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Late Devensian deglaciation of the Tyne Gap Palaeo-Ice Stream, northern England

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Abstract

The deglacial history of the central sector of the last British-Irish Ice Sheet is poorly constrained, particularly along major ice-stream flow paths. The Tyne Gap Palaeo-Ice Stream (TGIS) was a major fast-flow conduit of the British-Irish Ice Sheet during the last glaciation. We reconstruct the pattern and constrain the timing of retreat of this ice stream using cosmogenic radionuclide (^{10}Be) dating of exposed bedrock surfaces, radiocarbon dating of lake cores and geomorphological mapping of deglacial features. Four of the five ^{10}Be samples produced minimum ages between 17.8 and 16.5 ka. These were supplemented by a basal radiocarbon date of 15.7±0.1 cal. ka BP, in a core recovered from Talkin Tarn in the Brampton Kame Belt. Our new geochronology indicates progressive retreat of the TGIS from 18.7-17.1 ka BP, and becoming ice free prior to 16.4-15.7 ka BP. Initial retreat and decoupling of the TGIS from the North Sea Lobe is recorded by a prominent moraine 10-15 km inland of the present-day coast. This constrains the damming of Glacial Lake Wear to a period prior to ~18.7-17.1 ka BP in the area deglaciated by the contraction of the TGIS. We suggest that retreat of the TGIS was part of a regional collapse of ice-dispersal centres between 18-16 ka BP.

Key Words: Tyne Gap; palaeo-ice stream; radiocarbon dating; cosmogenic surface exposure dating; British-Irish Ice Sheet.

1. Introduction

The investigation of palaeo-ice sheet beds is critical to the assessment of recent and future changes in contemporary ice-sheets and for understanding the controls that influence their behaviour. However, despite the wealth of geomorphological and sedimentological evidence on the pattern of ice-flow in the central sector of the last British-Irish Ice Sheet (BIIS) (e.g. Livingstone *et al.,* 2008, 2010a, 2012; Evans *et al.,* 2009; Davies *et al.,* 2009, 2012), the timing and rate of its retreat are poorly constrained (Chiverrell and Thomas, 2010; Hughes *et al.*, 2011; Clark *et al.*, 2012). This is significant as the development of a robust geochronology is essential for correlating complex ice-flow phasing across different sectors of the last BIIS and for relating ice-dynamic behaviour to internal and external forcing mechanisms.

The mountainous spine of the central sector of the BIIS (northern Pennines and Southern Uplands) was characterised by high elevation cold-based plateau ice caps bisected by eastward draining terrestrial ice streams such as the Forth, Tweed, Tyne and Stainmore (Fig. 1) (e.g. Everest *et al.,* 2005; Davies *et al.,* 2009, 2011; Livingstone *et al.,* 2010a). Upland ice-dispersal centres such as the Cheviots, Southern Uplands, Lake District and Pennines played an important role in seeding and modulating ice flow through these fast-flowing corridors, and thus in controlling the relative dominance of the Irish Sea Ice Stream (ISIS) and North Sea Ice Lobe (NSL), both of which have their onset zones in this region (e.g. Livingstone *et al.,* 2012). This is reflected in the geological record, which indicates complex, multi-phase ice-flow behaviour and repeated marginal fluctuations (Livingstone *et al.*, 2008, 2012; Evans *et al.,* 2009).

Of the four palaeo-ice stream corridors, only the Forth is associated with any direct age control. This is from shells (*Nuculana pernula*) in a marine unit in the Firth of Forth, which provides a minimum age of 16.2±0.1 cal. ka BP for ice stream recession (Hedges *et al.,* 1988). Elsewhere, ^{10}Be surface exposure ages on four Shap granite erratics in the Vale of Eden, immediately to the west of the Stainmore Ice Stream, indicate that the Vale of Eden was deglaciated by ~17 ka BP (Wilson *et al.,* 2013) (Fig. 2). This is coincident with widespread thinning and retreat of ice in the Lake District (Hughes *et al.,* 2011; Wilson and Lord, 2014). In the Solway Lowlands, west of the Tyne Gap, an age of 14.4±0.4 ka BP from a bulk sample in a basal peat unit (Bishop and Coope, 1977) provides a minimum age for ice free conditions. With the exception of these examples there is limited dating control constraining deglaciation of the central sector of the last British-Irish Ice Sheet and almost no chronology for the four key east draining palaeo-ice stream corridors.

This paper focuses on the Tyne Gap Ice Stream (TGIS), which flowed eastwards towards the mouth of the River Tyne through a predominantly bedrock-floored, 15 to 30 km wide mountainous pass located between the Cheviot Hills and English Pennines (Figs. 1, 2). The TGIS was fed by ice from dispersal centres in the Lake District and Southern Uplands and was a major tributary of the NSL, which flowed southwards down the east coast of England (Eyles *et al.,* 1994; Davies *et al.*, 2011). The aim of this paper is to reconstruct the pattern and constrain the timing and rate of retreat of the TGIS, using cosmogenic radionuclide dating of exposed bedrock surfaces and radiocarbon dating of lake cores, combined with geomorphological mapping of deglacial features. Furthermore, the paper explores the implications of TGIS retreat for changing BIIS dynamics during deglaciation.

2. Glacial geomorphological context

The Tyne Gap corridor is heavily streamlined below 400 m asl, with lineations typically <1.5 km long, although forms up to 4 km have been observed (Figs. 1, 3, 4a). Lineations are composed of both till and bedrock, including visually striking streamlined bedrock ridges controlled by the geological structure (Livingstone *et al.,* 2010a; Krabbendam and Bradwell, 2011), particularly evident in the western Tyne Gap region (Fig. 3). This has resulted in obliquely-angled lineations, which may have formed during a single ice-flow phase (Livingstone *et al.*, 2010a). The ridges often display a distinctive asymmetry, with steep north and west faces and gently dipping southern and eastern flanks (Krabbendam and Bradwell, 2011) (Fig. 3). This is explained by the distinctive geology, which comprises Lower Carboniferous sedimentary rocks composed of rhythmic sequences of limestone, shale, sandstone, greywacke and coal (units 5-20 m thick) intruded in places by the resistant strata of the Whin Sill dolerite that dip ~10-20° SSE towards the edge of the northern Pennines (Krabbendam and Bradwell, 2011). Further to the NE the strike of the strata swings around to the NNE, with a dip of ~5-10° to the east. This was transverse to ice-flow, resulting in crag-and-tail features where till has been smeared across the ridges (Krabbendam and Bradwell, 2011). Till is more extensive in this region, with more subdued lineations orientated east to ENE.

Geomorphological mapping has revealed three distinct flow sets (Livingstone *et al.,* 2008, 2010a): (1) a central trunk zone of W-E to SW-NE lineated terrain; (2) lineations stretching SE down the North Tyne Valley; and (3) a small set of N-S orientated lineations trending down the NE coast (Fig. 3a). Flow set 1 records convergent ice-flow sourced from the Lake District and Scottish Southern Uplands, supplemented by locally-sourced ice flowing into the main artery from the northern Pennines. During this time, ice overtopped the Tyne Gap and flowed towards the east coast as a topographically-controlled ice stream (Beaumont, 1971; Bouledrou *et al.,* 1988; Livingstone *et al.,* 2010a). Subtle differences in lineation orientation (Fig. 3) reflect the sensitivity of the ice stream to western ice-dispersal centres (Livingstone *et al.,* 2008). Towards the east coast lineations become more subdued and eventually are overprinted by flow set 3. The second flow set, trending SE down the North Tyne Valley, documents the subsequent weakening of the Tyne Gap as an easterly draining ice stream and increased dominance of Southern Upland ice (Livingstone *et al.,* 2010a). This probably coincided with inland extension of the southwards flowing NSL (flow-set 3) (Davies *et al.,* 2009, 2012).

Meltwater channels and a prominent moraine ('Crowden Hill Moraine'; Figs. 4, 6) at the eastern end of the main W-E orientated flow set records nascent retreat of the TGIS into the Tyne and Wear Lowlands or an ice-marginal position of the NSL (Smythe, 1912; Livingstone, 2010a; Teasdale, 2013). Along the shallower western flank of the moraine triangular-shaped deposits of glacial sand and gravel have been observed within present-day river valleys (Smythe, 1912). These have been interpreted as outwash deposits from small lakes ponded against higher ground inland of the NSL (Teasdale, 2013). Westward retreat of the TGIS resulted in an extensive proglacial drainage system in the ice-free area between the NSL and TGIS (Davies *et al.,* 2012; Yorke *et al.,* 2012), terminating to the east in a major proglacial lake, Glacial-Lake Wear (Smith, 1994; Teasdale and Hughes, 1999). Ice-marginal and ice-contact deposits in the lower Tyne Valley recorded periods of stagnation and *in situ* downwasting (Yorke *et al.,* 2012). This proglacial system can be traced along the Tyne Valley to the west as far as the Brampton kame belt, a major glaciofluvial complex formed where ice stagnated in the lee of the Pennines (Trotter, 1929; Livingstone *et al.,* 2010b). At some point during deglaciation of the TGIS a switch in ice flow resulted in drawdown into the Solway Lowlands and Irish Sea Basin out of Bewcastle Fells and the Vale of Eden (Livingstone *et al.,* 2008, 2010c, 2012).

