An introduction to the history of glaciation and sea-level around Nairn and south of the Inner Moray Firth.

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Early studies.

The Quaternary geology of the area covered in this guide (Fig. 1) excited the interest of pioneer workers, notably Bell (1891, 1893a, b, 1895a, b, 1896, 1897a, b), Fraser (1877, 1879, 1880, 1882a, b, 1889), Jamieson (1874, 1882, 1906), Macdonald (1881) and Wallace (1883, 1898), who recorded evidence of glaciation in the form of striae, moraines and erratics. They recognised evidence of deglaciation in the form of terraces and outwash fans, and postulated the former existence of glacial lakes at many localities. The first coherent accounts were proposed by Horne and Hinxman (1914) and Horne (1923) following the primary geological survey of the region. Their models envisaged a period of 'maximum glaciation', in which an ice-sheet covered all but the highest ground. Measurements of striae on the high ground suggested that there had been an early flow of ice towards the north to north-north-west before it generally flowed north-eastwards across the area (Horne, 1923). During the subsequent 'valley glacier stage' ice thinned and individual glaciers coalesced on the lower-lying ground. The valley glaciers breached watersheds and formed numerous lateral moraines, particularly on the north-facing slopes of Strathnairn and the lower Findhorn valley. Deglaciation was accompanied by 'active recession' associated with widespread ponding behind ice or morainic deposits, such in Strathdearn, around Loch Moy (Horne, 1923). No evidence of the subsequent 'corrie glacier' phase occurred within the area. The evidence for active recession was accepted by Bremner (1934, 1939), who confirmed that an extensive ice-dammed lake (*Glacial Lake Findhorn*) formerly occupied the **Middle Findhorn Valley,** and Charlesworth (1956), who postulated ice-dammed lakes within most of the valleys. Following an alternative model presented by Sissons (1969), Young (1980) suggested that the geomorphological landforms that he mapped in Strathdearn (Fig. 1) indicated that deglaciation largely took place by down-wasting *in situ,* rather than by active retreat.

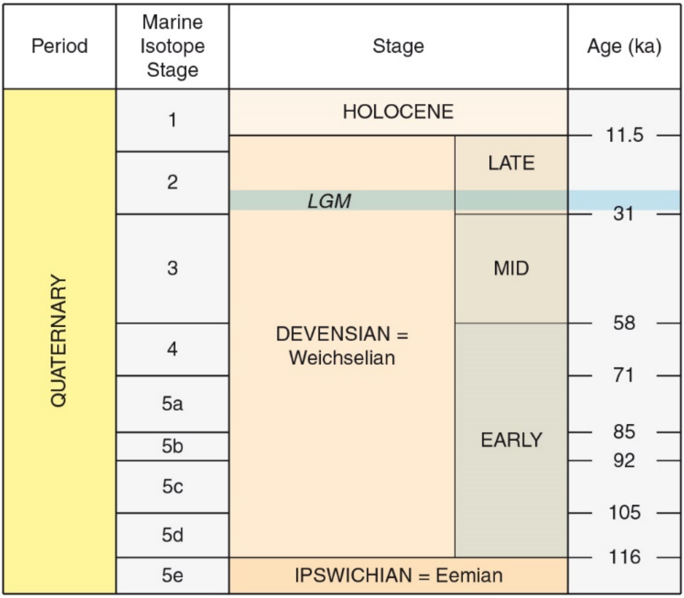

Figure 7. Summary of Late Quaternary chronostratigraphic stages (Great Britain) and their correlation with Marine Isotope Stages (after Bradwell et al., 2008). The approximate timing of the LGM is shown.

The pre-Late Devensian record.

One of the earliest descriptions of a pre-Late-Devensian (Fig. 7) deposit was made by Jamieson (1874), who claimed that a mass of fossiliferous clay containing shells of 'Arctic' affinity formerly exposed at Kirkton, on the **Ardersier Peninsula**, had been transported by a glacier and deposited amidst glacial sediments. Subsequent excavations have failed to locate this shelly clay, which is possibly of Late-Devensian age (Merritt et al., 1995), but another more famous shelly clay occurring beneath till at **Clava** is most probably of Mid Devensian age (Merritt, 1992). This deposit lies at an altitude of 150 m OD and contains a well-preserved littoral to shallow marine fauna of high-boreal character. The deposit excited considerable debate in the Nineteenth Century as to whether it was *in* *situ,* and thereby represented a great, pre-glacial submergence of the country, or whether it was transported by ice from off-shore (Horne et al., 1894; Gordon, 1993a). The shelly clay, together with associated masses of shelly diamict, are now generally agreed to be glacially transported rafts that were probably derived from the Loch Ness Basin (Merritt, 1992; Phillips and Merritt, 2008) (Fig. 8).

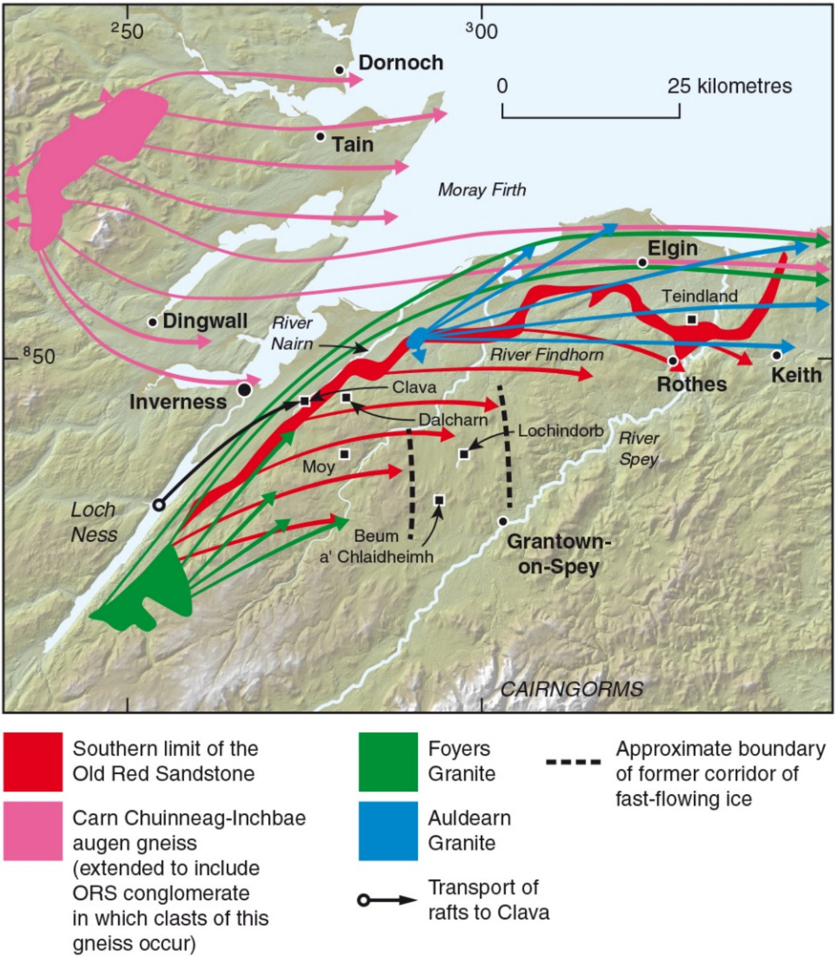

Figure 8. Transport paths of some indicator erratics across the Inner Moray Firth (after Mackie, 1905; Sissons, 1967; Fletcher et al., 1996).

At the important **Dalcharn** site, 6 km SW of Cawdor, cryogenically and glacitectonically disturbed biogenic sediments containing pollen of full interglacial affinity rest on deeply weathered gravel and are overlain by two distinct formations of subglacial traction till. An older till underlies the gravel. The biogenic material is assigned to the Ipswichian (MIS 5e) on the basis of TL dating (Duller et al., 1995), but the pollen suggests that it may be Hoxnian (MIS 11) in age (Walker et al., 1992). The **Allt Odhar** site lies on the Moy Estate, some 8 km south of Dalcharn (Fig. 1). Here compressed peat containing pollen, insect remains and plant macrofossils of interstadial affinity lies between tills. On the basis palaeo-environment, 'infinite' radiocarbon ages, and the results of TL and experimental Uranium Series Disequilibrium dating, the peat has been assigned to an interstadial in the Early Devensian (MIS 5a or 5c) (Walker et al., 1992; Duller et al., 1995).

