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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 to 17.1 ka, and becoming ice free before 16.4–15.7 ka. 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 before ~18.7–17.1 ka 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 and 16 ka. Copyright © 2015 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

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

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 characterized 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, SouthernUplands, 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.*, 2013a,b) (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 BIIS 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, 15–30-km-wide mountainous pass located between the Cheviot Hills and English Pennines (Figs 1 and 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.

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 and 4). Lineations are composed of both till and bedrock, including visually striking streamlined bedrock ridges controlled by the geological

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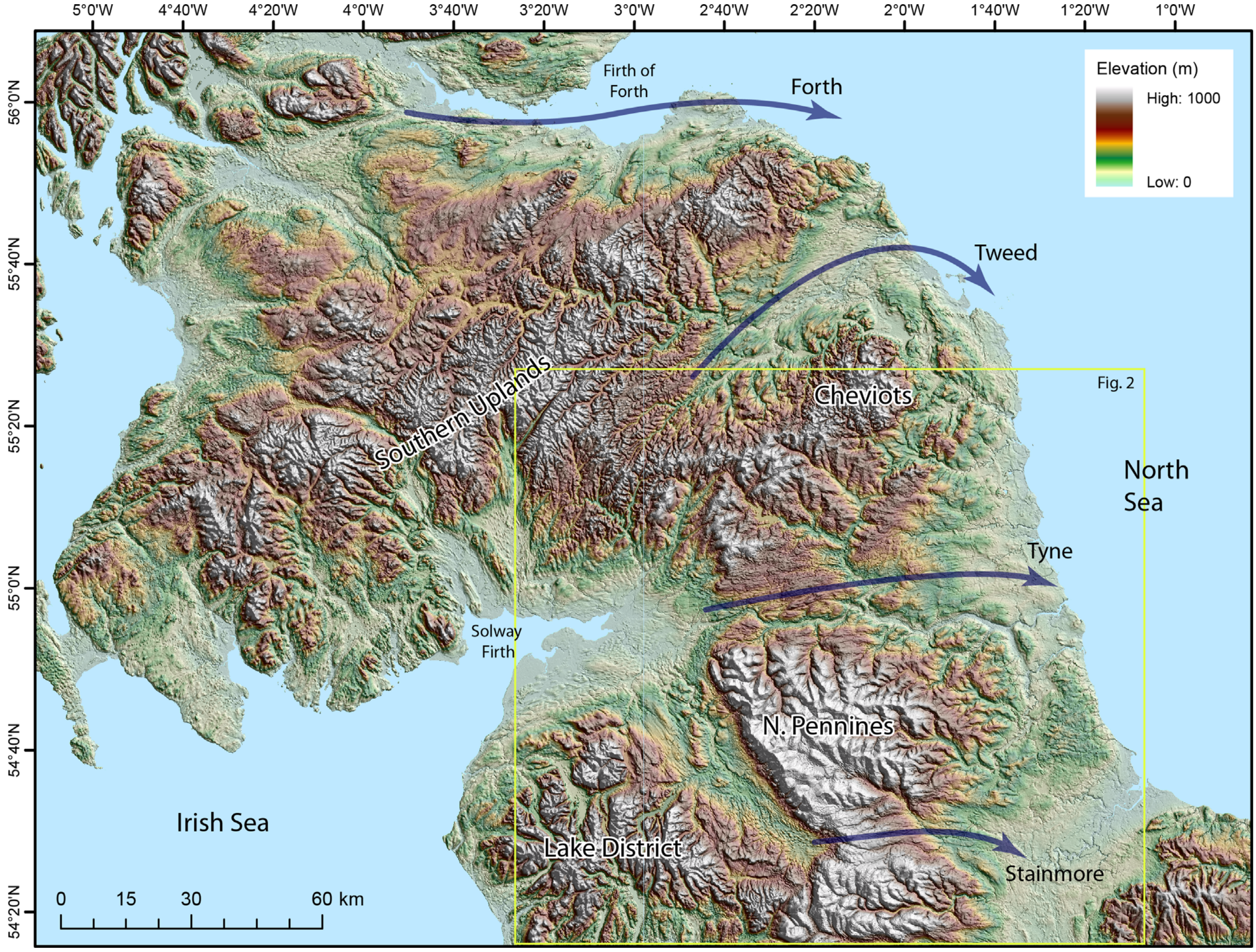