3. Field and laboratory methods

3.1 Geomorphological mapping

Glacial geomorphological mapping of palaeo-ice-flow from glacial lineations, and the derivation of flow-sets and relative timings based on cross-cutting relationships has been presented by Livingstone *et al.,* (2008, 2010a) and is summarised above and on Fig. 4a. This is supplemented here by detailed mapping of deglacial features, including: moraines, glaciofluvial deposits and meltwater channels, from NEXTMap (5 m resolution) and LiDAR data (1 m resolution) to reconstruct glacier geometry and ice-marginal positions during retreat.

3.2 Cosmogenic nuclide (^{10}Be) surface exposure dating

3.2.1 *Sampling strategy*

Samples for cosmogenic nuclide (^{10}Be) surface exposure dating were taken from five glaciated bedrock surfaces at locations along the length of the Tyne Gap to constrain palaeo-ice stream retreat (Figs. 4b and 5). All samples were from quartz-rich Carboniferous sandstones from the Stainmore Formation, Fell Sandstone Group and Border Group. Sites were chosen that showed evidence of glacial erosion, such as abraded and striated surfaces or roches moutonnées, to minimize the possibility of bedrock inheritance. Sampling sites that have had, or continue to harbour snow, vegetation or sediment cover were avoided. Samples were collected using a rock saw, which allowed the removal of intact surface blocks (10x10x4 cm; c. 3 kg) at least 30 cm from all outcrop edges. Sampled surfaces were roughened post sampling or filled to avoid leaving unsightly unnatural cuts in the bedrock. All samples had their position, altitude, topographic shielding, surface dip/direction, dimension, and surface characteristics (pitted/spalled) recorded.

3.2.2 *Sample preparation*

Samples were prepared at the Cosmogenic Isotope Analysis Facility (CIAF) in the Scottish Universities Environmental Research Centre (SUERC). Quartz was isolated from other minerals by mechanical (crushing, grinding, magnetic separation) and chemical (hexafluorosilicic acid treatment and hydrofluoric acid leaching) procedures. In this study 220 μg ^{9}Be was added as a carrier to each sample. ^{10}Be extraction and target preparation followed procedures modified from Kohl and Nishiizumi (1992) and Child *et al.,* (2000). The

$^{10}Be/^{9}Be$ ratios of mixed BeO-Nb targets were measured with the 5 MV accelerator mass spectrometer (AMS) at SUERC (Xu *et al.*, 2010). The Be ratios were converted to nuclide concentration in quartz. The processed blank $^{10}Be/^{9}Be$ ratio was between 2 and 6 % of the sample $^{10}Be/^{9}Be$ ratios and was subtracted from the measured ratios. Details of sample locations and relevant analytical data are given in Table 1.

3.2.3 *Exposure age calculation*

The exposure ages were calculated using the Cronus-Earth online calculator v. 2.2 (http://hess.ess.washington.edu/) and are presented in Table 1. ^{10}Be ages are calculated using a ^{10}Be half-life of 1.36 Ma and the SLHL production rate of 4.39±0.37 atoms g^{-1}-a^{-1} (Lm scaling) obtained from age-constrained calibration measurements (Balco *et al.*, 2008). In order to decrease the scaling uncertainties, we calculated the exposure ages using a locally derived production rate of 3.99±0.13 atoms g^{-1}-a^{-1} (Lm scaling; NWH LPR) based on a deglaciation age of 12.2 ka from the NW Scottish Highlands (Ballantyne & Stone 2012; Ballantyne, 2012). Thus the ages calculated using the local production rate become older and more precise than ^{10}Be ages calculated using the global production rate. Although the NWH LPR is not independently constrained, it matches the LLPR (Loch Lomond production rate) of 3.92 ± 0.18 atoms g^{-1}-a^{-1} (Lm scaling; Fabel et al., 2012; Fabel et al., in prep). The LLPR was calculated using the ^{10}Be concentration in boulders located on the Loch Lomond terminal moraine and is independently constrained by radiocarbon dating (MacLeod et al., 2011).

The calculated age uncertainties are expressed as 1σ error (Table 1). Corrections for sample thickness (4-5 cm) assume an exponential depth decrease of *in situ* production rate and an attenuation length of 160g cm^{-2}. Carboniferous sandstone surfaces show evidence of granular disintegration. We have therefore calculated exposure ages based on both zero erosion of sampling surfaces and for an erosion rate of 1 mm/ka to investigate the effect of bedrock erosion on sample age. Topographical and geometrical shielding were taken into account when calculating the exposure ages (Table 1). No correction was made for snow shielding because of the difficulty in constraining long-term snow cover. Any correction for snow shielding and bedrock erosion would increase the nuclide concentrations (and implicitly the ages), thus all reported ^{10}Be ages calculated with zero erosion in this study are regarded as minimum ages.

3.3 Radiocarbon dating

3.3.1 *Lake coring, sample preparation and age calculation*

Core samples from two small lakes were taken using a Russian-pattern corer (50 cm in length) from a small inflatable boat. Material for radiocarbon dating was sampled at Talkin Tarn, within the Brampton Kame Belt, and Crag Lough (Fig. 2; Table 2). Pre-treatment and AMS radiocarbon analyses of the samples (Beta-342469, -342470, -342471) was undertaken at the BETA Analytic Laboratories, following their standard procedures (http://www.radiocarbon.com/pretreatment-carbon-dating.htm). The peat sample (L2) from Crag Lough was subjected to an acid-alkali-acid pre-treatment process to eliminate carbonates and secondary organic acids. Due to the absence of macrofossils, samples L1a and L1b from Talkin Tarn were both from bulk organic fractions. These samples underwent repeat acid washes to ensure removal of carbonates. It is acknowledged that bulk organic samples may include some minor components of old carbon, resulting in age overestimations, typically of ~1000 years (e.g. Hågvar and Ohlson, 2013). Thus, although we are dating deglacial lake sediments that provide a minimum age for the onset of ice-free conditions, the bulk organic sediments are maximum age measurements. To ease comparison of radiocarbon and cosmogenic nuclide chronologies, all radiocarbon ages are presented in calibrated form using Calib 7.0.4, the IntCal13 curve (Reimer *et al.,* 2013), a marine ΔR of -525 years where appropriate (see also Chiverrell et al., 2013) and giving the 1 sigma error range in cal. ka BP.

3.4 *Bayesian analysis of deglacial chronology*

To provide further constraints on the deglaciation of the TGIS we constructed a 'prior model' of the expected chronological order of ice retreat reasoned solely from glacial geomorphological evidence (after Chiverrell *et al.,* 2013). Bayesian modelling was implemented using a simple Sequence model in Oxcal (http://c14.arch.ox.ac.uk; Ramsey, 2009), which requires the dated events to be in chronological order, and uses Markov Chain Monte Carlo sampling to form a probability distribution of dates through the sequence. The result is a *posterior* density, which is a product of the *prior* model and *likelihood* probabilities. To run the model we divided the TGIS into three sub-regions ('before inner TGIS', 'inner TGIS' and 'after inner TGIS'), which share common relationships and are separated by Boundary commands. We used a Phase command for the inner TGIS sub-region as relative ages are more difficult to define because of the additional complication of ice-flow down the North Tyne Valley (Livingstone et al., 2010a). Ages that did not fit the sequence were declared as outliers and excluded from the model.

4. Results

4.1 *General geomorphology*

Glacial geomorphological mapping of meltwater channels, glaciofluvial deposits and moraine hummocks and ridges has revealed three significant ice-marginal positions within the TGIS corridor (Fig. 4b, labelled 1-3). The eastern-most ice-margin position is delineated by a prominent moraine ~60 m asl, which stretches over 30 km S/SE from the River Croquet to the River Tyne. This is the extension of the 'Crowden Hill Moraine', previously identified by Smythe (1912) and Teasdale (2013).

A second ice-margin position (Thorneyford Moraine), 10-15 km further inland, is marked by a discontinuous series of ridges arranged in a lobate configuration, bisected at the northern end by flights of short SW-NE orientated meltwater channels (Fig. 6). To the east of the Thorneyford Moraine (Fig. 6) there are two flat-bottomed basins and a number of straight to sinuous channels that cut across higher ground on the eastern flank of the basins. The terrain to the west of the Thorneyford moraine comprises W-E orientated lineations associated with the main ice-flow phase. A third, less distinct ice-marginal position (North Tyne Moraine) is identified by a series of small moraine ridges, hummocky moraine and/or glaciofluvial deposits within the North Tyne Valley. This still-stand position is associated with the NW-SE flow-set.