The area is likely to have been fully glaciated on several occasions during the Quaternary, lying between the 'intermediate' and 'outer' zones of glacierization conceptualised by Boulton and Jones (1979) and likely to have been glaciated repeatedly during 'average' build-up of ice sheets during the Pleistocene (cf. Porter, 1989; Clapperton, 1997; Klemen, 1994). Theoretically, there was net erosion during glacial periods, but there were enclaves that were protected as a result of the local topographic configuration in relation to former ice flow. For example, several tributaries of the River Nairn that issue from the dissected upland plateau rising towards Carn nan Tri-tighearnan have excavated deep channels in their lower reaches, where 30 to 40 m thick sequences of glacigenic sediments are exposed that probably span several glaciations (Fig. 9).

Evidence for events during the last glaciation.

The terrestrial glacigenic sequence, striae, clast fabrics and distribution of indicator erratics in the region reveal that the relative importance of ice dispersion centres changed during the last glaciation, reinforcing the view that the last British Ice Sheet (BIS) was dynamic (Sutherland, 1984; Evans et al., 2005; Clark et al., 2012; Hughes et al., 2014, 2016; Merritt et al., 2017). Five distinct phases of glaciation may be recognised in the region, each correlated with distinctive till formations (Table 2).

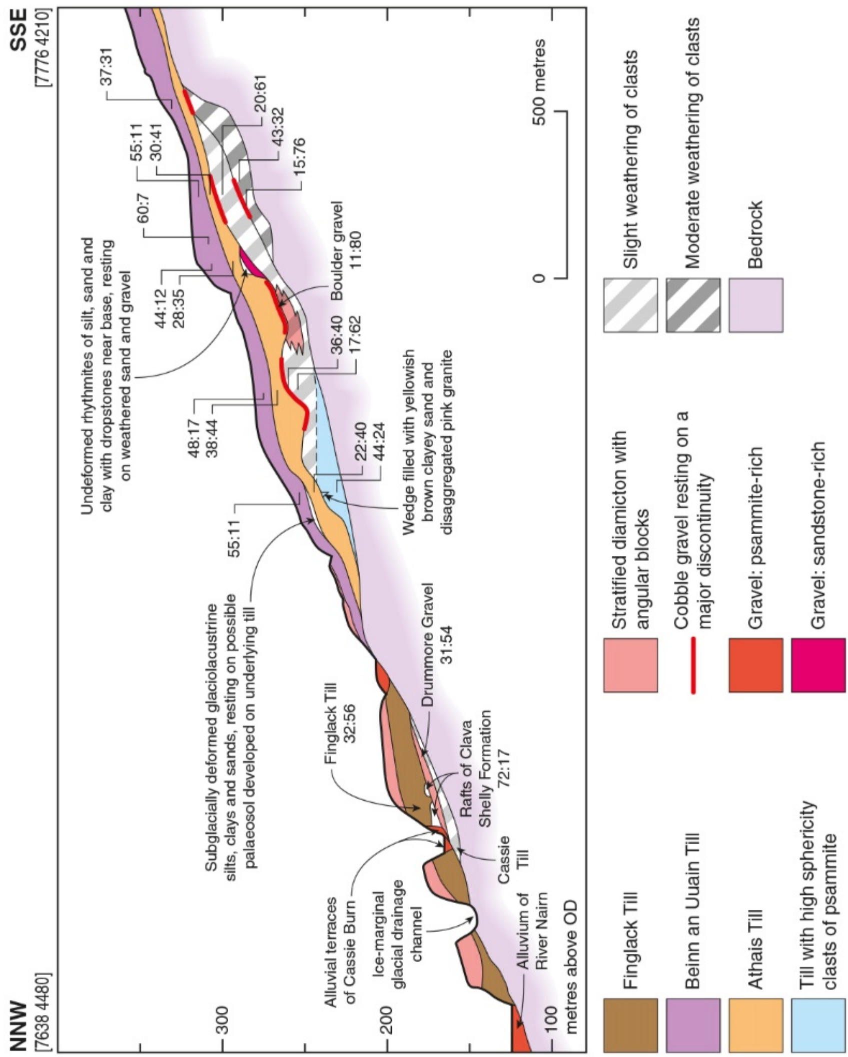

Figure 9. Schematic longitudinal profile of the Allt Carn a' Ghranndaich valley upstream of Clava (after Fletcher et al., 1996). Stone-count data (e.g. 20:60) are percentages of metamorphic and Old Red Sandstone clasts respectively.

Table2. Phases of glaciation and suggested correlations with flow-sets (F-s) of Hughes et al. (2014), Marine Isotope Stages (MIS), and lithostratigraphy.

Phase	Dominant flow	F-s	MIS	Till unit
5	Moray Firth Ice Stream	6	2	Baddock Till Mb
4	North-eastward flow	6	2	Finglack Till Fm
3	Early upland deglaciation	-	2	Carn Monadh Gravel Fm
2	Flow from south	34	3/2	Beinn an Uain Till Fm
1	Early eastward flow	92?	4/3	Athais Till Fm

Phase 1: Early eastward ice flow. The distribution of indicator erratics (Fig. 8) suggests that ice sourced in the western Highlands was forced eastwards across the Great Glen during the last glaciation (Sissons, 1967; Fletcher et al., 1996), possibly deflected by ice flowing eastwards from an ice divide stretching along the spine of the north-west Highlands (Read, 1923; Bremner, 1934, 1943; Merritt et al., 2017). The ice laid down sandy tills containing abundant 'Old Red Sandstone' (ORS) lithologies (sandstone, siltstone and conglomerate) on the north-west-facing slopes overlooking the Inverness Firth and Inner Moray Firth between Inverness and Forres (Horne and Hinxman, 1914; Horne, 1923). Material derived from Middle 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 Findhorn and Spey valleys (Horne, 1923; Sissons, 1967; Fletcher et al., 1996). As the sandy tills are generally overlain by younger metasandstone-rich tills across the uplands it has been generally concluded that they were laid down during a glaciation predating the last (Sutherland, 1984). The sandy tills generally appear to be weathered, but this may reflect their greater permeability or inclusion of previously weathered material.

The timing of this early phase of glaciation has not been firmly established, but with the discoveries of organic beds at lower levels in the glacigenic sequences at **Dalcharn** and **Allt Odhar**, the age has been constrained to being no older than the Early Devensian (Walker et al., 1992; Sutherland and Gordon, 1993). However, depending upon the interpretation of TL age determinations at Allt Odhar obtained by Duller et al. (1995), a late-Middle Devensian age cannot be ruled out, in which case it relates to the build-up of the last BIS (Merritt et al., 2017).