Figure 1. NEXTMap image illustrating the complex topography and array of glacial landforms of northern England and southern Scotland. The four major palaeo-ice stream corridors (Forth, Tweed, Tyne and Stainmore) are highlighted by dark blue arrows.

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 north-east 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. 4A). 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. 4) 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 southward-flowing NSL (flow set 3) (Davies *et al*., 2009, 2012).

Meltwater channels and a prominent moraine ('Crowden Hill Moraine'; Figs 4 and 6) at the eastern end of the main W–E orientated flow set record nascent retreat of the TGIS into the Tyne and Wear Lowlands or an ice-marginal position of the NSL (Smythe, 1912; Livingstone *et al*., 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).

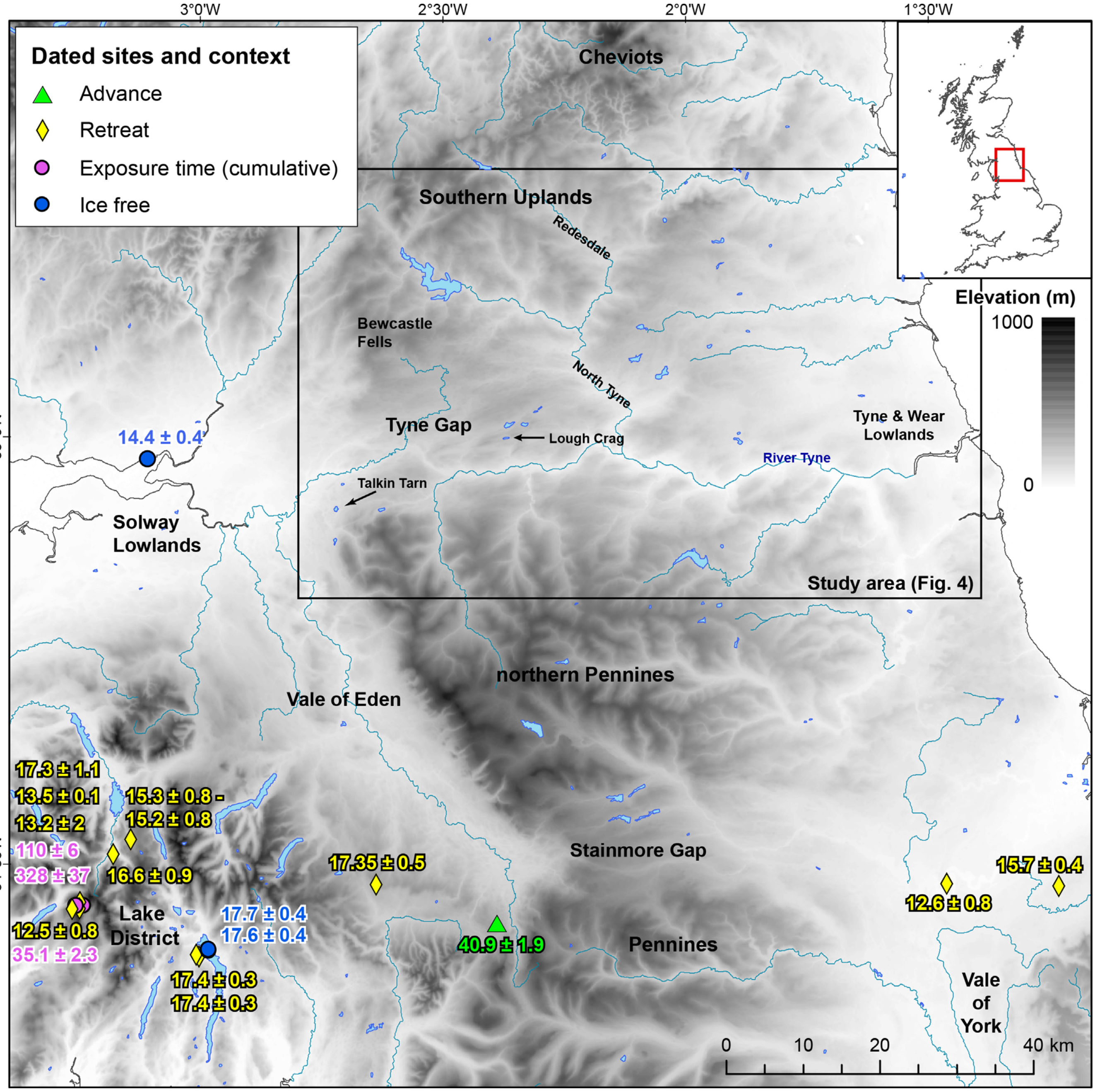

Figure 2. Location map of the central sector of the last British–Irish Ice Sheet. The black box is the Tyne Gap corridor that is the focus of this paper. We include all published ages relevant to the build-up and retreat of ice in this sector of the ice sheet (from Hughes *et al.*, 2011; and updated 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.

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).

Field and laboratory methods

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 summarized 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.

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

Sampling strategy

Single samples for cosmogenic nuclide (^{10}Be) surface exposure dating were taken from five separate glaciated bedrock surfaces at locations along the length of the Tyne Gap to constrain palaeo-ice stream retreat (Figs 4B and 5). The relatively small number of single samples from separate

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

glacial erosion features limits our geochronological reconstruction. In particular, a single age is less robust than one derived from multiple samples on the same feature. Moreover, as variance in the exposure age range also increases with number of samples (e.g. Balco, 2011; Applegate *et al.*, 2012) an age derived from one sample may give a false sense of chronological precision. 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 ($10 \times 10 \times 4$ cm; ca. 3 kg) at least 30 cm from all outcrop edges. Sampled surfaces were roughened after 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.

Sample preparation

Samples were prepared at the Cosmogenic Isotope Analysis Facility in the Scottish Universities Environmental Research Centre. 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 at Scottish Universities Environmental Research Centre (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.

Exposure age calculation

The exposure ages were calculated using the Cronus-Earth online calculator v.2.2 (hess.ess.washington.edu/) and are presented in Table 1. ^{10}Be ages are calculated using a ^{10}Be half-life of 1.36 Myr and the sea level and high latitude (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). To decrease the scaling uncertainties, we calculated the exposure ages using a locally derived production rate (LPR) 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 (NWH) (Ballantyne, 2012; Ballantyne and Stone, 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