4.2 *Overview of individual sites*

Most of the sites sampled for cosmogenic surface exposure ages occur within the central corridor of the palaeo ice stream with the exception of sample TY4. TY1-3 and TY5 are in areas of glacially abraded terrain situated on bedrock highs controlled by the predominant strike of the local Carboniferous Sandstone. TY4 is situated on the northern edge of the ice stream corridor. With respect to the lake samples, Crag Lough is also situated within the main ice stream corridor, at the foot of a bedrock escarpment controlled by a NNW-SSE striking Whin Sill intrusion. In contrast, Talkin Tarn is located to the west of the main flow corridor in an area of hummocky ice stagnation terrain related to a later deglacial phase of the icestream (Livingstone *et al.,* 2010b).

Sample TY1 was taken from the upper flat surface of Pipers Rock (202 m asl), which is part of Shaftoe Crags, a large Carboniferous escarpment located in the central corridor of the main W-E flow set of the ice stream. The escarpment comprises interbedded argillaceous rocks and sandstone from the Stainmore Formation. The surface is covered with lichens and has been heavily weathered, with signs of granular disintegration, large pits and numerous runnels, up to 30 cm deep in places. The bedrock promontory is 2-3 m above local ground level and has clearly not been vegetated for some time.

Sample TY2 is from Rothley Crags (230m asl), a Carboniferous ridge trending roughly N-S. The ridge comprises interbedded argillaceous rocks and sandstone from the Stainmore Formation. The western leading edge has roches moutonnées indicating moulding during easterly ice flow. The sample was taken on the upper surface of a roche moutonnée from a stoss/mid location about 1-2 m above ground-level. There are fractures and joints and some surface weathering, with large pits up to 20 cm deep and also evidence of granular disintegration. However, weathering appears limited at the sample site. The rock surface is lichen covered and may have been vegetated in the past.

TY3 is from Snabdaugh Crags (221m asl), a Carboniferous outcrop trending roughly N-S, with a partially glacially abraded upper surface. The outcrop comprises interbedded argillaceous rocks and limestone from the Border Group. This region is associated with the later NW-SE flow phase down the North Tyne Valley. The sample was taken from the upper surface of a bedrock promontory 1-3 m above local ground level. There is some evidence of surface weathering, including spalling, rills, small pits (up to 5 cm) and granular disintegration.

TY4 was sampled at Simmonside (431m asl), a W-E trending Carboniferous sandstone ridge of the Fell Sandstone Group, upstanding above the surrounding landscape. This site has been mapped as the northern edge of the ice stream (Livingstone *et al.,* 2010a), and is altitudinally distinct from the other samples which occupy the floor of the Tyne Gap corridor. The sample was taken from the upper surface of a large pedestal rising up to 5 m above the surrounding terrain. The structure is part of a large crag comprising independent (~2x2 m) pedestals. There is some lichen cover and evidence of granular disintegration, spallation and large (~5 cm) weathering pits.

Sample TY5 was from Brierwood Hill (110m asl), a W-E trending whaleback towards the southern margin of the ice stream corridor (Livingstone *et al.*, 2010). The whaleback comprises interbedded argillaceous rocks and sandstone from the Stainmore Formation. The sample was taken from a bedrock surface up to 0.5 m above the local ground level. The surface does not show significant weathering, although some granular disintegration and spalling is evident. The rock is also lichen covered.

Two lake sites were identified as coring targets to supplement the cosmogenic nuclide samples. This included Talkin Tarn (L1), an enclosed kettle hole in the Brampton kame belt, and Crag Lough (L2), a natural lake formed in the northern lee of the Whin Sill, Tyne Gap (Fig. 4b).

4.2 *Chronology*

Cosmogenic ^{10}Be from Carboniferous Sandstone bedrock and basal radiocarbon ages from lake cores in the palaeo-ice stream corridor reveal the timing and duration of ice stream deglaciation (Figs. 4b, 5, 7). Sample TY4 (431 m asl) yielded an age of 47±1.9 ^{10}Be ka BP, which is anomalously old compared to the other samples. Given this, and its ice-stream marginal position, we suggest the surface suffered minimal erosion during the Late Devensian and can therefore be excluded from our geochronological model of ice retreat due to incomplete re-setting.

The remaining four cosmogenic samples were taken between 100-220 m asl, within the main trunk of the TGIS. The two most easterly samples, TY1 and TY2, returned ^{10}Be ages of 17.8±0.9 and 17.6±1.1 ka BP respectively. TY5, from the southerly edge of the palaeo- ice stream, provided a ^{10}Be age of 17.2±0.9 ka BP, whilst further west sample TY3 was dated to 16.5±0.8 ka BP. With an erosion rate of 1 mm/ka the ^{10}Be ages become 242 to 260 years older.

Radiocarbon ages were taken from two lake cores at Talkin Tarn (L1) and Crag Lough (L2). The Crag Lough sediment core was 2.0 m long, consisting of two bio/lithofacies, an upper brown-black well-humified peat with some sand and silt stringers, and a lower grey silty-clay (Fig. 8). The radiocarbon sample was taken directly above the lower contact at the base of the humified peat (300-301 cm) and provided an age of 13.1±0.04 cal. ka BP. The 0.5 m long Talkin Tarn sediment core comprises a lower light-brown to grey partially laminated silt with some sand and an increasing organic content up core (Fig. 9). A bulk sample taken from the base of this facies (L1a) at 971-972 cm depth provided an age of 15.7±0.1 cal. ka BP. A further bulk sample was taken at the top of the lower facies (948-949 cm depth), 1 cm below a prominent 5 cm sand layer (L1b). This provided an age of 13.6±0.07 cal. ka BP. Above the sand facies is a 6 cm grey silt facies followed by 46 cm of gyttja, which comprises the bulk of the sequence.

Bayesian modelling of this geochronology used a relative age order (cf Chiverrell *et al.,* 2013) characterised by westward retreat of the TGIS into the Solway Lowlands (Fig. 7). The geochronological results are compatible with this model, with samples to the west across a distance of ~55 km yielding progressively younger ages. The exception is the ^{14}C date at Lough Crag, which is too young, and is therefore considered an outlier. The model constrains the retreat of ice from the eastern edge of the TGIS to before 18.7-17.1 ka BP (Boundary Basal, Fig. 7), from the western edge of the TGIS to before 16.4-15.7 ka BP (Boundary after Inner TGIS, Fig. 7) and from Talkin Tarn, at the confluence between the TGIS and ice in the Vale of Eden, to before 15.7±0.1 cal. ka BP (Fig. 9).

5. Discussion

5.1 *Decoupling of the Tyne Gap Ice stream from the North Sea Lobe*

Previous mapping has established the ice-flow history of the TGIS (Livingstone *et al.,* 2008, 2010a). This demonstrates three clear flow phases: (1) a main W-E ice flow through the Tyne Gap discharging into the North Sea at Newcastle; (2) a later NW-SE flow down the North Tyne Valley, which infers a switch to a more northerly Scottish ice source into the Tyne corridor; (3) encroachment of the N-S flowing North Sea Lobe into the coastal lowlands of Northumbria and Durham (Fig. 4). However, the deglacial dynamics and timing of these competing ice flows are currently poorly understood.

Our new mapping and geochronology help to constrain the decoupling of the TGIS and NSL, and the formation of Glacial-Lake Wear. Of the three still-stand positions mapped, the Crowden Hill Moraine (No. 1 on Fig. 4) is geomorphologically distinct and has a NNW-SSE orientation. Its westward-facing convexity in planform suggests it does not relate to the TGIS as it began to retreat westwards; more likely it relates to the onshore movement of the NSL. This is supported by the previous work of Smythe (1912) and Teasdale (2013), who link this ice-margin position to the formation of regional ice-dammed lakes, such as Glacial Lake Wear (Fig. 4).

The Thorneyford Moraine (No. 2 on Fig. 4) has a nested, arcuate planform that indicates ice downwasting in a westwards direction. It is the first definitive evidence for the uncoupling of the TGIS from the NSL, and documents an ice-marginal location that would have provided the first opportunity for the formation of Glacial-Lake Wear. The previous mapping of this suggests a regionally extensive lake extending from the Tyne, southwards into County Durham and westwards into the Tyne Valley (Smith, 1994).

There is additional evidence for local damming of glacial lakes other than Lake Wear. To the west of the Thorneyford Moraine the terrain is clearly glacially streamlined, whereas to the east the terrain is composed of channels and two flat-bottomed basins previously reported as ice-marginal lakes impounded by the NSL in the vicinity of Ponteland (Teasdale, 2013). An alternative hypothesis is that these lakes were dammed by local topography in-front of the westerly retreating TGIS. Overspill channels decanting across higher ground to the east of the basins suggests this terrain was at least partially deglaciated at the time of their formation. The North Tyne Moraine (No. 3 on Fig. 4) is the least distinctive, but may mark the continued retreat of ice into the North Tyne system.