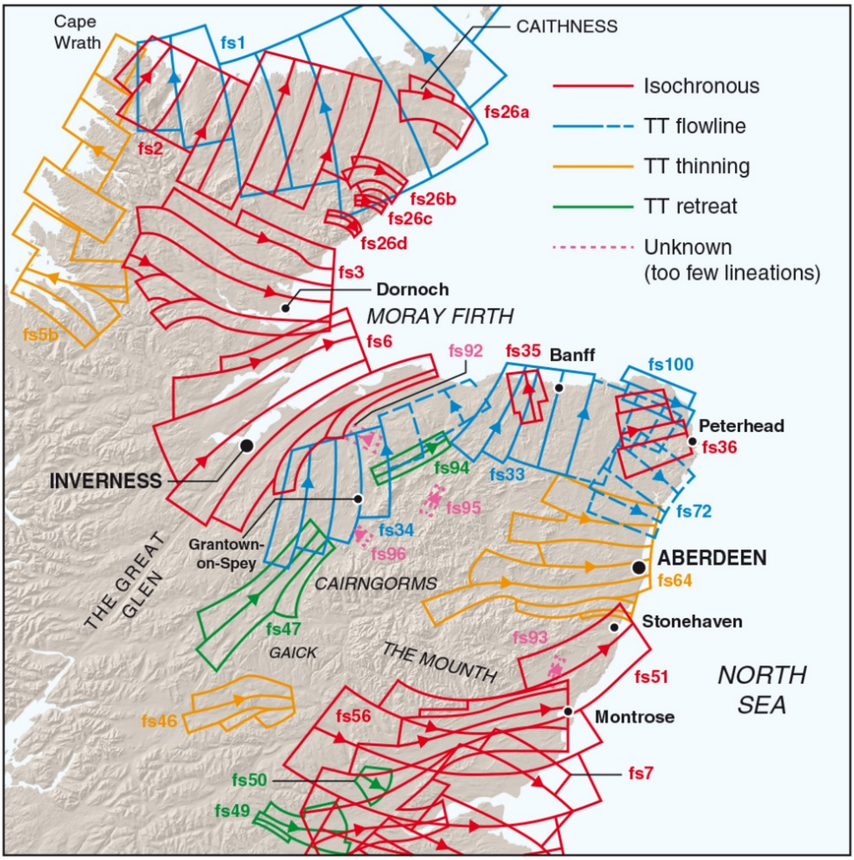

Figure 10. Flow-sets of the last British and Irish Ice Sheet in north-eastern Scotland (from Merritt et al., 2016 and modified after Hughes et al., 2014, fig. 3).

Phase 2: The Last Glacial Maximum (LGM). Inland of the coastal plain, the sandy tills are generally overlain by tills rich in metasandstone and granite derived from inland, as for example, at **Dalcharn** and **Allt Odhar**, where both the fabric and provenance of the upper till units indicate that substantial switches in flow occurred, firstly towards the north and then the east-north-east. These switches may be correlated with distinct sets of glacially streamlined landforms that have been identified by Hughes et al. (2014) (Fig. 10). The northward time-transgressive flow line (fs. 34) is associated with ice that flowed from a centre in the western Highlands via upper Strathspey to the vicinity of Grantown-on-Spey. Flow was concentrated across the Dulnain/Spey-Findhorn divide at the **Beum a' Chlaidheimh** (Fig. 11), at c. 360 m OD, and subsidiary breaches. South to north-orientated streamlined features indicate that a topographically-unconstrained corridor of relatively fast-flowing ice extended northwards across the **Middle Findhorn Valley** towards the Inner Moray Firth (Merritt et al., 2013). In contrast, the NEXTMap hill-shaded digital surface model reveals that the landscape to the east of this *'Lochindorb Corridor'* has experienced relatively little cumulative glacial modification, suggesting that local, sluggish, cold-based ice was generally centred over this part of the East Grampians, including the middle reaches of the Strathspey downstream of Grantown-on-Spey (Fig. 11). The ice-sheet was relatively thick during this phase, towards the end of the LGM, as flow was relatively unconstrained by the topography (Clark et al., 2012; Hughes et al., 2014). NEXTMap imagery reveals that the landscape to the east of Lochindorb has experienced relatively little cumulative glacial modification, suggesting that local, sluggish, cold-based ice was centred over this part of the East Grampians, which includes the middle reaches of the Spey Valley downstream of Grantown-on-Spey. The sinuous profile of Streens Gorge in the **Middle Findhorn Valley** seems to have been similarly protected from substantial glacial erosion.

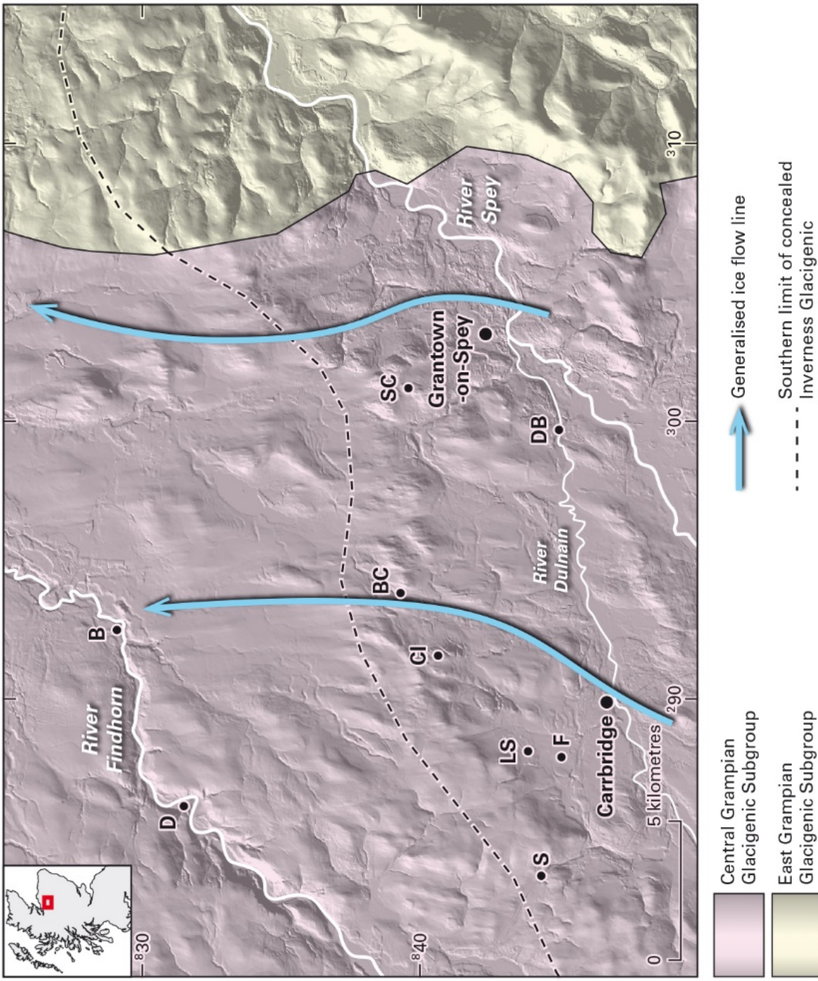

Figure 11. NEXTMap hill-shaded digital elevation model of the area around Lochindorb, revealing the imprint of a former, topographically unconstrained corridor of fast-flowing ice across the Dulnain-Findhorn catchment divide (after McMillan and Merritt, 2012). The streamlined landforms and widespread sheets of till of the Central Grampian Glacigenic Subgroup that formed beneath the ice stream contrast with the relatively minimal glacial modification of the landscape to the east, which was covered by more sluggish, cold-based, local ice during the LGM. B, Banchor; BC, Beum a' Chlaidheimh; CI, Craig na h-Iolair; D, Daless; DB, Dulnain Bridge; F, Foregin; LS, Loch nan Stuirteag; S, Slochd; SC, Shleanaferan Channel.

Based on thorough, systematic logging of natural sections in the area east of Inverness, Merritt and Auton (1993) found that the contact between the sandstone-rich and overlying metasandstone-rich tills was generally represented by a sharp change in colour and commonly by a planar, sub-horizontal discontinuity, as at **Dalcharn**. 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, hydrofractures, truncated gravel-filled channels, seams of glacitectonite and rip-up clasts of diamict suggest that ice-bed boundary conditions changed during the switches in flow (Fletcher et al., 1996; Walker et al., 1992), when the ice-sheet possibly became more dynamic and wet based.

