16.2ka]. There is stratigraphical evidence around Peterhead and Fraserburgh, supported by till provenance and striae, for a limited readvance of ice southwards from the MFB (Peacock, 2000b) (Figure 6b). This ice mass ice subsequently shrank and receded actively across the north-eastern tip of Buchan, where fs.100 was created in association with similarly orientated moraine ridges and glaciofluvial outwash (Figure 6c). Deep channels offshore (Figure 1) may have been partly created at this time. A huge ice lobe now occupied the MFB, fed from the NW through to the SE. Sea-bed features can be traced from Peterhead to the northern tip of Shetland via the Bosies Bank (Clark *et al.*, 2012) (Figure 8 and 9.6.9), where the Fladen 2 Readvance moraine has been dated at 16.2k cal. a BP (Sejrup *et al.*, 2015).

Stage 10 [c. 16 ka]. Evidence from St Fergus, north of Peterhead, suggests that the margin of the Moray Firth ice lobe terminated in the sea at c. 12 m OD, before a minor readvance created the *St Fergus Push Moraine (SFPM)* (Figure 6c). This feature includes faulted, tilted and deformed masses of bedded marine silt and sand formed by ice push from the east or NE. The

absence of contemporary late-glacial marine deposits south of Peterhead suggests that the sea had retreated from the area owing to rapid glacio-isostatic rebound. Radiocarbon dates on marine bivalves in the deformed raised glaciomarine deposits at St Fergus suggest that the readvance occurred sometime after 17.5k cal a BP (later if a marine reservoir adjustment of greater than 400 years is made). The SFPM has been linked tentatively with sea-bed features off the northern tip of Orkney (Clark *et al.*, 2012) (Figure 8 and 9.6.10) and it possibly correlates with a minor readvance that deposited the Wick Till in Caithness (Hall and Riding, 2016).

Stage 11 [c. 16-15 ka]. During subsequent retreat the southern margin of the Moray Firth ice lobe was pinned along the Banffshire coast where proglacial lakes, ice-marginal drainage channels and swathes of glaciofluvial outwash were formed (Figure 6c). Evidence of minor readvances of the Moray Firth ice lobe against the coast have been reported, notably to the west of Banff. A limit that swings around from the vicinity of Banff to the north-eastern tip of Caithness has been identified tentatively by Clark *et al.* (2012) (Figure 8 and 9.6.11). The pattern of sea-bed features off the northern coast (Figure 8) suggests that renewed ice accumulation occurred across the Orkney-Shetland Platform after Caithness had possibly become an ice-free corridor (Bradwell and Stoker, 2015b), but Hall et al. (2016) find evidence only of SE retreat across Orkney.

This stage possibly witnessed a general thickening of ice across the eastern Grampians when ice encroached northwards towards the MFB, depositing the so-called 'Northern Drift', which is associated with little till, but numerous blocks of locally-derived Huntly/Knock Gabbro (Read, 1923) (Figure 4). The re-advance probably created fs. 35, a suite of subdued subglacial bedforms of NNW orientation around Durn Hill (Figure 7 and 8).

Stage 12 [c.15 ka]. The configuration of retreat limits around Elgin (Figure 8) indicate that ice re-occupied the lower reaches of Strath Spey, supporting the 'Elgin Oscillation' (EO) proposed by Peacock *et al.* (1968). Ice at the coast ponded lakes in an area previously vacated by East Grampian ice. Deltaic deposits preserved in Glen Rothes and Glen Rinnes indicate that meltwater entered the lakes from the north and south respectively. Ice flowing from the eastern Cairngorms probably formed fs. 95 at this time to the south of Glen Rinnes, possibly coevally with fs. 94 in the middle reaches of Strath Spey (Table 1). Ice sourced in the western Highlands flowed via upper Strath Spey (fs. 47), terminating in the vicinity of Grantown-on-Spey, whilst the middle reaches of the Findhorn remained blocked by ice.

Sets of N-S orientated linear ridges around Elgin (Merritt *et al.*, 2003, map1) subsequently formed at the westward retreating margin of ice that created fs. 6. These ridges, together with others on the Black Isle, have been identified as de Geer moraines at an elevation of c. 55 m OD (Finlayson *et al.*, 2007). These ridges most likely formed in water ponded behind ice that continued to block drainage out into the Moray Firth. As similar features have not been recorded to the east of the Spey their presence within the EO glacial limits

suggests that glaciological conditions may have changed following that event, associated with the initiation of the Moray Firth Ice Stream (fs. 6). The age of the EO may be estimated circumstantially to have occurred at c. 15 ka.

Discussion

Glaciological inversion from the subglacial bedform record led Hughes *et al.* (2014) to conclude that the last BIIS had two modes of flow-pattern geometry. An early, thick (relative to topography) integrated ice sheet reaching the shelf edge with a simple ice-divide structure and a later, much thinner mode of ice sheet comprising multiple dispersion centres and a more complex flow structure. The two modes of ice flow geometry compare favourably with forward transient modelling experiments of the last BIIS reported by Boulton and Hagdorn (2006) and Hubbard *et al.* (2009), which produce very dynamic ice sheets with numerous 'binge-purge', advance - retreat cycles dominated by ice streaming. However, the flow set models and ice sheet simulations have until now not been compared closely with the lithostratigraphical records of NE Scotland, considered here, Caithness (Hall and Riding, 2016) and Orkney (Hall *et al.*, 2011; Hall et al., 2016).

The experiments predict multiple advances and retreats of Grampian ice across NE Scotland, but this is not substantiated by the stratigraphical record. Although there is evidence in the form of stacked till and gravel sequences for multiple phases in Caithness (Hall and Riding, 2016) relatively fewer units have been recorded across Buchan, probably because ice was mainly cold-based and relatively inactive for long periods of time, as predicted by the simulations. The experiments build-up substantial thicknesses of ice across the NW Highlands, Orkney and Shetland that feed into the Moray Firth at 35.3, 33.6 and 32.3 ka, which is not at variance with the stratigraphical record of those areas (Hall and Riding, 2016: Hall *et al.*, 2016) (Stage 1). However, they do not satisfactorily accommodate the extensive, early, south-easterly flow of ice deduced to have crossed Buchan from the MFB during the local LGM (Figure 9. 2). This discrepancy probably results partially from the impracticality of these modelling experiments to consider interactions with Scandinavian ice, which may significantly affect reconstructions of the NE quadrant of the BIIS. It may be pertinent, however, that although Hubbard *et al.* (2009) conclude that the maximum build-up of ice occurred between 27.5 and 18.5 ka, they could not discount two 'noteworthy' experiments using their optimal subset of data that yielded maximum ice conditions between 29 and 24 ka.

Some conclusions of Hubbard *et al.* (2009) are particularly relevant, notably that the coldest periods result in the slow growth of cold-based, high-viscosity ice that advances with high aspect ratios across NE Scotland primarily by viscous creep, accompanied by very localised zones of warm-based flow. 'Binge phases' such as these consequently result in very limited, patchy subglacial erosion and till deposition, and are probably conducive to the transport and preservation of glacial rafts, which are common in coastal

regions of Scotland (Merritt *et al.*, 2014). The binge phases build up large ice volume, which is the essential precursor to subsequent purge-advance phases. These relatively short-lived events, characterised by streaming, wet-based ice with a lower aspect ratio tend to dominate the geomorphological legacy through formation of extensive flowsets and to be more fully represented in the stratigraphical record through deposition of deforming-bed till.

Hubbard *et al.* (2009) find that the periods of maximum areal extent of the BIIS and ice-streaming do not occur during the coldest periods, rather to the transitions to warmer conditions irrespective of relative sea level changes. They predict very rapid deglaciation between 18 and 15 ka accompanied by the release of vast amounts of meltwater, which is supported by the occurrence of swathes of glacial outwash deposits in the region and evidence for ice-marginal lakes. However, they do not predict the Fladen readvances into the WGB identified by Sejrup *et al.* (2015).

There is general agreement that following earlier expansions during MIS 4 and 3 the western margin of the BIIS reached the shelf-edge by c. 29 ka and that the ice sheet reached its maximum size by Heinrich (H) 2 (c. 24 ka) at the end of the local LGM (Scourse et al., 2009; Chiverrell and Thomas, 2010). The sequence and chronology of events in the NSB is uncertain and clearly awaits further research to resolve (Clarke *et al.* 2012; Hughes *et al.*, 2016). The sequence there includes glacially-overridden sediments (Carr et al., 2006) likely to embrace complex structural relationships, rafts of partially reworked material and pockets of subglacially deposited sand and gravel containing reworked shells, making correct interpretation of radiocarbon dates, palynology and provenance studies difficult from boreholes. On balance, a marine embayment probably opened up twice in the central NSB. Firstly during GI 2 and again shortly following the global LGM when the sea reached as far south as Lunan Bay by an adjusted age of c. 20k cal a BP. This dating is not easy to accommodate with cosmogenic isotope exposure ages as late as 17.5 ± 2.6 ka for the deglaciation of ground above 200 m in Buchan (Phillips *et al.*, 2008; Ballantyne, 2010), although adoption of alternative production rates to those determined by Ballantyne (2010) could change the cosmogenic age quoted above to 19.1 ±2.5 ka (Hughes et al., 2016).