In order to dam Glacial-Lake Wear (Smith, 1994; Teasdale and Hughes, 1999) the NSL must have decoupled from the TGIS. At this time, the western edge of the NSL must have been located sub-parallel to the present east coast, damming the Tyne Valley. It is probable that this margin was coincident with the Crowden Hill Moraine, which extends south of the Tyne into County Durham where it is also associated with the formation of Glacial Lake Wear (Davies *et al.,* 2009; Teasdale, 2013). TY1 and TY2 provide maximum limiting dates for moraine two, which constrains the formation of Glacial Lake Wear to a period prior to 18.7 to 17.1 ka BP (Fig. 7, Boundary Basal), in the area deglaciated following contraction of the TGIS. This broadly agrees with dating control at Dimlington along the east coast of Yorkshire, which suggests the Skipsea Till, associated with the NSL, was deposited between 21.7 and 16.2 ka BP (Bateman *et al.,* 2011), while Glacial-Lake Humber was still in existence until 16.6 ka BP (Bateman *et al.*, 2008, 2011; Murton *et al.,* 2009).

5.2 Retreat of the Tyne Gap Ice Stream

The ^{10}Be surface exposure ages and ^{14}C radiocarbon ages recovered from bedrock and lake cores respectively indicate deglaciation of the TGIS from 18.7-17.1 ka BP, with progressive retreat from the east coast of England into the Solway Lowlands over a distance of ~55 km by 16.4-15.7 ka BP at the latest (Fig. 7). In particular, Bayesian modelling indicates that the basal ^{14}C radiocarbon age from Talkin Tarn is consistent with the ^{10}Be surface exposure age history (Fig. 7). Together these dates provide the first constraints on the deglacial history of the Tyne Gap region. At Crag Lough it appears there was a lag between deglaciation and the ^{14}C age that sampled a horizon stratigraphically higher in the deglacial sequence compared with the Talkin Tarn measurements.

Our new geochronology was unable to differentiate between the main eastwards ice-flow across the Tyne Gap and later SE ice-flow down the North Tyne. This favours ice-flow reorganisation rather than a two-phase model of TGIS retreat into the Solway Lowlands followed by re-advance of ice down the North Tyne Valley. This may be a product of eastward expansion of the Southern Upland-Scottish Highlands ice divide (Finlayson *et al.,* 2010; Livingstone *et al.,* 2010a) and increased topographic control during deglaciation (Hughes *et al.,* 2014). The Thorneyford and North Tyne moraines constrain the pattern of rapid retreat through the ice stream corridor as ice downwasted. At the eastern end of the corridor, Yorke *et al.,* (2012) demonstrate that retreat was accompanied by the widespread deposition of ice-marginal glaciolacustrine and glaciofluvial sediments, which may have fed down valley into Glacial Lake Wear during early deglaciation.

The Brampton Kame Belt records downwasting of ice at the confluence between the TGIS and ice in the Vale of Eden. The basal radiocarbon age of 15.7±0.1 cal. ka BP, from Talkin Tarn provides a minimum age for downwasting of the two ice streams and potentially limits the deglaciation of the Solway Lowlands. The timing of retreat out of the Tyne Gap raises questions over the timing of ice-drawdown and flow-phase switching in the Solway Lowlands (Livingstone *et al.,* 2010c, 2012). ^{10}Be surface exposure ages on four Shap granite erratics at the upstream head of the Vale of Eden (275-325 m asl), immediately to the west of the Stainmore Gap (Fig. 2), suggest ice-free conditions prevailed by ~17 ka BP (Wilson *et al.,* 2013a), and is consistent with widespread emergence of the Lake District during this period (cf. Wilson and Lord, 2014). Combined with our new geochronology, this evidence limits the window for complex flow-phase switching westwards into the Solway Firth (Blackhall Wood-Gosforth Readvance) to before 17-16 ka BP. Indeed, to account for the continued activity of the TGIS during this flow switch we need to invoke an ice divide across the Tyne Gap, allowing drainage of ice westwards into the Solway Firth and eastwards into the North Sea.

5.3. *Wider implications for the British Ice Sheet*

Livingstone *et al.,* (2012) produced a six-stage model of ice-flow history and behaviour in the central sector of the last BIIS (Fig. 10a). Our new mapping and geochronology has enabled us to further constrain and finesse this model (Fig. 10b).

Given that complex flow-phase switching westwards into the Solway Firth (Blackhall Wood-Gosforth Readvance – Stage IV) must have occurred before 17-16 ka BP, it is unlikely to be associated with the Killard Point Stadial, which reached its maximum ~16.5 ka (McCabe *et al.,* 2007). This supports our previous reconstruction, although the timing may have been slightly later (Fig. 10a, Livingstone *et al.,* 2012). The influence of this switch on the ice-flow history of the eastern Irish Sea Basin is poorly constrained. The ISIS is thought to have retreated back into the northern Irish Sea Basin by 22.6–20.9 ka, with relatively rapid retreat of the Western Irish Sea Basin by 20-19.1 ka BP (Chiverrell *et al.,* 2013). There is, therefore, no indication that flow-phase switching in the central sector of the BIIS was part of a wider pan-Irish Sea reorganisation.

The retreat of the TGIS from 18.7 to 17.1 ka, deglaciation of the Brampton Kame Belt by 15.7±0.1 cal. ka BP (Fig. 7) and the southern edge of the Vale of Eden by ~17 ka BP (Wilson *et al.,* 2013a), coupled with widespread thinning of Lake District ice between 17-15 ka BP (e.g. Ballantyne *et al.,* 2009; McCarroll *et al.,* 2010; Wilson *et al.,* 2013b) suggests widespread collapse of the southern and central source areas between about 18 and 16 ka BP (Fig. 10b). This occurred during a period when the NSL and ISIS both were both active and extended considerable distances southwards (e.g. Bateman *et al.,* 2011; Clark *et al.,* 2012). In the northern Irish Sea Basin, ice re-advanced at Killard Point, NE Ireland, sometime after 16.9±0.2 ka BP, reaching a maximum extent at ~16.5 ka BP (Killard Point Stadial - McCabe *et al.,* 2007). Optically stimulated luminescence ages ranging from 16.4-14.1 ka on Isle of Man outwash deposits provide further constraints (Thrasher *et al.,* 2009), while this event may also have been coincident with the Scottish Re-advance in the Solway Lowlands, although there is currently no age control. In eastern England the NSL, fed by Scottish ice emanating from the Forth and Tweed (Davies *et al.,* 2011), readvanced southwards to the Yorkshire coast, depositing the Withernsea Till within the period 16.2-15.5 ka (Bateman *et al.,* 2011; Roberts et al., 2013). Together, the geochronology implies that the smaller and lower latitude dispersal centres had already crossed a threshold for collapse and were no longer sustainable by 18-16 ka. Conversely, northern dispersal centres remained healthy and were able to respond to renewed climatic cooling possibly associated with Heinrich Event 1 at ~17-16 ka (e.g. McCabe and Clark, 1998; McCabe *et al.,* 1998, 2005, 2007; Bateman *et al.,* 2011; Chiverrell *et al.,* 2013; Roberts *et al.,* 2013).

6. Conclusions

There is considerable uncertainty over the timing and rate of retreat and complex flow phase switching in the central sector of the last British-Irish Ice Sheet during deglaciation. This makes it difficult to correlate ice-flow phases across the ice sheet and ultimately to identify and investigate controls (internal and external) governing ice-sheet behaviour. In this paper we present new ^{10}Be surface exposure and ^{14}C radiocarbon ages, which provide the first constraints on deglaciation of the TGIS corridor. This is supplemented by high-resolution mapping of deglacial features, including meltwater channels and moraine ridges and hummocks.

We demonstrate that westward retreat of the TGIS had begun by 18.7-17.1 ka BP and reached the Solway Lowlands by 16.4-15.7 ka BP. The first definitive evidence for retreat and uncoupling from the NSL is a prominent lobate moraine, 10-15 km inland of the present-day coast. ^{10}Be ages of 17.8-17.6 ka BP provide maximum bounds on the moraine's formation, and thus for the formation of Glacial Lake Wear in the area deglaciated by the retreating TGIS. Several smaller lakes also became dammed and overspilled across higher ground to the east of the TGIS during this still-stand. Our new geochronology is not of high enough resolution for us to differentiate between the W-E and later NW-SE ice flow phases. This short time window favours a reorganisation of ice flow rather than a separate late phase re-advance of ice down the North Tyne Valley.