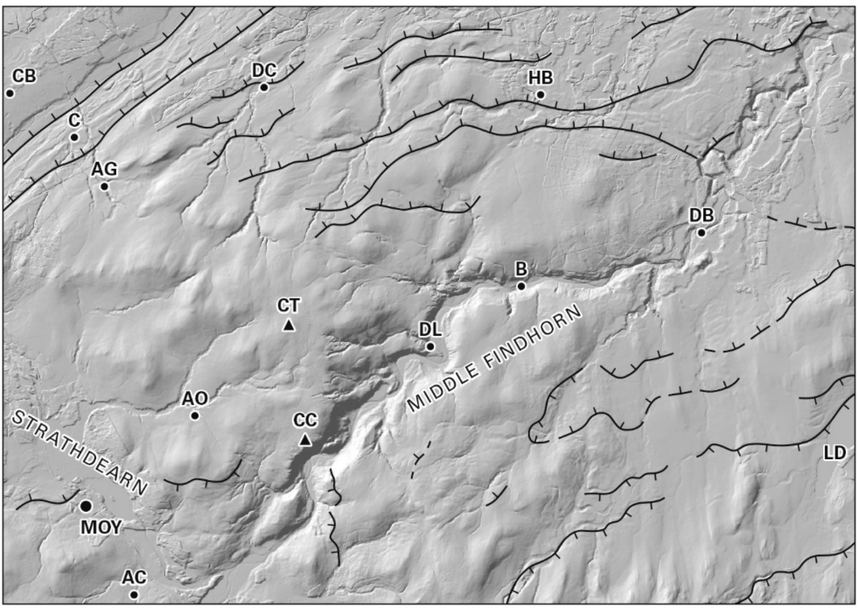

Figure 12. NEXTMap hill-shaded digital elevation model of the area around the Middle Findhorn Valley, revealing the pattern of glacial retreat superimposed on the dominant imprint of ice flow during the LGM. AC Allt a' Chùil section; AG, Allt Carn a' Ghranndaich sections; AO, Allt Odhar interstadial site; B, Banchor glaciolacustrine site; C, Clava site; CB, Culloden Battlefield; CC, Craig a' Chròcain; CT, Carn nan Tri-tighearnan; DB, Dulsie Bridge; DC, Dalcharn interglacial site; DL, Daless; HB, Highland Boath; LD, Lochindorb.

Phase 3: Early upland deglaciation following the LGM. At a particular stage in deglaciation the ice sheet became too thin for ice to flow across the Dulnain-Findhorn divide and the ice-stream centred on the Lochindorb Corridor switched off and decayed. A major glacial reorganisation ensued. Ice thinned and eventually Dulnain/Strathspey-derived ice parted from Monadhliath/Great Glen/Moray Firth ice roughly along the axis of the **Middle Findhorn Valley** (Fig. 12), which subsequently witnessed widespread ponding. A large outlet glacier became established in Strathspey, upstream of the vicinity of Grantown-on-Spey, with lobes penetrating into Abernethy Forest and the Loch Garten, Rothiemurchus and Glenmore depressions (Young, 1974, 1975b, 1977; Merritt et al., 2013; Hall et al., 2016). It produced subglacial landforms of flow-set 47 (Fig. 10). There is abundant evidence in the form of ice-marginal glacial drainage channels and moraines around the **Beum a' Chlaidheimh** for the active retreat of the outlet glacier from the southern flanks of the Dulnain-Findhorn catchment divide (Young, 1977b). Similar suites of features formed along the margin of the vast Great Glen-Moray Firth outlet glacier that became established to the north, creating flow-set 6 (Fig. 10). Once the high ground around Carn nan Tri-tighearnan [NH 823 390] was free of ice, widespread sheets of silty sand, gravel and diamict of the *Carn Monadh Gravel Fm* (Table 2) were laid down in the upper catchments of the streams that now drain that area, as for example, at the **Allt Odhar** site. The material slowly accumulated adjacent to ice that still occupied the lower ground. Fan-deltas locally formed within ephemeral ice-marginal lakes on the Findhorn-Nairn divide at elevations of up to 570 m OD, whereas staircases of outwash terraces and fans formed sequentially within the Middle Findhorn Valley, much as envisaged by Bremner (1939) and Charlesworth (1956). In the middle and lower reaches of this valley meltwaters were firstly ponded behind a succession of temporary barriers of stagnant ice and glacial sediment (Auton, 1990), and then constrained to follow the present axis of the valley towards the coast.

The spectacular systems of hydrofractures described by Phillips et al. (2013) at the **Meads of St John**, in the lower Findhorn valley, probably formed during the glacial reorganisation that followed the LGM. These features formed sub-glacially within bedrock in the vicinity where the waning flow of ice from the 'Lochindorb Corridor' merged with the more powerful flow of ice from the western Highlands towards the Moray Firth. Other good examples of hydrofractures are displayed at **Clava**.

Phase 4: Renewed dominance of ice flowing from the Monadhliath and the Great Glen. The final flow of ice across the coastal hinterland was towards the north-east, as indicated by glacially streamlined landforms, the orientation of glacial striae and the clast-composition of the youngest tills (Fletcher et al., 1996; Hughes et al., 2016). Ice sourced over the Monadhliath Mountains flowed north-eastwards towards the Moray Firth, laterally constrained by relatively faster flowing ice centred on the Great Glen (Boston et al., 2013). A swathe of glacially streamlined megagrooves, whalebacks and rock drumlins identified recently to the north of Loch Ness (BGS, 2012; Merritt et al., 2013) suggests that a topographically-unconstrained ice stream delivered ice directly towards the Moray Firth. This north-eastward ice flow coalesced with ice from the uplands of Ross and Cromarty to impinge on the coastal lowlands towards Elgin (Fig. 10; fs 6). The contact between fast-flowing ice centred on the Great Glen and more stable portions of the ice sheet to the south is seen to the south-west of Daviot, in **Upper Strathnairn**, where pronounced bedrock sculpturing is evident and a train of large boulders and blocks crosses the strath (Fletcher et al., 1996). The fluting is associated with parallel elongate ridges formed of sandstone blocks and rubble on Drummossie Muir, south of Inverness (BGS, 1997).

The configuration of glacial retreat limits in lower Strathspey determined by Clark et al. (2012) support the concept that a significant readvance of Moray Firth ice occurred during overall deglaciation. Proposed and named as the *Elgin Oscillation* (EO) by Peacock et al. (1968) the ice at the coast ponded lakes inland where ground had become deglaciated. There is converging evidence that Moray Firth ice re-advanced into the lower reaches of the Findhorn Valley, such as at **Banchor**, causing ice-marginal lakes to deepen. A prominent ice-marginal moraine ridge at **Highland Boath** may have formed contemporaneously.

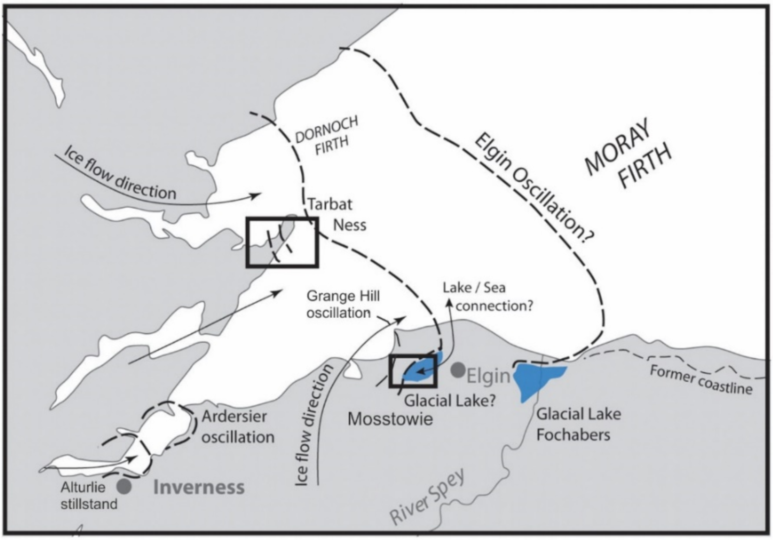

Figure 13. Stillstand and oscillation limits proposed for the retreat of the Moray Firth ice stream, locating possible De Geer moraines on Tarbat Ness and proposed ice-dammed lakes on the southern side of the Moray Firth (after Finlayson et al., 2007).