Conclusions

- The proposed 12-stage event stratigraphy for the last glaciation of NE Scotland broadly accords with recent reconstructions of the last BIIS, which was dynamic and reached its greatest thickness between 29 and 24 ka during the local LGM. At least three ‘binge-purge’ cycles are identified.
- The last ice sheet to cover NE Scotland witnessed abrupt changes in ice flow direction and geometry, but its peripheral location in respect both to accumulation centres to the west and the shelf-edge margin

probably resulted in large sectors remaining cold-based for long periods, dampening its response to rapid changes in climate.
- The pattern of retreat across NE Scotland suggests that re-expansions of ice occurred leading to local readvances.
- Events inferred from the lithostratigraphy are not always represented by flowsets, and some flowsets are not only time-transgressive, but developed during different flow events, making recognition of spatial and age relationships problematic when based on cross-cutting relationships alone.
- The integration of lithostratigraphy with the subglacial bedform record provides a powerful tool for the reconstruction of the last BIIS in its north-eastern section, but more detailed till lithostratigraphy, provenance studies and dating is required, especially in eastern Buchan, where varved sediments are likely to occur, and offshore.
- The review strengthens concerns regarding the published geochronometry, particularly the integration of ages produced by different dating methods and of adjustments and recalibrations that have been made to them.

Acknowledgements

We are grateful to Dr Anna Hughes for her comments on earlier versions of this manuscript and for providing clipped subsets of her UK-wide interpretations. AMH thanks the Carnegie Trust for the Universities of Scotland for supporting fieldwork in northern Scotland. Some of ERCs work was undertaken when in receipt of an NERC Studentship during 1977-1980 for which he is most grateful and he would like to thank Dr Al Gemmell for his help and interest since he first worked in NE Scotland. We all thank Dr Jim Riding (BGS, Keyworth, Nottingham) for his detailed palynological analyses of tills and Dr Douglas Peacock for information, advice and support over many years. Craig Woodward is thanked for cartographic support. JWM publishes as an Honorary Research Associate with the permission of the Executive Director, BGS (NERC).

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Table 1. Hierarchy and correlation of flow-sets in NE Scotland; top after Hughes et al. (2014); bottom as suggested here with asterisks denoting change in deduced flow direction. Size of box denotes uncertainty in age or time-transgressive nature of flowset.

6	47,96	92		100			56	
3	34		35	36		64		
	33				72		51	
						93		7

6	47,96						
3	95, 94						
				100			56
			35*		64,93		
		33					51
	34			36			
	92*					72	7

Figures

1. Merged onshore-offshore (topographic-bathymetric) surface model for the northern UK and surrounding continental shelf (after Bradwell *et al.*, 2008). Offshore data from Olex AS; onshore data from NEXTMap Britain digital surface model (Intermap Technologies). Boxes show areas covered by Figure 3 and 4.

2. Summary of Late Quaternary chronostratigraphic stages (Great Britain) and their correlation with Marine Isotope Stages. The approximate timing of the local LGM (c. 30-25 ka) (Bradwell *et al.*, 2008) and global LGM (23-21 ka) (Hughes *et al.*, 2016) is shown.

3. Transport paths of some indicator erratics in NE Scotland (after Read, 1923; Bremner, 1928; Synge, 1956; Sissons, 1967; Merritt *et al.*, 2003). NEXTMap Britain digital surface model (Intermap Technologies).

4. Transport paths of some indicator erratics across the inner Moray Firth (after Mackie, 1905; Sissons, 1967; Fletcher *et al.*, 1996). NEXTMap Britain digital surface model (Intermap Technologies).

5. Generalised flow-lines of ice and conceptual profile map of the five subgroups of glacigenic deposits present in NE Scotland (after Merritt *et al.*, 2003). Area of minor glacial erosion after Synge (1956). NEXTMap Britain digital surface model (Intermap Technologies).

6. Reconstruction of ice-free enclaves and proglacial lakes in Buchan: (a) confluence between ice lobes during stage 5, creation of 80 m Glacial Lake Ugie (GLU) followed by the 'Logie-Buchan Readvance' and creation of 50 m GLU during stage 6; (b) decay of the Logie-Buchan ice lobe, further retreat of East Grampian ice followed by re-advance of Moray Firth ice during stages 7-9; (c) St. Fergus Readvance and subsequent ponding along the Banffshire coast during stages 10-11.

7. Flowsets of the last BIIS in north-eastern Scotland (modified after Hughes *et al.*, 2014, fig. 3). NEXTMap Britain digital surface model (Intermap Technologies).

8. Reconstruction of the retreat pattern of the last BIIS across north-eastern Scotland (modified after Clark *et al.*, 2012, fig 12). Limits off the north coast of Caithness and Sutherland taken from Bradwell and Stoker (2015b). Boxes A and B show hill-shaded digital surface models of two areas lying to the south of the Moray Firth. Boxes C-E show linear seabed features interpreted as possible de Geer moraines (after Bradwell *et al.*, 2008). Merged onshore-offshore (topographic-bathymetric) surface model with offshore data from Olex AS; onshore data from NEXTMap Britain digital surface model (Intermap Technologies).

9. Conceptual glacial reconstructions depicting stages in the evolution of the north-eastern quadrant of the last BIIS: (1) Reconstruction of Boulton *et al.*

(1985, fig. 10); (2) Local LGM (stage 2); (3) Considerable thinning and glacial reorganisation during stages 3 and 4; (4) Re-expansion following initial marine ingression into WGB during stage 5, followed by probable coalescence of BIIS and the Norwegian Channel Ice Stream at the Tampen Ridge (see cartoon 6 for limits); (5) Marine ingression to Lunan Bay during Stage 7; (6) Stages 8-12 and other limits after Clark *et al.* (2012, fig.12 and 13). Red hexagons show the centre of the Witch Ground Basin. Ice divides shown by thick black lines with open diamonds; single filled ticks denote ice divide receding by ice stream headward scavenging.

Tables

1. Hierarchy and correlation of flowsets in NE Scotland; top after Hughes *et al.* (2014); bottom as suggested here with asterisks denoting change in deduced flow direction. Size of box denotes uncertainty in age or time-transgressive nature of flowset.

2. Main stratigraphically important sites (numbered localities are described in Merritt *et al.*, 2003, Appendix A).

3. Correlation of lithostratigraphical units in NE Scotland (modified after Merritt *et al.*, 2003).

4. Lithology, matrix palynology and interpreted ice flow directions derived from clast fabrics (and associated striae) for Middle-Late Devensian till units in NE Scotland. From published and unpublished sources.

Table 1. Hierarchy and correlation of flow-sets in NE Scotland; top after Hughes et al. (2014); bottom as suggested here with asterisks denoting change in deduced flow direction. Vertical axes denote relative age. Size of boxes denote uncertainty in age or time-transgressive nature of flowset.

6	47,96	92		100			56	
3	34		35	36		64		
	33				72		51	
						93		7

6	47,96						
3	95, 94						
				100			56
			35*		64,93		
		33					51
	34			36			
	92*				72	7	

Table 2. Main stratigraphically important sites (numbered localities are described in Merritt et al., 2003, Appendix A)