An age of 15.7±0.1 cal. ka BP from Talkin Tarn provides a minimum age for deglaciation of the Brampton Kame Belt, which records downwasting of ice at the confluence of the TGIS and ice in the Vale of Eden. This indicates continued retreat of the TGIS into the Solway Lowlands and limits the timing of complex flow-phase switching westwards into the Solway Firth to before 17-16 ka BP.

Together with other published ages (cf. Wilson and Lord, 2014) our data indicate that southern ice dispersal centres (e.g. Lake District, Howgill Fells and Pennines) and their drainage outlets (e.g. Tyne and Vale of Eden) collapsed between 18-16 ka BP. This response is in stark contrast to more northerly ice dispersal centres, which remained active, feeding the re-advance of the NSL into Yorkshire (~16-15 ka BP) and the Killard Point Stadial in the northern Irish Sea Basin (~16.5 ka BP).

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Figures

Figure 1: NEXTMap image illustrating the complex topography and array of glacial landforms of northern England and southern Scotland. The four major palaeo-ice stream corridors (Forth, Tweed, Tyne and Stainmore) are highlights by dark blue arrows.

Figure 2: Location map of the central sector of the last British-Irish Ice Sheet. The black box is the Tyne Gap corridor that is the focus of this paper. We include all published ages relevant to the build-up and retreat of ice in this sector of the ice sheet (from Hughes *et al.,* 2011; and updated by Wilson and Lord, 2014). These are displayed according to the dating context. Note the absence of any deglacial ages in the Tyne Gap corridor.

Figure 3: Examples of two bedrock ridges at the western end of the Tyne Gap palaeo-ice stream corridor (ice-flow left to right in both instances). Note the steeper stoss side and shallow lee side in 2A.

Figure 4: A. NEXTMap image showing the geomorphology of the study area. The black dotted lines demarcate the edge of the lineated terrain associated with the palaeo-ice stream (see Livingstone *et al.,* 2010a). The three main ice-flows are depicted by the white arrows. B. The mapped deglacial features (meltwater channels, moraine) and interpreted ice-marginal positions (black-dotted lines). Moraine 1 is the Crowden Hill Moraine, moraine 2 is the Thorneyford Moraine and moraine 3 is the North Tyne Moraine. ^{10}Be ages are presented as ka BP with 1 σ error (see Table 1). Black text refers to ages calculated with a zero erosion rate and red text refers to ages calculated with an erosion rate of 1 mm/ka. Radiocarbon ages are presented as calibrated years before present (cal. ka BP) with 1 σ error (see Table 2). The black box refers to Fig. 6.

Figure 5: Plate of photographs illustrating the five bedrock exposures sampled along the Tyne Gap Palaeo-Ice Stream corridor, including: A. TY1: upstanding (1-2 m) bedrock promontory on a Carboniferous Sandstone escarpment; B. TY2: ice-moulded bedrock (roche moutonee) at the western edge of a Carboniferous Sandstone ridge; C. TY3: upstanding (1-3 m) bedrock promontory on a glacially abraded Carboniferous Sandstone crag; D. TY4: Large upstanding Tor standing up to 5 m above the surrounding crags of the Carboniferous Sandstone ridge; and E. TY5: Upstanding (0.5 m) bedrock surface at the les side of a bedrock moulded, W-E trending drumlin composed of Carboniferous sandstone.

Figure 6: The Crowden Hill and Thorneyford moraine ridges (white dotted lines) (see Fig. 4B for locations). The Thorneyford Moraine has a distinctive lobate planform. The terrain to the west of the moraine is lineated, while to the east there are two small basins, with overspill channels at their eastern margin. The DEM is a combination of NEXTMap and LiDAR data.

Figure 7: Bayesian Sequence model of the dating control for the palaeo-TGIS, showing the OxCal keywords that describe the model (Ramsey, 2009). Each distribution (light grey) represents the relative probability of each age estimate with the *posterior* density estimate (dark grey) generated by the modelling.

Figure 8: Log and photograph of the 2.0 m Crag Lough cores. The numbered photographs relate to cores 1-4, which are shown in a general log with the radiocarbon age.

Figure 9: Log and photograph of the 0.5 m Talkin Tarn core.

Figure 10: A. Reconstruction of ice dynamics in the central sector (stages IV-VI) from Livingstone *et al.,* 2012). B. Updated reconstruction based on our new geochronological and geomorphological constraints. Red lines numbers 1-3 refer to the three moraine systems identified in Figure 4B. In particular, note that the central sector underwent widespread and

collapse between 18-16 ka BP, while regions sourced from Scottish ice continued to stream a considerable distance south during this time.

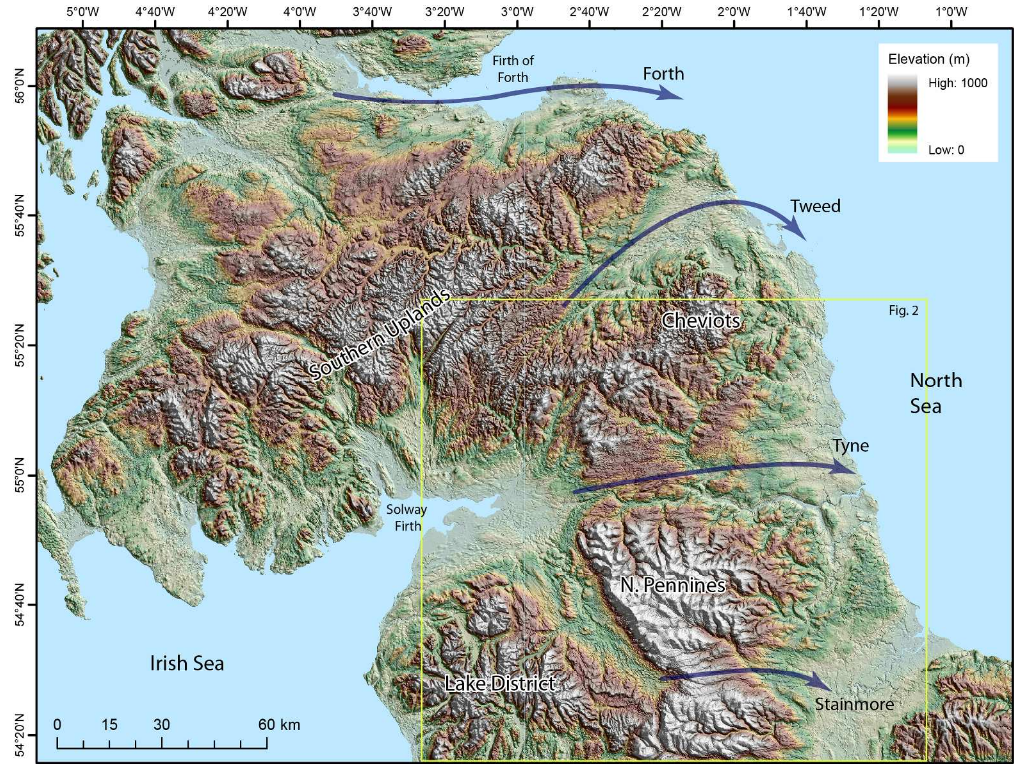
Tables

Table 1: ^{10}Be cosmogenic exposure ages, sample locations, analytical details for the Tyne Gap region, northern England. [a]The ^{10}Be concentrations are corrected for the procedural blank value of (5.83±1.19) x104 atoms. ^{10}Be/^{9}Be blank-corrected ratios and ^{10}Be concentrations are referenced to NIST SRM 4325 (2.79 x 1011; Nishiizumi *et al.,* 2007). Uncertainties (±1σ) include all known sources of analytical error. Corrections for sample thickness assume an exponential depth decrease of *in situ* production rate and an attenuation length of 160g cm^{-2}. Exposure ages calculated using the Lm scaling schemes in the Cronus-Earth (http://hess.ess.washington.edu/). NWH LPR12.2 exposure ages are calculated using a production rate of 3.99 ± 0.13 atoms g-1 yr-1 based on a deglaciation age of 12.2 ka in Scotland (Ballantyne & Stone, 2012). The calculated age uncertainties are expressed as 1σ. The external uncertainties include the internal (analytical) and the total (systematical) uncertainties.