Phase 5: Retreat of a dynamic Moray Firth Ice Stream. Sets of north-south orientated linear ridges around **Mosstowie,** west of Elgin, and on Tarbat Ness (Fig. 13) subsequently formed at the westward retreating margin of Moray Firth ice. These ridges are possibly De Geer moraines formed at a tidewater glacial margin (Finlayson et al., 2007), but their relatively high elevation (c. 55 m OD) compared to the established sea-level curve for the area (see below) suggests that, if they are De Geers, they formed in water ponded behind ice that continued to block drainage into the outer Moray Firth, rather than into the sea. However, the features appear to be broadly similar to transverse ridges that others have reported from former calving bay margins (e.g. Dowling et al., 2016). Broadly similar transverse ridges occur around **Kingsteps**, **Easterton** and

Croy [NH 795 495] (BGS, 1997) (Fig. 14), but the features around Croy are lower (Fletcher et al., 1996) and are more likely either to represent winter push moraines (cf. Boulton, 1986), or to be ‘crevasse-fill’ or ‘squeeze’ ridges formed as sediment was squeezed up into basal crevasses in highly fractured ice, possibly following glacial surging (cf. Boulton et al., 1996; Evans et al., 1999; Evans and Rea, 2005).

Transverse ridges features have not been recorded to the east of the Spey, outwith the limit of the Elgin Oscillation (EO), suggesting glaciological conditions may have changed following that event, possibly associated with the initiation of a marine-based Moray Firth Ice Stream (MFIS) (Merritt et al., 2003, 2017) (Fig. 10; fs. 6). The EO may be estimated circumstantially to have occurred at c. 15 ka (Peacock, 1999) (Fig. 15). Until recently, ice was thought to have subsequently retreated towards Inverness before re-advancing back to the **Ardersier Peninsula**, but new evidence at **Grange Hill**, near Forres, indicates that at least one intermediate oscillation occurred, emphasizing the dynamism of the former MFIS (Fig. 13).

The orientation of subglacial drainage channels, eskers and low, cross-valley morainic ridges around Culloden Muir (Fig. 14) suggests that there was a general, south-westward retreat of the ice-sheet margin from the vicinity of Nairn, where meltwaters formed the **Flemington Eskers** and then flowed into the late-glacial sea, which had entered the inner Moray Firth (Fig. 15). These braided eskers, one of the best examples in Scotland, together with other systems to the north-east around **Easterton**, were possibly located at a former suture or ‘shear margin’ that separated stagnating ice flowing down Strathnairn (from the Monadhliath) from ice that issued actively from the Great Glen.

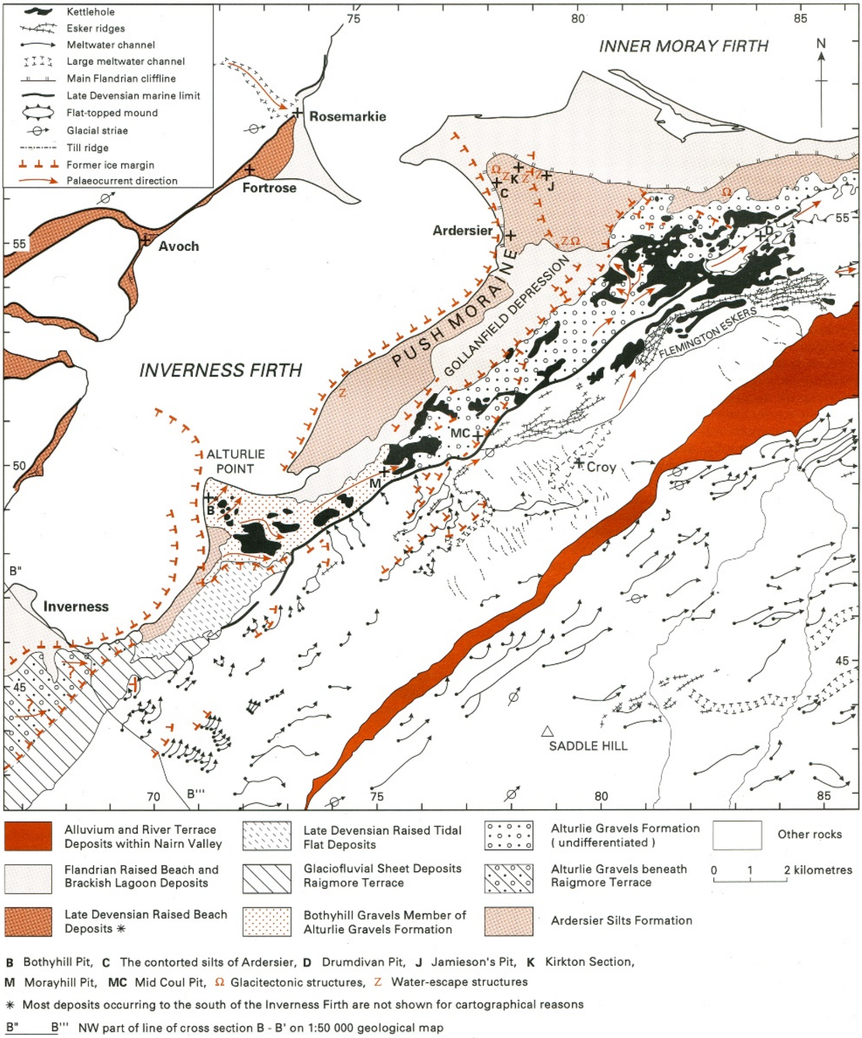

Figure 14. Geomorphological features and deposits associated with deglaciation of the Inverness Firth and its hinterland, including evidence supporting the Ardersier Oscillation (after Fletcher et al., 1996).

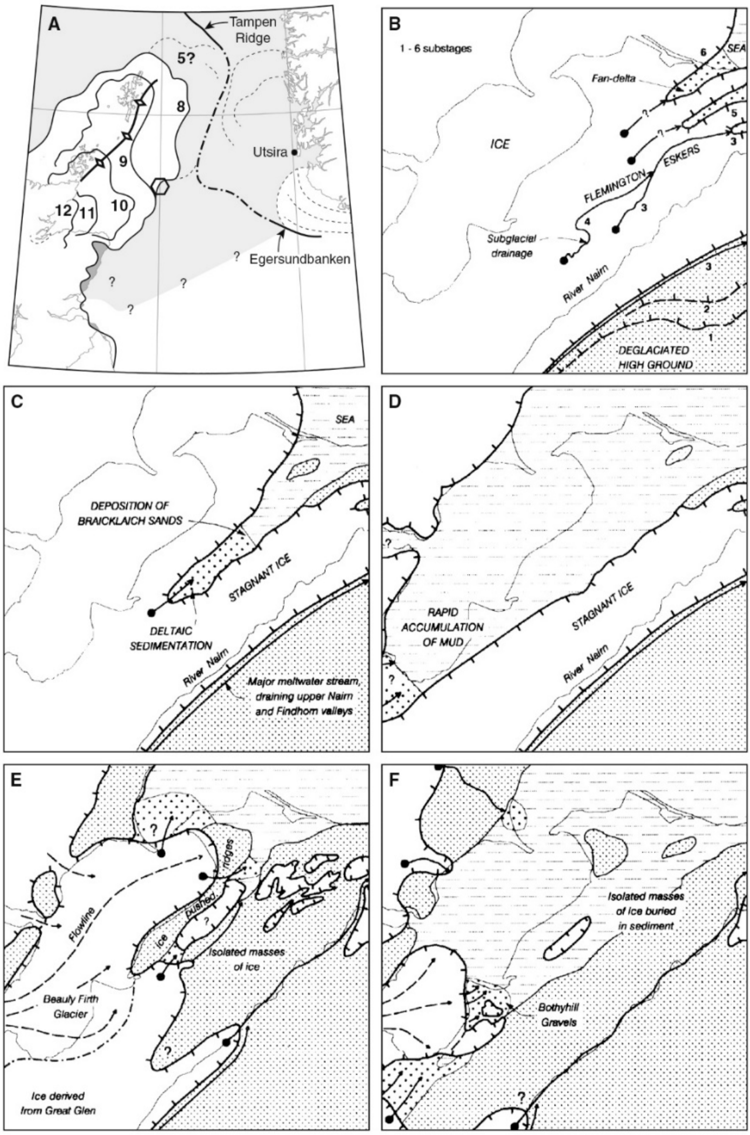

Figure 15. Palaeo-geographical reconstructions showing stages in the deglaciation of the Moray Firth. (A) early limits after Clark et al. (2012) with stages 5 to 12 of Merritt et al. (2017) {stages 5 and 6 at 22-19 ka; stage 7 at 19 ka; stage 8 at 18-17.5 ka; stage 9 at 17.5-16.2 ka; stage 10 at 16 ka; stage 11 at 16-15 ka; stage 12 (Elgin Oscillation) at c.15 ka}. Hexagon represents the centre of the Witch Ground Basin. Ice divide shown by thick black line with open diamonds. (B to F) stages in the deglaciation of the Inverness Firth after Merritt et al. (1995).