Site name	n	Location	Sheet	Grid Ref	Site characteristics and significance	Main original reference
Allt Odhar, Moy	-	16 km SE of Inverness	84W	NH 798 368	Early Devensian peat bed beneath till and overlying till.	Walker et al., 1992
Balnakettle	24	Fettercairn	66E	NO 618 757	Tectonised sequence of till and gelifractate revealing late readvance of inland ice after retreat of Strathmore ice lobe.	Merritt et al., 2003
Baluss Bridge	10	1 km S of Mintlaw	87W	NK 005 473	Organic mud with Mesozoic palynomorphs associated with 50 m Glacial Lake Ugie; late MIS 2 readvance of offshore ice lobes.	Hall and Connell, 1991
Boyne Quarry	2	2.5 km E of Portsoy	96W	NJ 612 658	Rafts of Mesozoic mudstone and shelly Pleistocene sediment, glacitectonites, 3 tills, late-stage coastal ice-marginal lake deposits.	Peacock and Merritt, 2000
Burn of Benholm	26	14 km N of Montrose	57E	NO 795 691	Strathmore till on rafted shelly diamict with clasts and microfossils from North Sea basin; intervening bed of Early Devensian peat.	Auton et al., 2000
Camp Fauld	14	Moss of Cruden	87E	NK 049 410	Two tills separated by Early Devensian peat beds	Whittington et al., 1993
Castle Hill	3	Gardenstown	96E	NJ 795 642	Rafts of Mesozoic strata and shelly Pleistocene sediment capped by till, glacitectonites, late-stage coastal ice-marginal lake deposits.	Peacock and Merritt, 1997
Clava	-	9 km E of Inverness	84W	NH 766 442	Rafts of MIS 3? shelly clay and gravel within sequence of tills.	Merritt, 1992
Crossbrae Farm	5	3 km NE of Turriff	86E	NJ 753 512	Early Devensian peat bed beneath gravel and diamict.	Whittington et al., 1998
Cross-Stone	-	3 km S of Ellon	87W	NJ 954 278	End-moraines of Logie-Buchan ice lobe, multiple tills, sands and gravels indicating complex interaction of inland and coastal ice.	Gemmell et al., 2007
Dalcharn	-	6 km SW of Cawdor	84W	NH 815 452	Ipswichian palaeosol with till below and 3 till units above.	Walker et al., 1992
Ellon; Bellscamphie	15	Area NE of Ellon	87E	NK 018 337	Interbedded tills and gravel of contrasting provenance, including shelly 'indigo' till.	Hall and Jarvis, 1995
Errollston	17	Cruden Bay	87E	NK 088 368	Red lacustrine clay and diamict with clasts from the North Sea basin and inclusions of organic mud with Mesozoic palynomorphs.	Peacock, 1984
Howe of Byth	6	17 km ESE of Banff	97	NJ 839 753	MIS 3? ice-proximal fan capped by till and younger outwash fan.	Hall et al., 1995
King Edward	4	6 km N of Turriff	86E	NJ 722 561	Rafted MIS3/4 shelly deposits and diamict.	Sutherland, 1981, 1984b
Kippet Hills	16	Slains, Logie-Buchan	87E	NK 030 315	Esker and fan gravel with early Pleistocene shells and Permo-Triassic to Tertiary lithologies from offshore in the North Sea basin.	Gordon, 1993b
Kirkhill and Leys quarries	7	13 km NW of Peterhead	87W	NK 011 528, NK 005 525	Unique sequence of glacial, glaciofluvial, periglacial, pedogenic and fluvial units spanning three 100 ka glacial cycles.	Connell et al., 1982 Hall and Connell, 1991; Hall and Jarvis, 1993a
Mill of Dyce	18	Lower Don valley	77	NJ 871 152	Deltaic deposits formed during 'unzipping' of inland and offshore ice.	Aitken, 1995
Nigg Bay	22	Lower Dee valley, Aberdeen	77	NJ 965 045	Interbedded tills and gravel of inland and Strathmore provenance. Type site of the 'Aberdeen Readvance'. Lowest exposed sands and gravels of MIS 4? date	Gordon, 1993c, Merritt et al., 2003

Kingswells, Aberdeen	22	6 km W of Aberdeen	77	NJ 879 061	Till deposited by ice flowing SE overlain by till deposited by ice flowing ESE. Similar sequence observed by earlier works in gas pipe line trenches to the N.	Merritt et al., 2003
Oldmill	8	10 km WSW of Peterhead	87E	NK 024 439	Rafts of Mesozoic mudstone and Pleistocene glaciomarine mud, glacitectonites, capped by tills, MIS4? Deltaic gravel at base.	Hall, 1984a
Sandford Bay	12	3 km S of Peterhead	87E	NK 125 434	Inland till overlain by clays deposited in Glacial Lake Ugie, capped by red shelly diamict deposited by ice flowing onshore from SE.	Hall and Connell, 1991
St.Fergus	11	6 km WNW of Peterhead	87E	NK 124 434	12 m OD late-glacial raised beach and glaciomarine silts disturbed by ice pushing from E/NE during the St Fergus Readvance.	Hall and Jarvis, 1989; Peacock, 1997.
Strabathie	19	8 km N of Aberdeen	77	NJ 958 135	Deltaic and glaciolacustrine sequence formed during parting of inland and offshore ice lobes.	Thomas and Connell, 1985; Aitken, 1993
Teindland	1	Lower Strath Spey	85E	NJ 297 570	Multiple tills, 4 of which overlie a MIS5e palaeosol.	Hall et al., 1995a
Tillybrex	15	6 km NE Ellon	87W	NK 001 347	Interbedded tills and gravel of contrasting provenance and age.	Hall and Jarvis, 1995
Toddlehills	-	6 km WSW of Peterhead	87E	NK 069 453	Devensian and pre-Devensian tills separated by Early Devensian? fluvial sands	Gemmell et al., 2007

Table 3. Correlation of lithostratigraphical units in NE Scotland (modified after Merritt et al., 2003).

Colour key to Glacigenic Subgroups ; Inverness (IGS); Central Grampian (CGGS) ; East Grampian (EGGS) ; Banffshire Coast and Caithness (BCCGS) ; Logie-Buchan (L-BGS) ; Mearns (MGS).

Stage	Flowset	NAIRN	TEINDLAND/ELGIN	BOYNE Q / KEITH	BANFF	BYTH / CROSSBRAE	KIRKHILL / LEYS	PETERHEAD / CRUDEN	ELLON	ABERDEEN	STRATHMORE
			Spynie Clay								
12	Elgin Oscillation	Finglack Till	Waterworks Till								
11	47	Finglack Till	laminated clays of	Arnhash Till							
11	94, 95	Finglack Till	Glacial Lake Rothes	Blackhills S&G	Blackhills S&G						
11	35	Finglack Till		'Northern Drift"	Kirk Burn Silt						
10	St Fergus Rdv	Finglack Till		Blairdaff Moraine				St Fergus Moraine			
10		Finglack Till						St.Fergus Silt			
9	100	Finglack Till						Essie Till F			
?8						Crossbrae Gelifluct	Manse Gelifluct				
7									Tullos Clay	Tullos Clay	Lunan Bay Clay
7	56										Drumlithie S&G
6		Ruallan Till						50m Lake Ugie deltas		'Balnagask Till"	Mill of Forest Till
6		Ruallan Till							Kippet Hills S & G	Drumlithie S&G	Mill of Forest Till
6	64	Ruallan Till						Ugie Silt	L-BGS undif	Mill of Forest Till	Mill of Forest Till
5		Ruallan Till				Auchmeddon Gr	Kirkhill Church Sand	80m Lake Ugie deltas	L-BGS undif	Lochton S&G	Mill of Forest Till
5	51, 33	Ruallan Till						Hatton Till	Hatton Till	Banchory Till	Mill of Forest Till
4	34	Cantray Till	Tofthead Till	Old Hythe Till	Crovie Till	Byth Till				Den Burn Till	
3	36						Hythie Till	Sandford Bay Till	Bearnie Till	?Ness S & G	
2	7, 72?	Athais Till	Altonside Till	Whitehills Glaci F	Whitehills Glaci F	cryoturbate	Corse Diamict	Whitehills Glaci F	Pitlurg Till	Anderson Drive Dm	
1	92?	Athais Till	Woodside Diamict			Howe of Byth Gr					
MIS 3		Athais Till					Corsend Gelifluct				
					Pushlinn Burn Gr			Aldie Till			
MIS 4			Badentinian Sand (MIS 4-5a)					Hardslacks Gelifluct		?Ness S & G	
MIS 5a-c		Moy Burn Pal				Crossbrae F Peat		Berryley Peat			Benholm Peat
MIS 5e		Dalcharn Pal	Teindland Pal	Truncated palaeosol			Fernieslack Pal				
			Deanshillock Gravel					Moreseat F Sand			
MIS 6?		Cassie Till	Red Burn Till	Craig of Boyne Till		Crossbrae Till	Rottenhill Till	Camp Fauld Till	Bellscamphie Till		Benholm Clay
>MIS 6							West Leys S & G		Tillybrex S&G		Birnie Gravel

Note: The first column refers to both Marine Isotope Stages (MIS) and the 12-stage event stratigraphy of the paper.