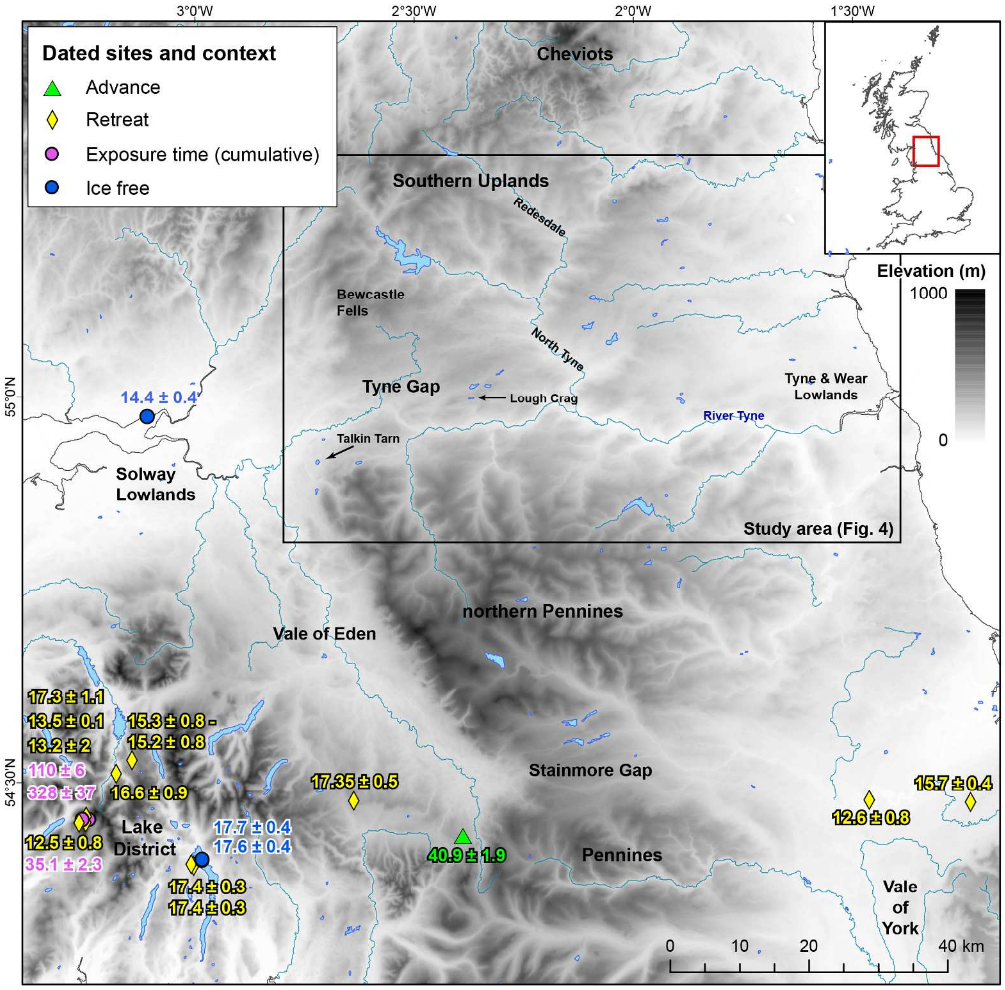
									NWH LPR 12.2			Erosion 1 mm/ka		
Sample	AMS ID	Latitude (°N)	Longitude (°W)	Altitude (m)	Thickness (cm)	Density (g cm^{-3})	Shielding (factor)	^{10}Be ± σ (atoms g^{-1} quartz)[a]	Exposure age (yr)	Internal σ (yr)	External σ (yr)	Exposure age (yr)	Internal σ (yr)	External σ (yr)
TY1	b6981	55.13	-1.92	202	4	2.42	0.9988	88730 ± 3335	17839	673	904	18099	694	932
TY2	b6982	55.19	-1.93	230	4.5	2.03	0.9999	89777 ± 4755	17626	938	1111	17880	965	1144
TY3	b6986	55.14	-2.36	221	4	1.94	0.9998	83515 ± 2827	16478	560	790	16699	576	812
TY4	b6987	55.28	-1.96	431	4	2.46	0.9999	289070 ± 6634	47128	1094	1944	49022	1187	2108
TY5	b6988	55.00	-2.19	110	5	2.63	0.9999	77507 ± 2830	17218	631	859	17460	650	884

Table 2: Radiocarbon ages. [a]AMS radiocarbon ages are ^{14}C yrs BP ± 1σ. Calibrated ages are in calendar years before present (BP) ± 1σ.

Laboratory code	Site	Sample ID (depth cm)	Material	$^{13}C/^{12}C$	Measured ^{14}C age (yrs BP)	[a]Calibrated ^{14}C age (cal. yrs BP)
BETA-342471	Talkin Tarn	L1a (971-972)	Organic sediment	-22.2	13080 ± 60	15690 ± 130
BETA-342470	Talkin Tarn	L1b (948-949)	Organic sediment	-24.7	11760 ± 50	13550 ± 70
BETA-342469	Lough Crag	L2 (320-321)	Peat	-26	11190 ± 50	13060 ± 40

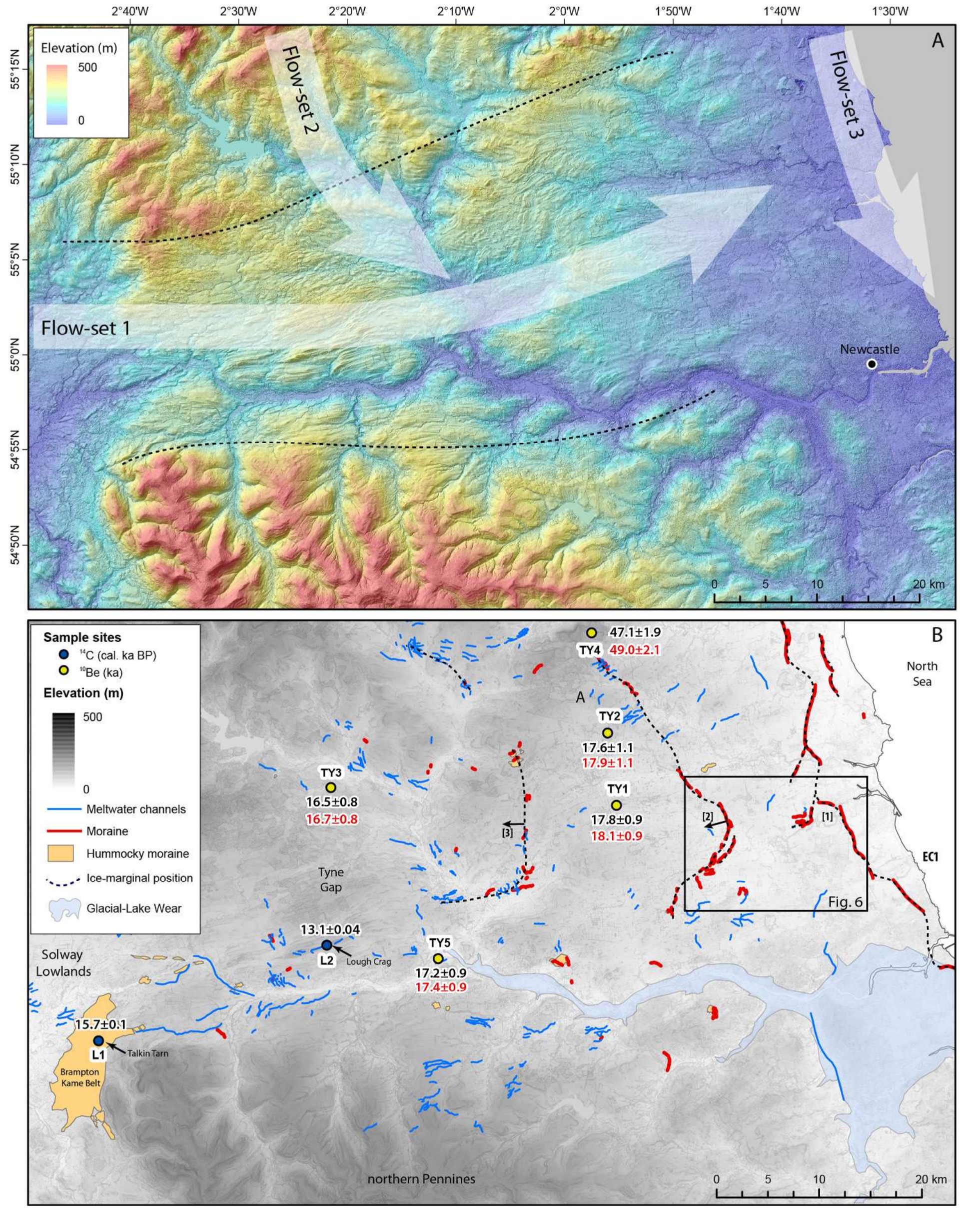


NEXTMap image illustrating the complex topography and array of glacial landforms of northern England and southern Scotland. The four major palaeo-ice stream corridors (Forth, Tweed, Tyne and Stainmore) are highlights by dark blue arrows.