Meltwaters that issued from the Findhorn Valley upstream of Tomatin drained north-westwards through Strathdearn ('Moy Gap') (Young, 1980) and into lower Strathnairn, where they cut flights of ice-marginal channels into the north-facing slopes of the valley, as at **Clava** and **Piperhill** (Fig. 14). These features are associated with terraces and lateral morainic deposits (BGS, 1997). On further retreat, meltwaters created impressive, but now largely destroyed, systems of parallel eskers in **Upper Strathnairn,** at Midlairgs and Little Mill (Gordon, 1993). Extensive ponding occurred high on the eastern flanks of the Great Glen during deglaciation and meltwater drained into the Nairn (and possibly Findhorn) valleys at declining elevations, whilst the Ness outlet glacier retreated towards its sources in the Northwest Highlands (Boston et al., 2013).

Evidence for changes in relative sea-level (RSL) associated with glacial readvances around the Inverness Firth.

Early deductions for RSL during deglaciation. The first comprehensive models stemmed from the work of Kirk *et al.* (1966), Smith (1968, 1977), Synge (1977) and Synge and Smith (1980). The earliest stage was attributed to a general down-wasting and retreat of ice that resulted in the creation of a suite of glaciofluvial terraces, ten of which can be recognized in the Ness Valley, at the mouth of the Great Glen. Both Smith and Synge concluded that ice mainly issuing from the Great Glen into the Inverness Firth initially retreated as far west as Inverness, where they identified a controversial shoreline fragment at 42 m OD. The ice subsequently re-advanced north-eastwards to terminate at the **Ardersier Peninsula** during the *'Ardersier Readvance'*, when a lateral moraine was created between Castle Stuart and Ardersier and the promontory at Fortrose formed as a 'kame moraine' (Fig. 14). A still-stand at **Alturlie Point** interrupted retreat back towards Inverness and Kessock, where meltwaters formed extensive marine deltas whilst RSL stood at 33-34 m OD. The ice then retreated westwards along the Beauly Firth to Englishton, whilst RSL stood at 34 m OD, and south-westwards down the

Great Glen to Drumnadrochit, where they cited evidence that a proglacial lake had formed at 54 m OD, ponded behind a barrier of glacial drift in the valley of the River Ness, at the mouth of the Great Glen.

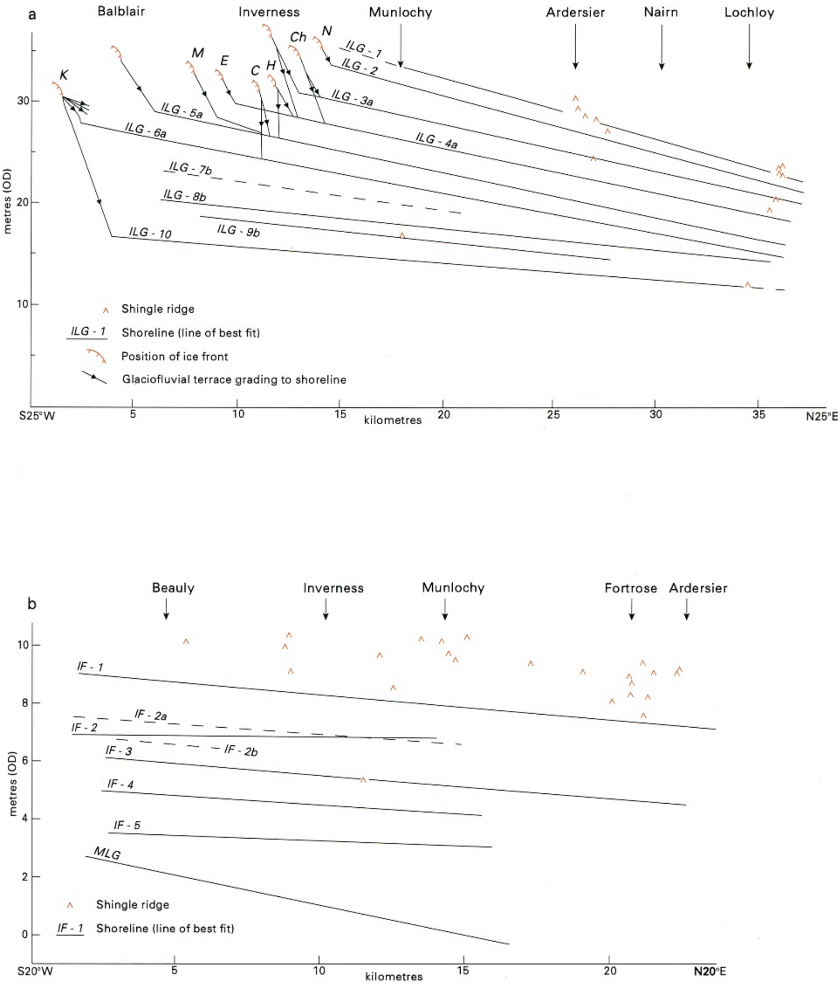

Figure 16. Height-distance diagrams of raised shorelines around the Beauly and Inverness Firths (from Fletcher et al., 1996). (a) Late-glacial shorelines ILG 1 to 10 (modified after Firth, 1989, fig.7). C, Contin; Ch, Charlestown; E, Englishton; H, Highfield; K, Kiltarity; M, Muir of Ord; N, North Kessock. (b) Main Late-glacial Shoreline (MLG) (probably Younger Dryas in age) and Holocene (Flandrian) shorelines IF 1 to 5 (modified after Firth and Haggart, 1989, fig.5).

Synge (1977) proposed that RSL fell to an altitude close to that of the present-day whilst the ice-margin remained at Englishton and a large outwash fan formed on the southern shore of the Beauly Firth. Meanwhile the barrier of glacial drift in the Ness Valley was breached and the level of Loch Ness fell from 54 m to 46-47 m and then 37 m OD.

This fall in the lake level was associated with punctuated retreat of the ice-front south-westwards along the Great Glen to Foyers and beyond. Controversially, Synge and Smith (1980) postulated that various outwash fans around the Beauly Firth formed whilst RSL rose back to 29 m OD and that the sea invaded Loch Ness during this transgression, forming shorelines at between 28 and 31 m OD around the loch and in the valley of the River Ness. The latter were considered to be of particular significance, because they apparently truncated older, more steeply-sloping outwash terraces associated with earlier, lower RSLs. This so-called 'Contin-Balblair' stage was followed by a fall in RSL whilst deglaciation was completed.

The current model of RSL changes during ice-sheet deglaciation. Following comprehensive, systematic levelling and associated palaeo-environmental investigations, Firth (1984) concluded that there was no evidence to substantiate either the Ardersier Readvance (Firth, 1989b), or any late-glacial marine transgression into Loch Ness (Firth, 1986). He proposed a simpler model of deglaciation associated with progressive, uninterrupted fall in RSL from about 35 m OD to present-day sea-level at Inverness. He identified ten glacio-isostatically tilted raised shorelines of Late Devensian age (Firth, 1984; 1989a) (Fig. 16), each one sloping downwards towards N025° at progressively gentler gradients of between 0.57 and 0.15 m/km (Fig. 17). The gradients indicated that the rate of ice-sheet retreat varied from one place to another depending upon whether the margin terminated in the sea, where rates of retreat were rapid, or was land-based, where retreat was slower. The most laterally extensive of these shoreline fragments are preserved to the east of **Kingsteps**.