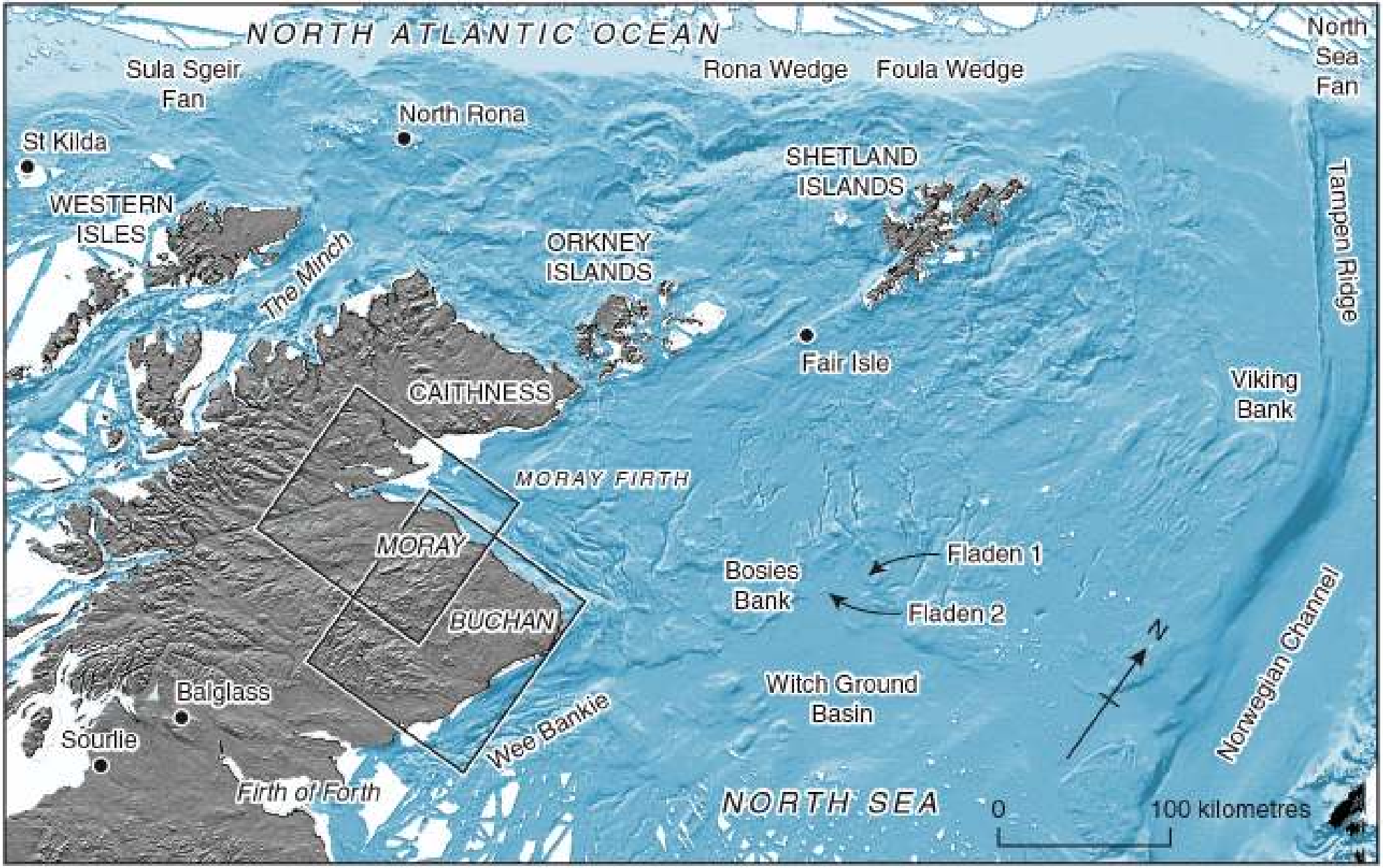
Flowsets after Hughes et al. (2014), but some straddle more than one stage (Table 1). Dated units of the Britannia Catchments Group in bold black.

Some units (eg Auchmeddon Gravel, Crossbrae Gelifluctate, Kirkhill Church Sand and Manse Gelifluctate) are depicted in the oldest event likely. Deposition may have continued over time or been restricted to younger events in the chronology.

Table 4. Lithology, matrix palynology and interpreted ice flow directions derived from clast fabrics (and associated striae) for Middle-Late Devensian till units in NE Scotland. From published and unpublished sources.

Glacigenic subgroup	Formation, member	Till lithology and interpreted ice flow direction
Mearns (MGS)	Mill of Forest Till F	Typically very weakly calcareous, reddish brown (5YR 4/4), sandy silty clay matrix. Dominated by ORS conglomerate clasts and other Devonian lithologies together with a range of igneous and metamorphic types. Where sampled (Nigg Bay, Aberdeen) matrix palynology reveals sparse assemblages with Carboniferous, Permian and Jurassic forms present. Ice flow toward NE and N.
Logie-Buchan (L-BGS)	Hatton Till F	Typically moderately calcareous, reddish brown (5YR 4/4) to red (2.5YR 4/6) sandy clayey silt matrix. Clast assemblages include ORS lithologies, Permian limestones, Mesozoic sediments, flint and shell fragments. Matrix palynology comprises rich assemblages of Jurassic dinocysts and miospores, less quantities of Permian pollen and rare Carboniferous, Cretaceous?, Palaeogene and Quaternary forms. Ice flow to N and NNW.
East Grampian (EGGS)	Banchory Till F Nigg Till M Kingswells Till M Den Burn Till M	These tills typically have non calcareous, brown-dark brown (10YR 4/3) to very dark greyish brown (2.5YR 3/2) sandy silty clay matrices. Clast assemblages are dominated by locally derived igneous and metamorphic lithologies. Matrix palynology of the Nigg Bay Till at Nigg Bay revealed a moderately rich assemblage containing some Carboniferous spores, a diverse assemblage of Jurassic forms and Quaternary elements. The assemblage probably has been locally reworked from the Anderson Drive Till (see below). Ice flow in the Nigg and Kingswells Tills towards the E and ENE. The Denburn Till records flow towards ESE and SE.
	Hythie Till F Sandford Bay Till M Bearnie Till M Aldie Till M Bellscamphie Till M	These tills typically have non calcareous, strong brown (7.5YR 5/4), brown/dark brown (10YR 4/3 - 3/3), dark yellowish brown (10YR 4/4), and locally greenish grey (5GY 6/1), sandy silty clay matrices. Clast assemblages in these deposits are dominated by locally derived acid and basic igneous rocks and metamorphic clasts. Locally well rounded flint and metaquartzite clasts are derived from the Buchan Gravels. Matrix palynology has investigated only for the Bellscamphie Till, which contains a rich assemblage of Early Carboniferous spores. Ice flow towards ESE, E and ENE.
	Byth Till F	Non calcareous, reddish brown (5YR 4/3) sandy silty clay matrix with clast assemblage dominated

		by metaquartzite, psammite and ORS lithologies. Ice flow to E and ESE.
	Crovie Till F	Reddish brown sandy clay matrix with clasts of Dalradian metasediment and ORS conglomerate. Ice flow towards ESE and SE.
Banffshire Coast and Caithness (BCCGS)	Whitehills Glacigenic F Corse Diamicton F Pitlurg Till F Anderson Drive Till F	These units typically have non to very weakly calcareous, very dark grey (10YR 3/1) to dark grey (5Y 4/1) and locally very dark grey (2.5YR N/3) to dark olive grey (5Y 3/1) sandy clay silt matrices. Clasts are typically dark mafic igneous and metamorphic rock types with subsidiary ORS or Triassic sandstones, Mesozoic sandstone? and shell fragments. Matrix palynology assemblage are dominated by Jurassic miospores and microplankton. Ice flow towards S and SE.
	Altonside Till F	Similar lithology to the above and ice flow towards the SE.
	Essie Till F	Moderately calcareous, very dark greyish brown (10YR 3/2) to very dark greyish brown (2.5Y 3/2) and very dark grey (5Y 3/1) clayey silt matrix. Clasts are typically few, but include igneous and metamorphic lithologies, chalk, Mesozoic? sandstone and shell fragments. Reconnaissance level palynology indicates a significant Jurassic component to the assemblages with a probably higher contribution from Cretaceous rocks. Flow towards the SE, ESE and S.
	Arnhash Till M	Typically reddish brown sandy textured matrices with clasts derived principally from Devonian sediments with subsidiary igneous and metamorphic lithologies. Ice flow towards the SE and S.
Central Grampian (CGGS)	Waterworks Till F Ruallan Till F Tofthead Till F Cantray Till F Woodside Diamicton F	These tills typically have reddish brown, sandy silty clay matrices. Clast assemblages are dominated by metaquartzites and psammites with subsidiary acid and basic igneous rocks, some ORS lithologies and Mesozoic rocks. Ice flow towards the ESE and SE.