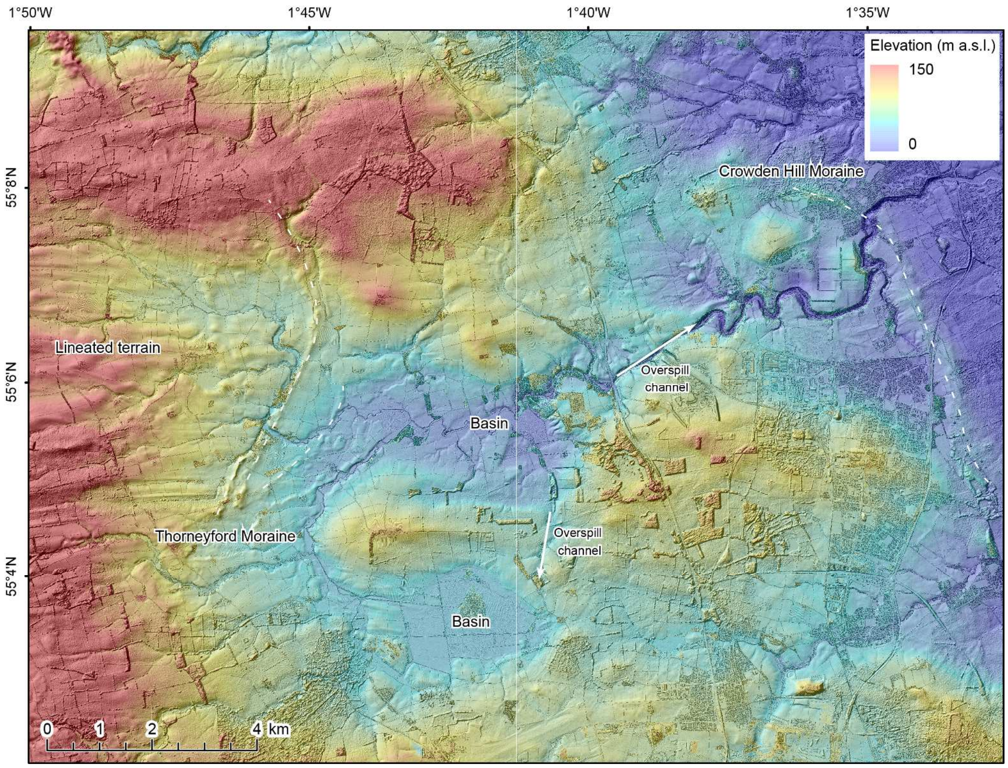
Location map of the central sector of the last British-Irish Ice Sheet. The black box is the Tyne Gap corridor that is the focus of this paper. We include all published ages relevant to the build-up and retreat of ice in this sector of the ice sheet (from Hughes et al., 2011; and updated by Wilson and Lord, 2014). These are displayed according to the dating context. Note the absence of any deglacial ages in the Tyne Gap corridor.

Examples of two bedrock ridges at the western end of the Tyne Gap palaeo-ice stream corridor (ice-flow left to right in both instances). Note the steeper stoss side and shallow lee side in 2A.

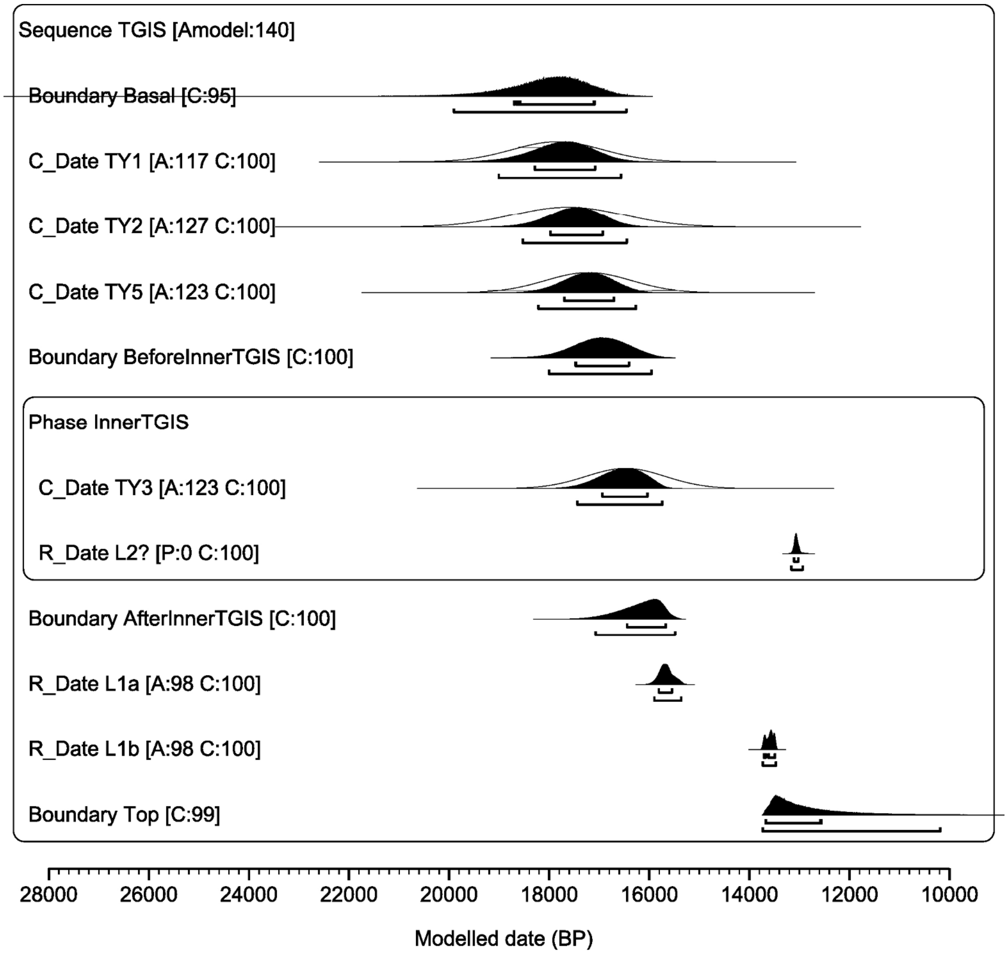


A. NEXTMap image showing the geomorphology of the study area. The black dotted lines demarcate the edge of the lineated terrain associated with the palaeo-ice stream (see Livingstone et al., 2010a). The three main ice-flows are depicted by the white arrows. B. The mapped deglacial features (meltwater channels, moraine) and interpreted ice-marginal positions (black-dotted lines). Moraine 1 is the Crowden Hill Moraine, moraine 2 is the Thorneyford Moraine and moraine 3 is the North Tyne Moraine. 10Be ages are presented as ka BP with 1 σ error (see Table 1). Black text refers to ages calculated with a zero erosion rate and red text refers to ages calculated with an erosion rate of 1 mm/ka. Radiocarbon ages are presented as calibrated years before present (cal. ka BP) with 1 σ error (see Table 2). The black box refers to Fig. 6.

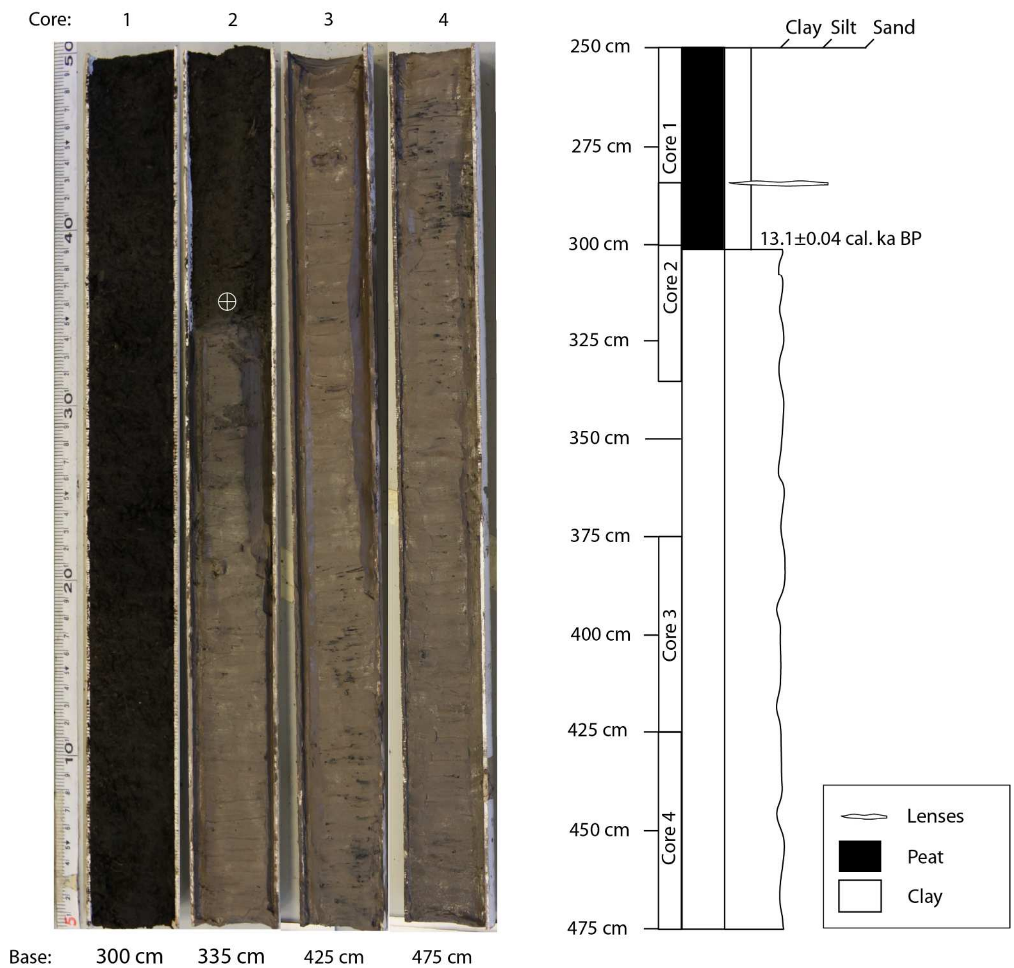
Plate of photographs illustrating the five bedrock exposures sampled along the Tyne Gap Palaeo-Ice Stream corridor, including: A. TY1: upstanding (1-2 m) bedrock promontory on a Carboniferous Sandstone escarpment; B. TY2: ice-moulded bedrock (roche moutonee) at the western edge of a Carboniferous Sandstone ridge; C. TY3: upstanding (1-3 m) bedrock promontory on a glacially abraded Carboniferous Sandstone crag; D. TY4: Large upstanding Tor standing up to 5 m above the surrounding crags of the Carboniferous Sandstone ridge; and E. TY5: Upstanding (0.5 m) bedrock surface at the les side of a bedrock moulded, W-E trending drumlin composed of Carboniferous sandstone.