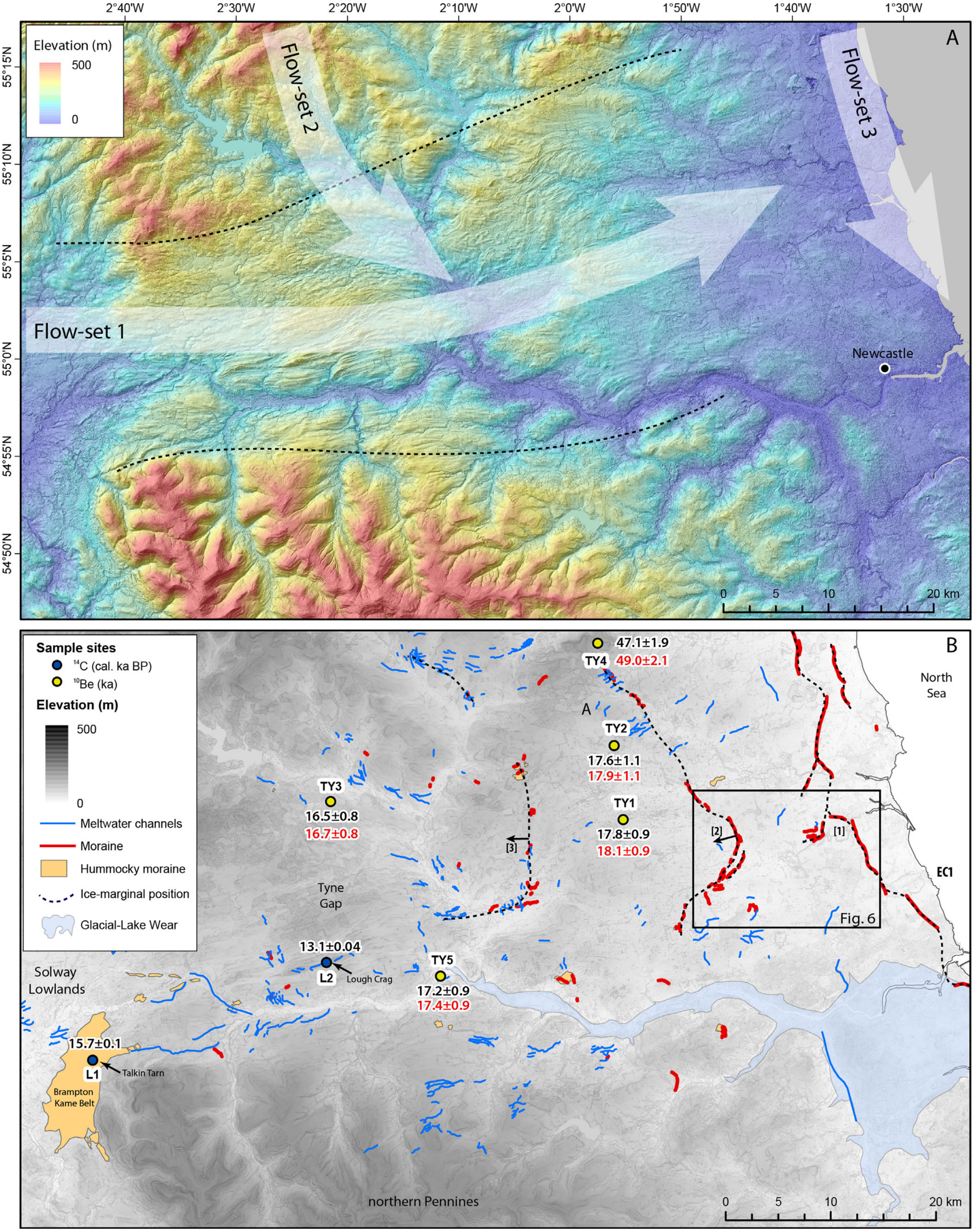

Figure 4. (A) NEXTMap image showing the geomorphology of the study area. The black dotted lines demarcate the edge of the lineated terrain associated with the palaeo-ice stream (see Livingstone *et al.*, 2010a). The three main ice flows are depicted by the white arrows. (B) The mapped deglacial features (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 1σ error (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^{-1}. Radiocarbon ages are presented as calibrated years before present (cal ka BP) with 1σ error (Table 2). The black box refers to Fig. 6.

Figure 5. Photographs illustrating the five bedrock exposures sampled along the Tyne Gap Palaeo-Ice Stream corridor: (A) TY1: upstanding (1–2 m) bedrock promontory on a Carboniferous Sandstone escarpment; (B) TY2: ice-moulded bedrock (roche moutonée) 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; (E) TY5: upstanding (0.5 m) bedrock surface on the lee side of a bedrock-moulded, W–E trending drumlin composed of Carboniferous sandstone.

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, unpublished data). 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 160 g cm^{-2}. Carboniferous sandstone surfaces show evidence of granular disintegration. We have therefore calculated minimum exposure ages based on both zero erosion of sampling surfaces and for an erosion rate of 1 mm ka^{-1} to investigate the effect of bedrock erosion on sample age. Higher erosion rates are not considered because they result in unfeasibly old ages that pre-date deglaciation

Table 1. ^{10}Be cosmogenic exposure ages, sample locations and analytical details for the Tyne Gap region, northern England.