NORTH ATLANTIC OCEAN
Sula Sgeir Fan
Rona Wedge
Foula Wedge
North Sea Fan
North Rona
St Kilda
SHETLAND ISLANDS
Tampen Ridge
WESTERN ISLES
The Minch
ORKNEY ISLANDS
Fair Isle
CAITHNESS
Viking Bank
MORAY FIRTH
MORAY
BUCHAN
Fladen 1
Bosies Bank
Fladen 2
Balglass
Witch Ground Basin
Sourlie
Wee Bankie
Norwegian Channel
Firth of Forth
NORTH SEA
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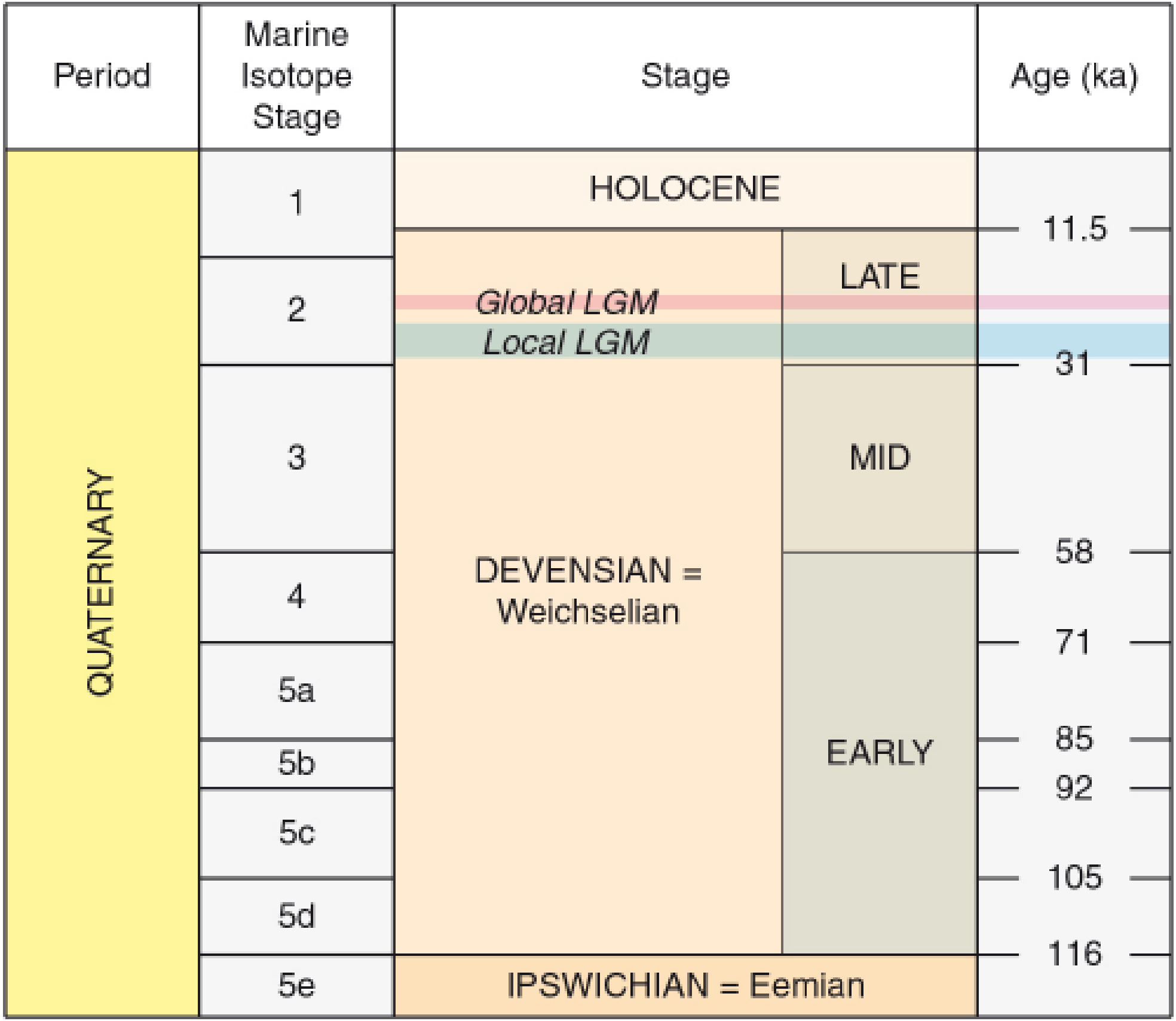
100 kilometres


Period
Marine Isotope Stage
Stage
Age (ka)
QUATERNARY
1
HOLOCENE
11.5
2
LATE
Global LGM
Local LGM
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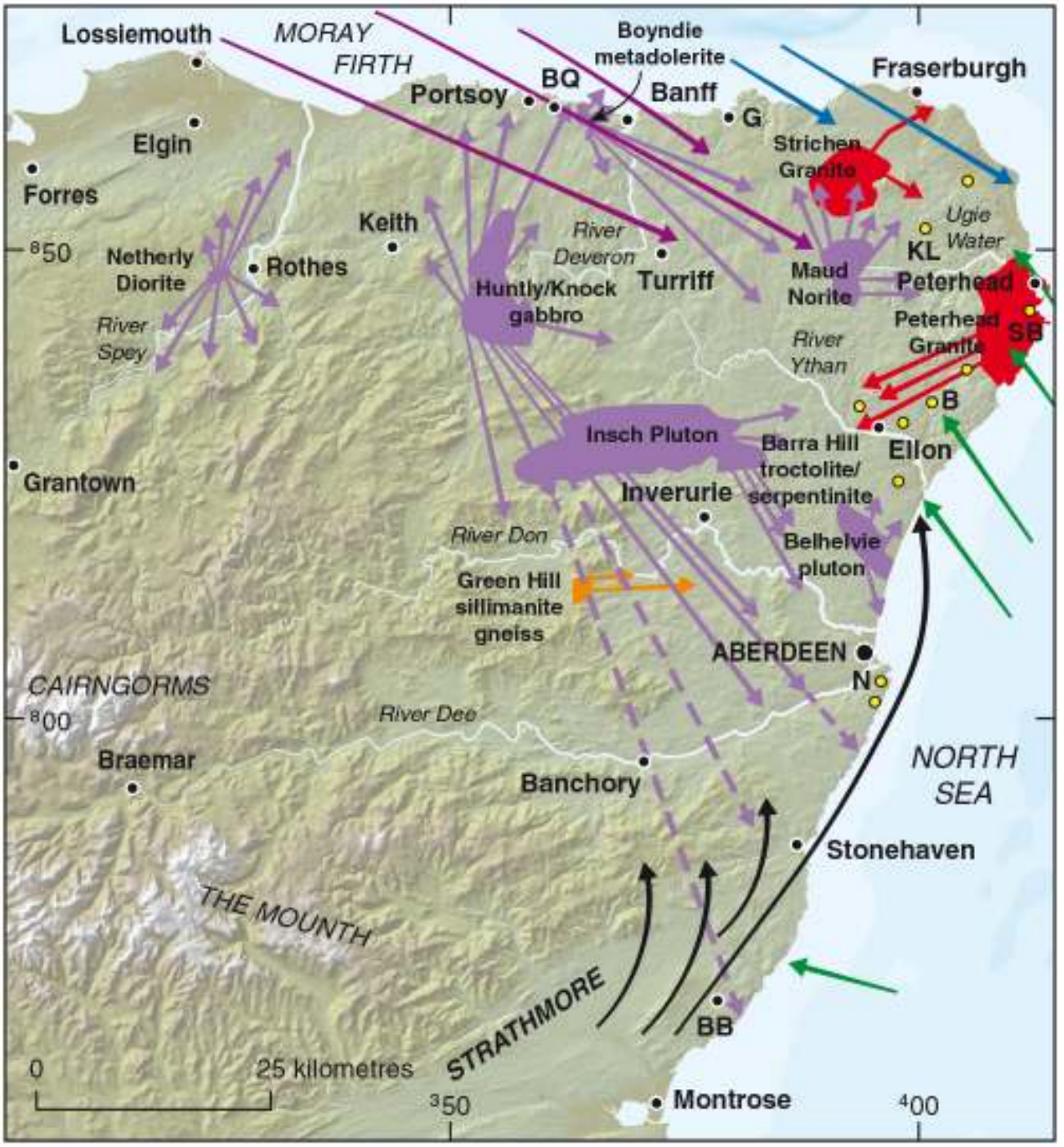
3
MID
58
4
DEVENSIAN = Weichselian
71
5a
85
5b
EARLY
92
5c
105
5d
116
5e
IPSWICHIAN = Eemian