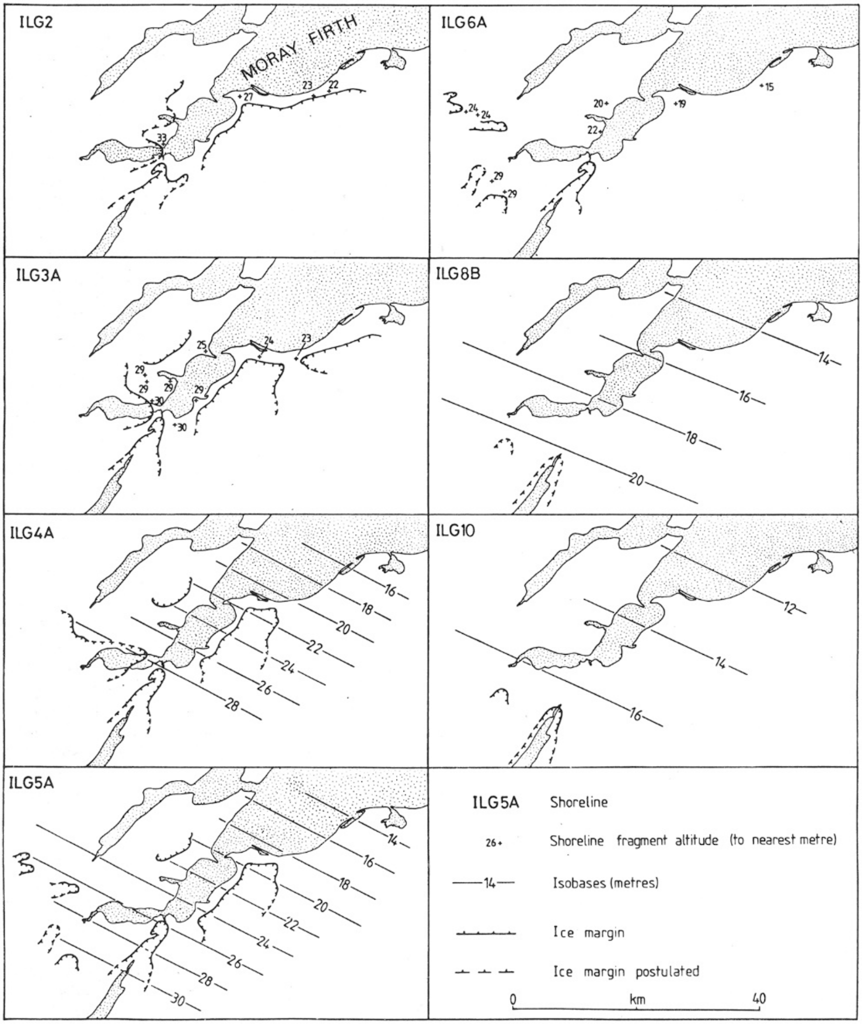

Figure 17. Isobases of raised shorelines with their associated ice-margins around the Beauly and Inverness Firths (after Firth, 1989a). Isobases are given for the best-developed shorelines only, otherwise altitudes of shoreline fragments are quoted to the nearest metre.

To the north-east of Inverness, and as far as Forres, some 40 km from the city, Firth (1984) reported that large tracts of moundy, ice-contact topography lie inland, and below the elevation of the highest Late

Devensian marine shoreline (the 'marine limit'), yet include little if any evidence of any marine incursion. These low-lying areas were therefore considered to have remained either beneath glacier ice, or sediment containing buried ice-masses, until RSL had fallen to less than 13 m OD. The absence of marine fossils in sediments cored within several large kettleholes, such as at **Alturlie Point**, supported the view that some ice remained buried seaward of the marine limit while RSL fell (Firth, 1984).

However, the widespread occurrence of deltaic sequences within the marine limit suggests that the ice occupying the Inverness Firth must have retreated substantially in order to create the deep water into which the deltas prograded (Merritt et al., 1995). The ice within the firth probably progressively uncoupled from adjacent land-based ice, forming a tidewater outlet glacier beyond which fine-grained silty sediments were deposited, such as at **Cloddy Moss**, several kilometres from the contemporary ice terminus (Fig. 15B). Unlike the land-based ice, which either stagnated or slowly retreated, the tidewater glacier was likely affected by minor changes in RSL as its mass balance would have been determined mainly by the rate of iceberg calving (cf. Boulton and Deynoux, 1981). Following a critical re-examination of key sites on the **Ardersier Peninsula,** Merritt et al. (1995) established that there had indeed been a significant glacial readvance at Ardersier (Fig. 15E), but that it occurred earlier than envisaged by Smith and Synge (1980). In order to avoid possible confusion they suggested that it should be known thenceforth as the *'Ardersier Oscillation'* (Fig. 15). RSL probably stood at 35 m or more above OD during the subsequent still-stand at **Alturlie Point** (Fig. 15F), which was possibly associated with a minor raising of RSL (Merritt et al., 1995). Significantly, cobbles of 'Inchbae' augen gneiss are commonly found in the deltaic gravels at Alturlie, whereas they have been rarely recorded elsewhere around the Moray Firth. These cobbles, derived from Carn Chuinneag, in Easter Ross (Fig. 8), suggest that ice issued from the Beauly Firth into the Inverness Firth basin after the Great Glen outlet glacier had retreated past the location of Inverness.

Recent results of geophysical surveys in Loch Ness suggest that the margin of the Great Glen glacier terminated in water throughout its retreat (Turner et al., 2012). It had a lightly grounded, or potentially floating, ice shelf at the mouth of the glen, but subsequently retreated to a more grounded position in the Loch Ness basin, where a major cross-glen moraine was created during a stillstand at Foyers. Subsequent retreat of the glacier was punctuated by further stillstands and oscillations.

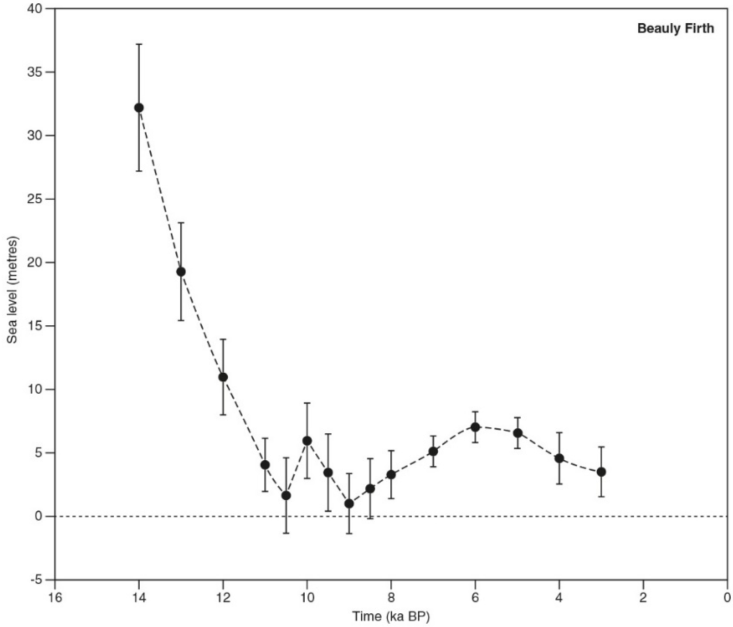

Figure 18. Sea level curve for the head of the Beauly Firth (after Lambeck, 1995)

RSL changes during the Loch Lomond Stadial and Holocene. The Beauly and Inverness firths are bordered by a prominent, laterally extensive abandoned cliff line that was generally thought to have been created by marine erosion during the Holocene. However, Sissons (1981a) proposed that this '*Main Postglacial Cliff Line*' had been formed mainly in the cold climate of the Loch Lomond Stadial (LLS) (Younger Dryas) and that the feature had only been trimmed subsequently during the mid- Holocene.