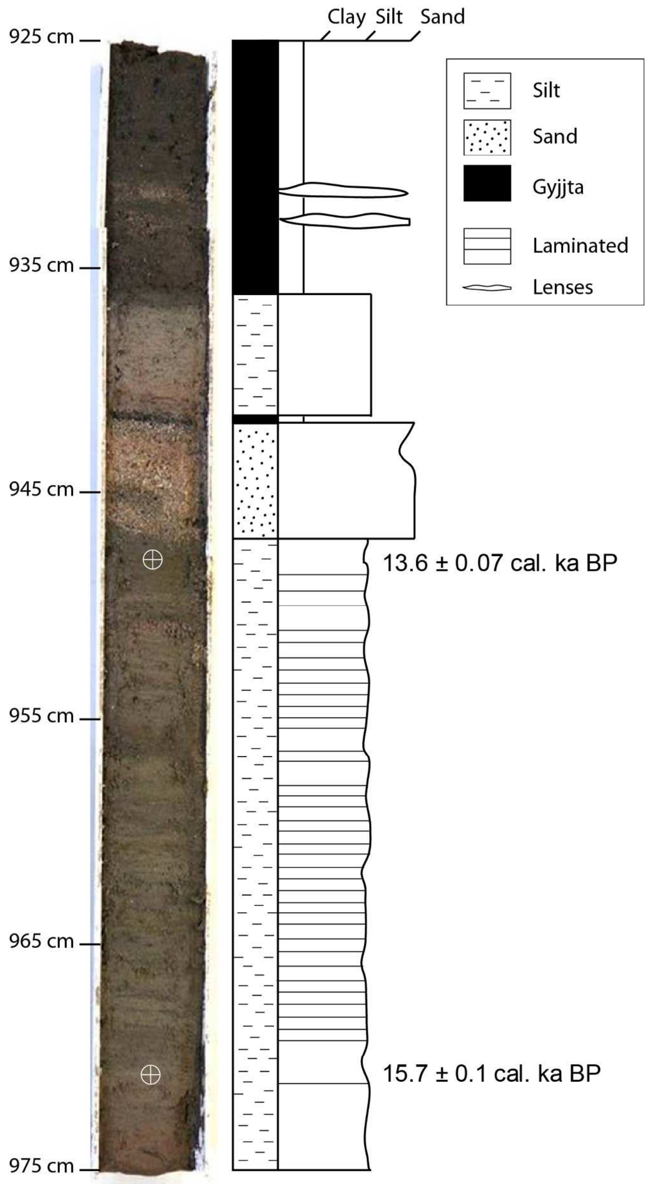
The Crowden Hill and Thorneyford moraine ridges (white dotted lines) (see Fig. 4B for locations). The Thorneyford Moraine has a distinctive lobate planform. The terrain to the west of the moraine is lineated, while to the east there are two small basins, with overspill channels at their eastern margin. The DEM is a combination of NEXTMap and LiDAR data.



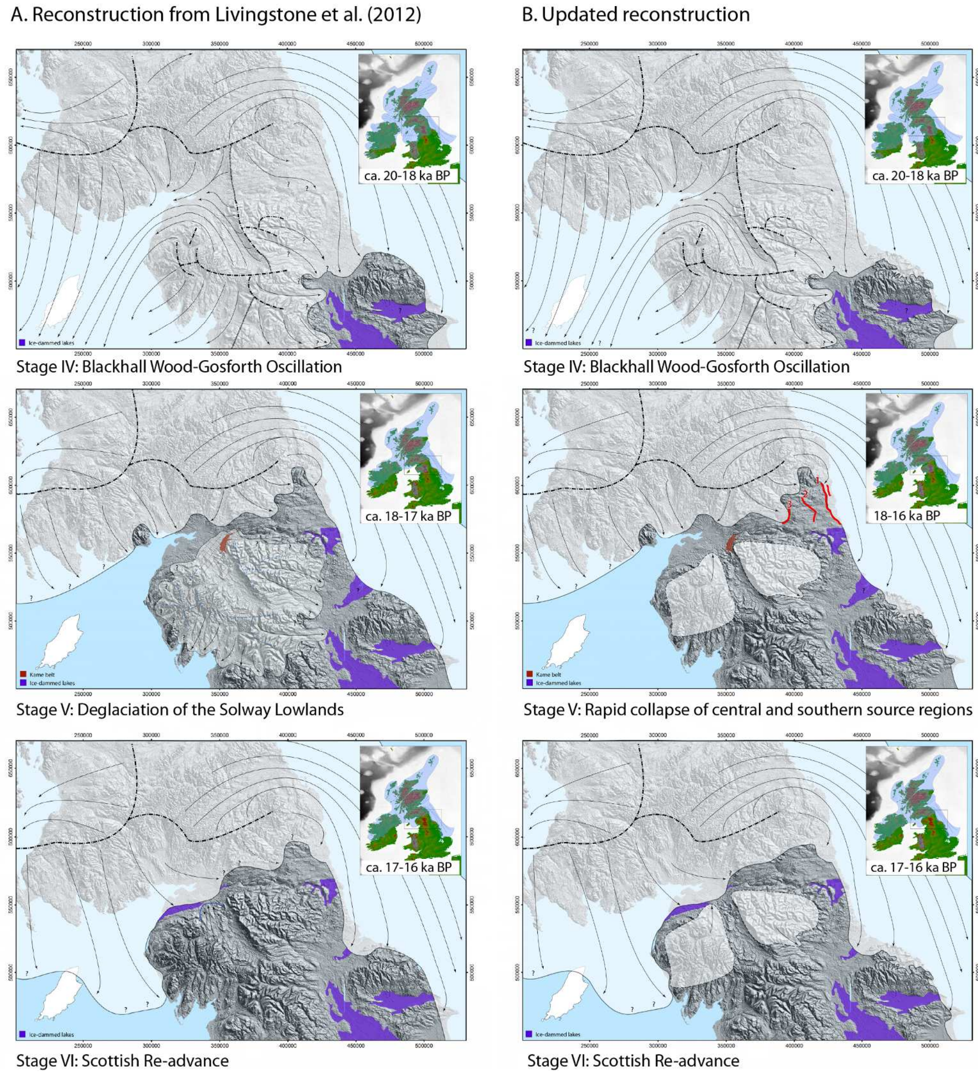
Bayesian Sequence model of the dating control for the palaeo-TGIS, showing the OxCal keywords that describe the model (Ramsey, 2009). Each distribution (light grey) represents the relative probability of each age estimate with the posterior density estimate (dark grey) generated by the modelling.



Log and photograph of the 2.0 m Crag Lough cores. The numbered photographs relate to cores 1-4, which are shown in a general log with the radiocarbon age.



Log and photograph of the 0.5 m Talkin Tarn core.



A. Reconstruction of ice dynamics in the central sector (stages IV-VI) from Livingstone et al., 2012). B. Updated reconstruction based on our new geochronological and geomorphological constraints. Red lines numbers 1-3 refer to the three moraine systems identified in Figure 4B. In particular, note that the central sector underwent widespread and collapse between 18-16 ka BP, while regions sourced from Scottish ice continued to stream a considerable distance south during this time.