Basic and ultrabasic igneous rocks

Granites

Green Hill sillimanite gneiss

Note: Arrows show direction of transport of distinctive erratics

Old Red Sandstone erratics from Strathmore

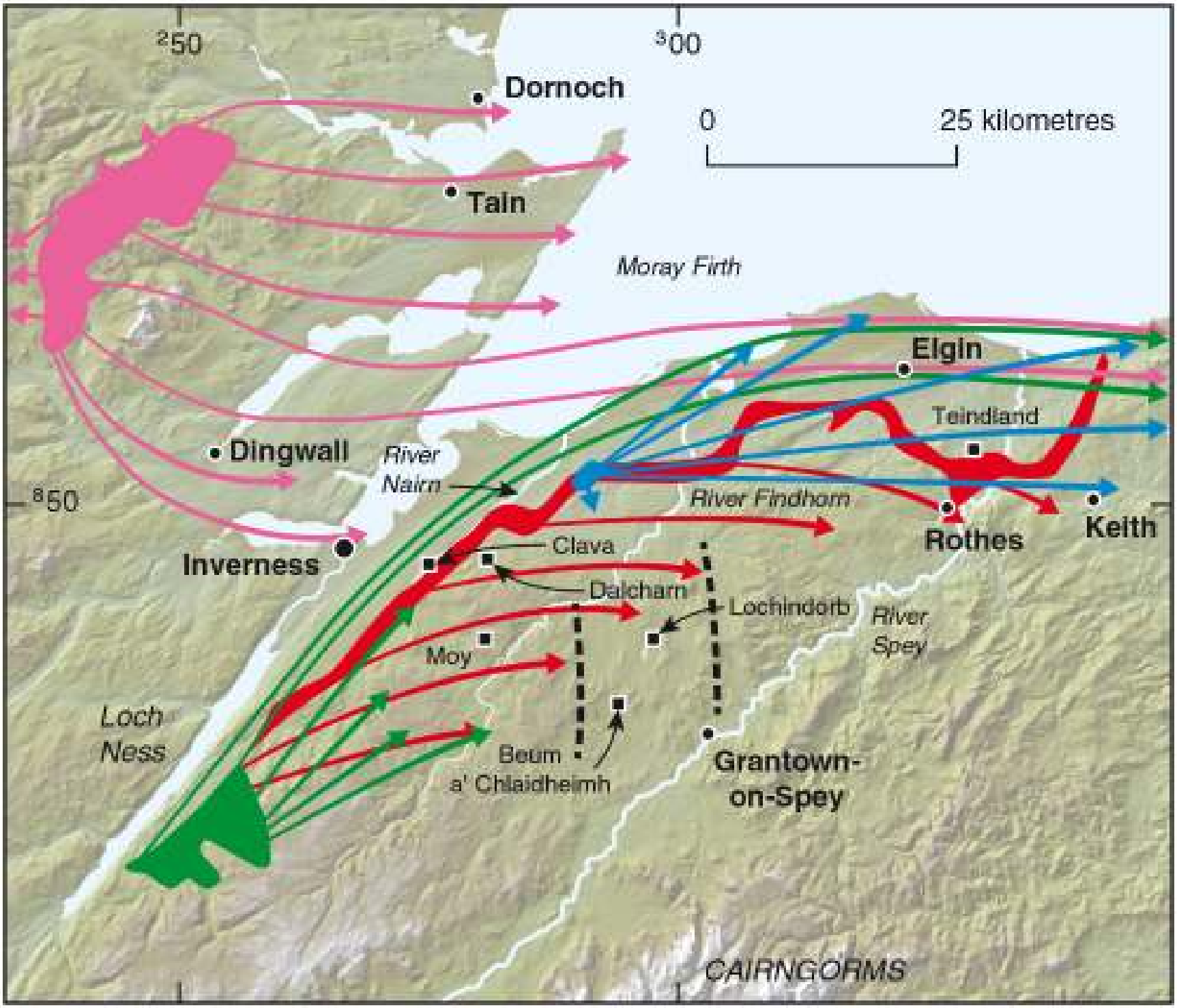
Distinctive erratics from the North Sea (Permian and Mesozoic limestones and dolomites)

Jurassic erratics from the Moray Firth

Lower Cretaceous erratics from the Moray Firth

Site with Scandinavian erratics found within Pleistocene deposits

B	Bellscamphie
BB	Burn of Benholm
G	Gardenstown
BQ	Boyne Quarry
KL	Kirkhill/Leys
N	Nigg
SB	Sandford Bay



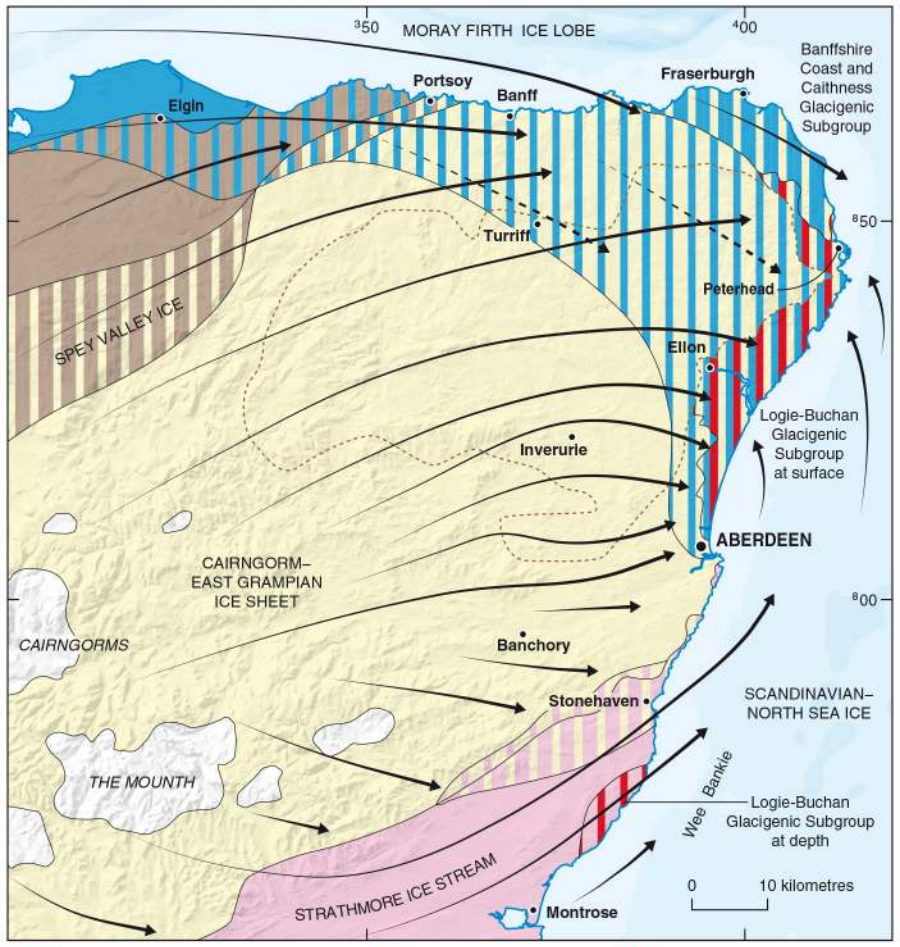
Southern limit of the Old Red Sandstone

Carn Chuinneag-Inchbae augen gneiss (extended to include ORS conglomerate in which clasts of this gneiss occur)