The cliff line is associated with an extensive raised shoreline that slopes north-eastwards from a maximum height of about 2 m OD at the head of the Beauly Firth (Fig. 16 MLG) and probably correlates with the 'Main Late-glacial Shoreline' of the Forth Valley (Sissons, 1969, 1974, 1976): it slopes at a gradient of 0.20 m/km (Firth and Haggart, 1989). Peacock (1977) proposed that cobble gravels underlying the low-lying ground at Longman, adjacent to the Kessock Bridge, were the topset beds of a delta that formed by successive floods from the Great Glen during the LLS (Merritt et al., 1995; BGS, 1997). Sissons (1981a) maintained that such coarse material was more likely to have formed in a single event, proposing that it resulted from the catastrophic drainage of the 260-m, ice-dammed lake in Glen Roy/Glen Spean towards the end of the LLS. He argued that the lake drained beneath ice to Fort Augustus and then via Loch Ness and the Ness Valley to the sea at Inverness.

The RSL curve for the Beauly-Inverness area (Fig. 18) has been derived from detailed morphological, stratigraphical and palaeobiological investigations carried out mainly at the head of the Beauly Firth by Haggart (1982, 1986, 1987, 1988) and Firth and Haggart (1989; 1990). Haggart (1982, 1986) demonstrated that estuarine sediments lying at 6.0 m OD were abandoned there whilst RSL fell. He correlated these 'Barnyards Beds' with the 'Main Buried Beach' of the Forth Valley, which has a radiocarbon age of 9.6k BP (Sissons, 1966). RSL continued to fall until it reached a low-stand at about 8. 8k BP (Haggart, 1986). It subsequently rose to 9.0 m OD at Beauly (7 m OD at Ardersier), when the highest Holocene shoreline formed (Fig. 16b, IF1). This shoreline slopes towards N015° at a gradient of 0.76 m/km and is correlated with the 'Main Postglacial Shoreline' of eastern Scotland (Sissons *et al.,* 1966). It has a radiocarbon age of between 7.1k and 5.8k BP (Firth and Haggart, 1989) and formed at the culmination of the 'Main Postglacial Transgression' in the area, when the isostatic recovery of the land was outstripped by a rapid phase of eustatic rise in sea level. Its abandonment resulted from a slackening in the rate of eustatic rise such that the continued isostatic recovery, though itself diminishing in rate, lifted the shoreline and its associated estuarine flats clear of the sea (Cullingford et al., 1991). The late-Holocene witnessed mainly falling RSL interrupted by 4 or 5 minor transgressive events (Fig. 16b, IF2-1F5) (Firth and Haggart, 1989). Woodworth (1987) has suggested that RSL movement in the region is currently minimal, however, the saltmarshes bordering the Beauly, Cromarty and Dornoch Firths are currently degrading, which indicates that relative sea level is rising.

It is worthy of note that the Inverness area is a seismically active region. Three major earthquakes due to movements on local faults were experienced in 1816, 1890 and 1901. Each caused considerable damage, especially the 1901 event which reached magnitude 5 on the Richter scale and was followed by aftershocks felt well beyond this district (Browitt et al., 1976; Musson et al., 1987).

Quaternary lithostratigraphy

The traditional approach of establishing lithostratigraphical relationships and correlations has been used to help decipher the particularly complex sequence of events and glacial interactions that have occurred in the region (Fletcher et al., 1996; Merritt et al., 2003; 2017). The earlier informal 'series' (Synge, 1956; Sutherland, 1984) 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. Non-glacial, terrestrial sediments, periglacial deposits and soils that provide important biostratigraphical and geochronometric evidence are included in the *Britannia Catchments Group*. Coastal marine and estuarine deposits are placed in the *British Coastal Deposits Group*.

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 (Fig. 19). The 'inland series' of Hall (1984) has become the

East Grampian Glacigenic Subgroup (EGGS), whereas deposits laid down by ice that followed circuitous routes from the western Central Highlands are assigned to the *Central Grampian Glacigenic Subgroup* (CGGS). Ice that flowed from the NW Highlands across outcrops of the ORS laid down relatively sandy, gravelly tills of the *Inverness Glacigenic Subgroup* (IGS). Each subgroup includes formations, members and beds (abbreviated to Fm, Mb and Bd respectively). The distribution of the glacigenic subgroups shown in Fig. 19 indicates where sandy till of the IGS (*Athais Till Fm*) underlies metasandstone-rich till of the CGGS (*Beinn an Uain Till Fm*) laid down in a later phase of glaciation (Table 2). The *Finglack Till Fm* represents the surficial diamict of the IGS within the mouth of the Great Glen and across the Black Isle where ice flowed out into the Moray Firth.

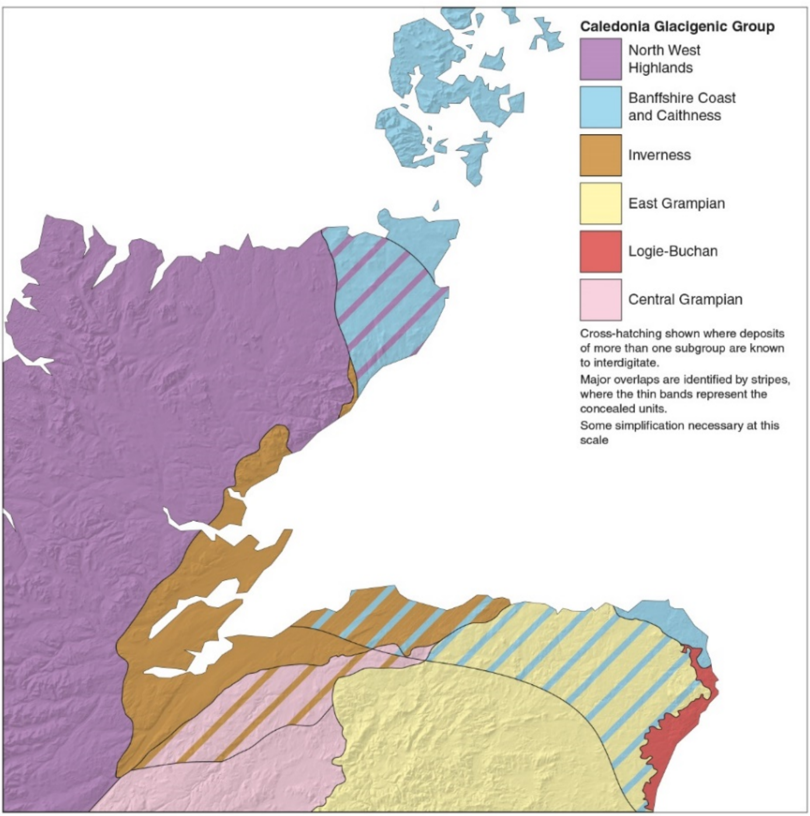

Figure 19. Subgroup lithostratigraphy.

Three formations of raised glaciomarine deposits (Ardersier Silts Fm, Alturlie Gravels Fm and Grange Hill Sand Fm) have been mapped extensively along the southern shore of the Inverness and Inner Moray firths south-east of Forres. These formations were probably laid down in a seasonally frozen fjord that lay beyond the oscillating tidewater margin of the Moray Firth Ice Stream (Merritt et al., 1995). The bottomset beds of marine deltas and subaqueous fans that prograded in front of the tidewater glacier during still-stands and minor readvances have been assigned to the *Ardersier Silts Fm*, whereas the foreset and topset beds of such bodies are included in the *Alturlie Gravels Fm* Type sections are found on the **Ardersier Peninsula** and at **Alturlie Point** respectively. Towards Elgin, around **Grange Hill** and **Mosstowie**, the Grange Hill Sand Fm appears to pass laterally, or inter-finger with fossiliferous raised estuarine deposits of the *Spynie Clay Mb* of the *Errol Formation* (Peacock, 1999; Merritt et al., 2003). Type sections of the Grange Hill Sand Fm are established at Grange Hill and in the pit on the Kinloss Country Golf Course at Miltonhill.