Foyers Granite

Auldearn Granite

Approximate boundary of former corridor of fast-flowing ice



Banffshire Coast and Caithness Glacigenic Subgroup (BC) at surface

Logie-Buchan Glacigenic Subgroup (LB) at surface

Central Grampian Glacigenic Subgroup (CG) at surface

Mearns Glacigenic Subgroup (M) at surface

East Grampian Glacigenic Subgroup (EG) at surface

BC beneath CG

BC beneath EG

EG beneath BC

EG beneath CG

EG beneath M

EG and BC beneath LB

EG and BC beneath CG

LB beneath M

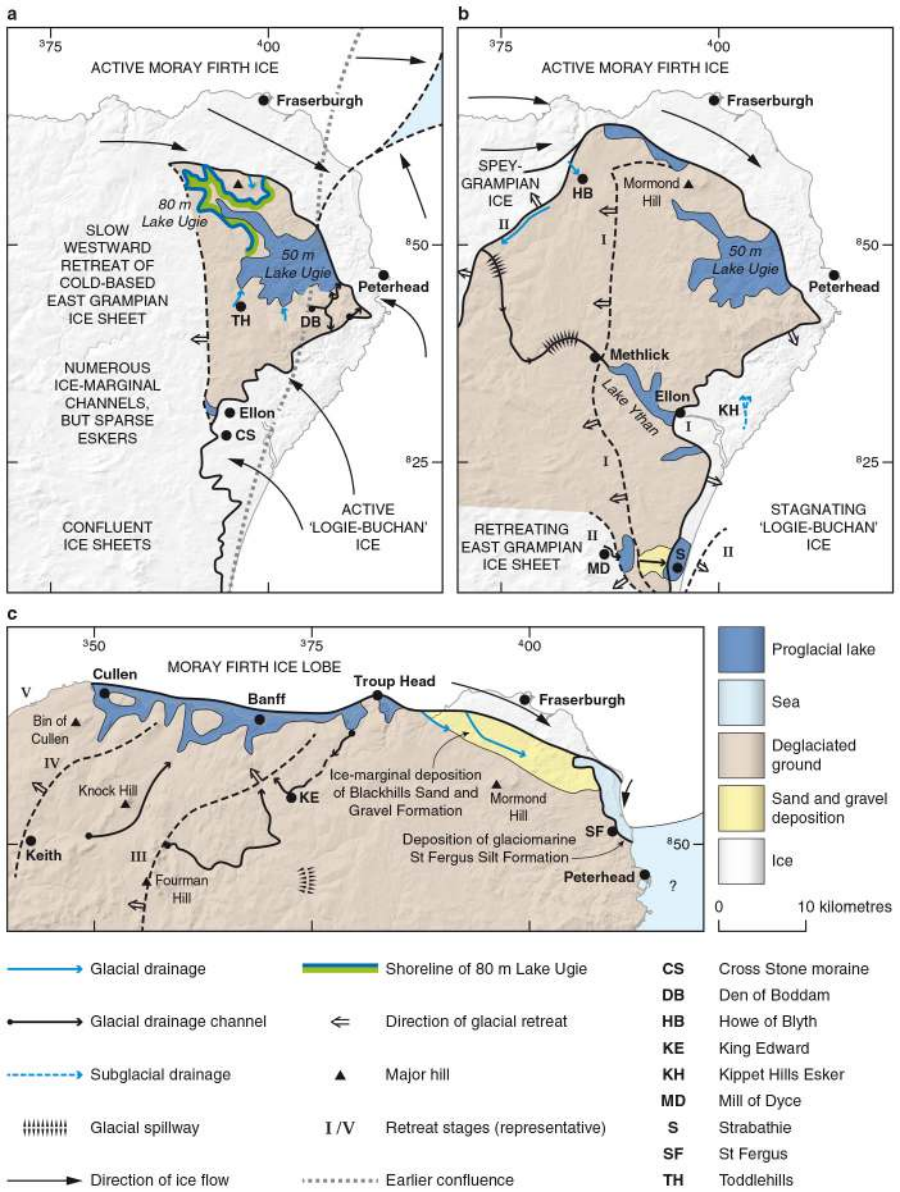
M beneath EG

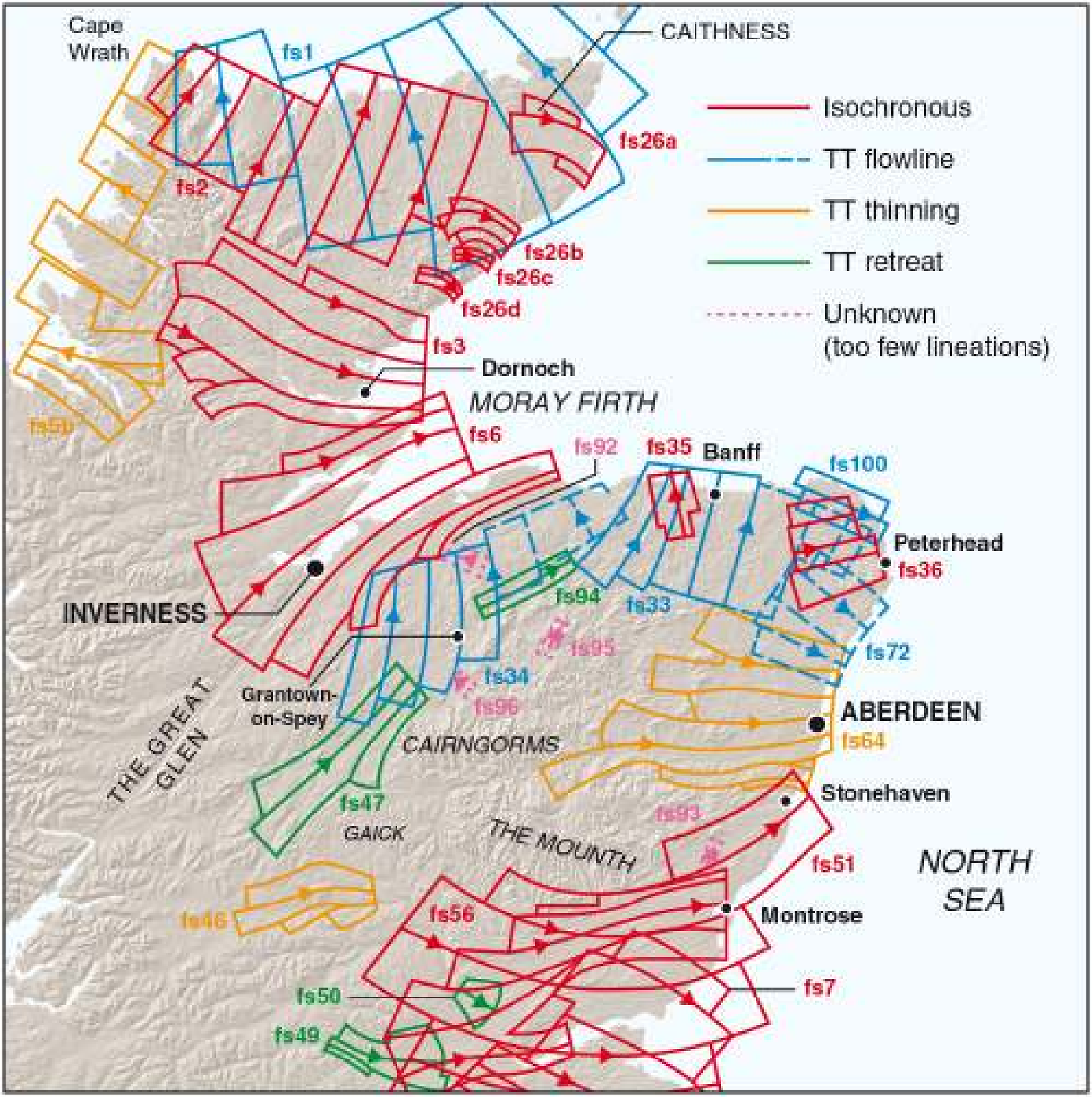
Cairngorm and Grampian mountain tops (thin ice)

Generalised flow line of ice

Earlier flow of ice from the Moray Firth

Area of relatively minor glacial erosion and deposition


a
ACTIVE MORAY FIRTH ICE
Fraserburgh
80 m Lake Ugie
50 m Lake Ugie
SLOW WESTWARD RETREAT OF COLD-BASED EAST GRAMPIAN ICE SHEET
TH
DB
Peterhead
NUMEROUS ICE-MARGINAL CHANNELS, BUT SPARSE ESKERS
Ellon
CS
ACTIVE 'LOGIE-BUCHAN' ICE
CONFLUENT ICE SHEETS
b
ACTIVE MORAY FIRTH ICE
Fraserburgh
SPEY-GRAMPIAN ICE
HB
Mormond Hill
50 m Lake Ugie
Peterhead
Methlick
Lake Ythan
Ellon
KH
STAGNATING 'LOGIE-BUCHAN' ICE
RETREATING EAST GRAMPIAN ICE SHEET
MD
S
c
MORAY FIRTH ICE LOBE
Cullen
Banff
Troup Head
Fraserburgh
Bin of Cullen
Knock Hill
KE
Ice-marginal deposition of Blackhills Sand and Gravel Formation
Mormond Hill
SF
Deposition of glaciomarine St Fergus Silt Formation
Keith
Fourman Hill
Peterhead
Proglacial lake
Sea
Deglaciated ground
Sand and gravel deposition
Ice
0
10 kilometres
Glacial drainage
Glacial drainage channel
Subglacial drainage
Glacial spillway
Direction of ice flow
Shoreline of 80 m Lake Ugie
Direction of glacial retreat
Major hill
I / V
Retreat stages (representative)
Earlier confluence
CS Cross Stone moraine
DB Den of Boddam
HB Howe of Blyth
KE King Edward
KH Kippet Hills Esker
MD Mill of Dyce
S Strabathie
SF St Fergus
TH Toddlehills


Cape Wrath
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CAITHNESS
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fs2
fs26b
fs26c
fs26d
fs3
Dornoch
MORAY FIRTH
fs5b
fs6
fs92
fs35
Banff
fs100
Peterhead
fs36
INVERNESS
fs94
fs33
fs95
fs72
fs34
fs96
Grantown-on-Spey
THE GREAT GLEN
CAIRNGORMS
ABERDEEN
fs64
Stonehaven
fs47
GAICK
THE MOUNTH
fs93
fs51
NORTH SEA
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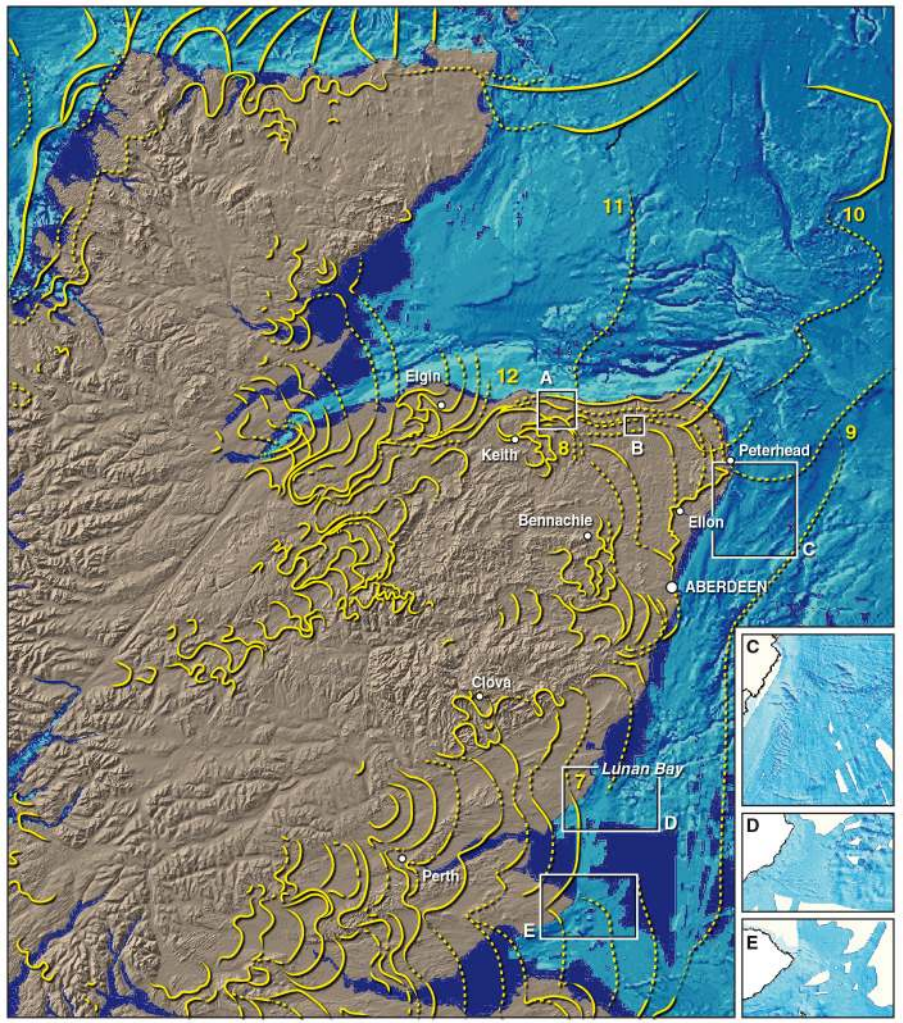
fs56
Montrose
fs50
fs7
fs49
Isochronous
TT flowline
TT thinning
TT retreat
Unknown
(too few lineations)


11
10
12
A
Elgin
Keith
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B
Peterhead
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Bennachie
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ABERDEEN
Clova
Lunan Bay
7
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Perth
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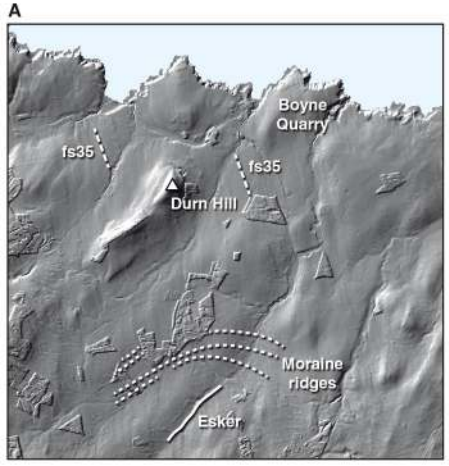
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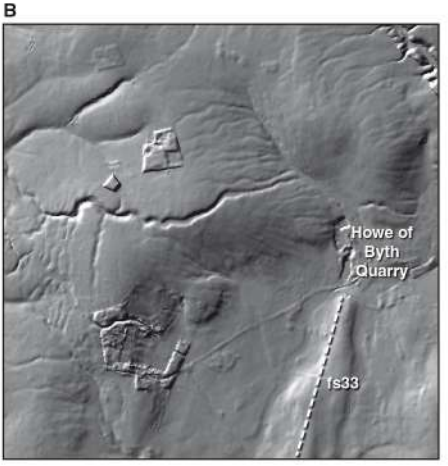
Durn Hill
Moraine ridges
Esker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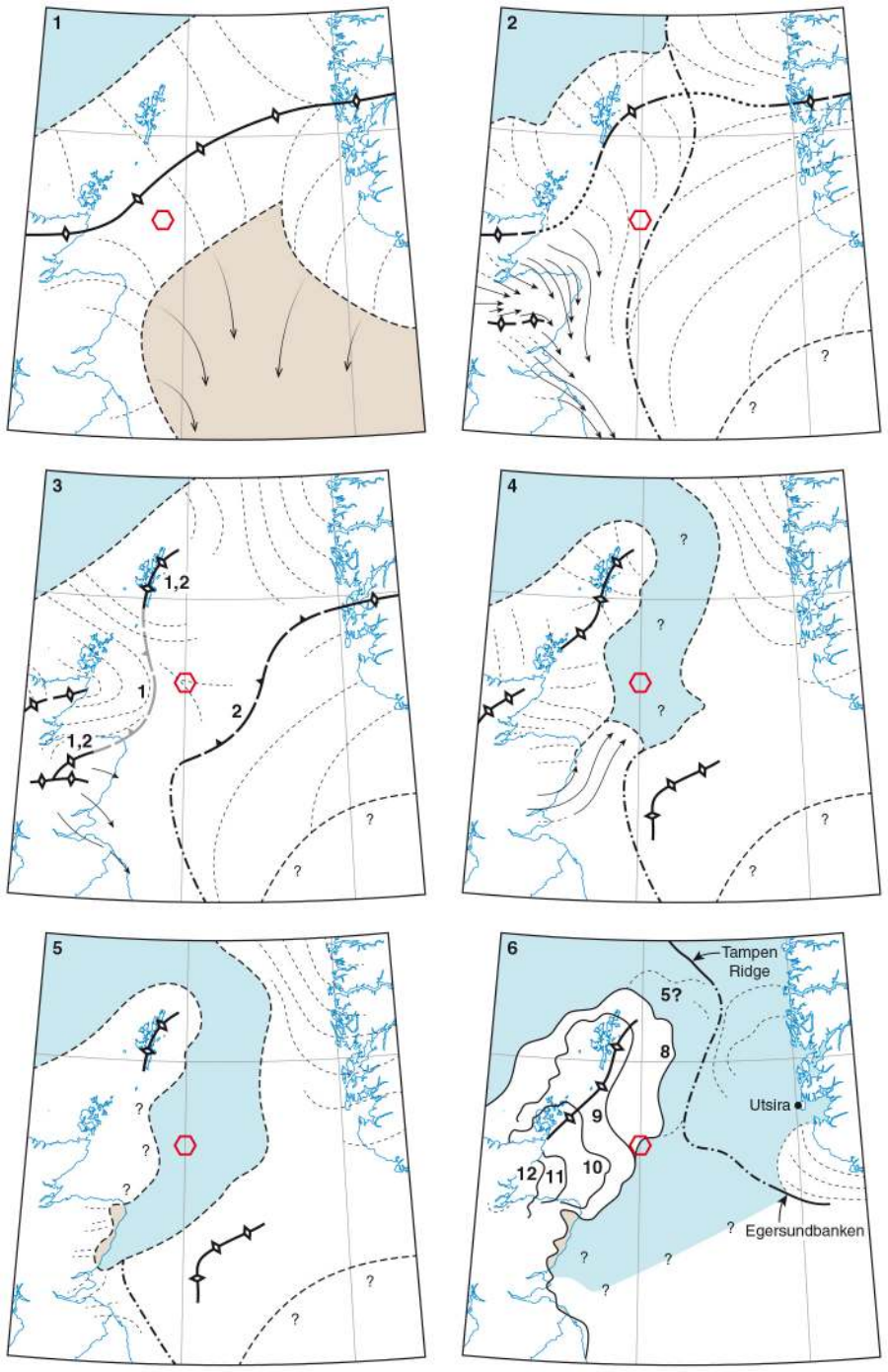
1
2
3
1,2
1
2
1,2
4
5
6
Tampen
Ridge
5?
8
9
10
11
12
Utsira
Egersundbanken
?