Sample	AMS ID	Latitude (°N)	Longitude (°W)	Altitude (m)	Thickness (cm)	Density (g cm^{-3})	Shielding (factor)	$^{10}Be \pm \sigma$ (atoms g^{-1} quartz)*	NWH LPR 12.2 Exposure age (a)	NWH LPR 12.2 Internal σ (a)	NWH LPR 12.2 External σ (a)	Erosion 1 mm ka^{-1} Exposure age (a)	Erosion 1 mm ka^{-1} Internal σ (a)	Erosion 1 mm ka^{-1} External σ (a)
TY1	b6981	55.13	−1.92	202	4	2.42	0.9988	88 730 ± 3335	17 839	673	904	18 099	694	932
TY2	b6982	55.19	−1.93	230	4.5	2.03	0.9999	89 777 ± 4755	17 626	938	1111	17 880	965	1144
TY3	b6986	55.14	−2.36	221	4	1.94	0.9998	83 515 ± 2827	16 478	560	790	16 699	576	812
TY4	b6987	55.28	−1.96	431	4	2.46	0.9999	289 070 ± 6634	47 128	1094	1944	49 022	1187	2108
TY5	b6988	55.00	−2.19	110	5	2.63	0.9999	77 507 ± 2830	17 218	631	859	17 460	650	884

*The ^{10}Be concentrations are corrected for the procedural blank value of $(5.83 \pm 1.19) \times 10^4$ atoms. $^{10}Be/^9Be$ blank-corrected ratios and ^{10}Be concentrations are referenced to NIST SRM 4325 $(2.79 \times 10^{11}$; Nishiizumi *et al.*, 2007). Uncertainties ($\pm 1\sigma$) 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 160 g cm^{-2}. Exposure ages were calculated using the Lm scaling schemes in the Cronus-Earth (hess.ess.washington.edu). NWH LPR12.2 exposure ages are calculated using a production rate of 3.99 ± 0.13 atoms g^{-1} a^{-1} based on a deglaciation age of 12.2 ka in Scotland (Ballantyne and Stone, 2012). The calculated age uncertainties are expressed as 1σ. The external uncertainties include the internal (analytical) and the total (systematical) uncertainties.

(e.g. 3 mm ka^{-1} gave ages of >25 ka BP). Topographic and geometric 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), and thus all reported ^{10}Be ages calculated with zero erosion in this study are regarded as minimum ages.

Radiocarbon dating

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 accelerator mass spectromety radiocarbon analyses of the samples (Beta-342469, 342470, 342471) was undertaken at the BETA Analytic Laboratories, following their standard procedures (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.

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 (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.

Results

General geomorphology

Glacial geomorphological mapping of meltwater channels, glaciofluvial deposits and moraine hummocks and ridges has

Table 2. Radiocarbon ages.

Lab code	Site	Sample ID (depth cm)	Material	$^{13}C/^{12}C$	Measured radiocarbon age (^{14}C a BP)	Calibrated ^{14}C age (cal a BP)*
BETA-342471	Talkin Tarn	L1a (971–972)	Organic sediment	−22.2	13 080 ± 60	15 690 ± 130
BETA-342470	Talkin Tarn	L1b (948–949)	Organic sediment	−24.7	11 760 ± 50	13 550 ± 70
BETA-342469	Lough Crag	L2 (320–321)	Peat	−26	11 190 ± 50	13 060 ± 40

*Accelerator mass spectromety radiocarbon ages are ^{14}C a BP $\pm 1\sigma$. Calibrated ages are in calendar years before present (BP) $\pm 1\sigma$.

revealed three significant ice-marginal positions within the TGIS corridor (Fig. 4B, labelled 1–3). The easternmost 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 several 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.

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

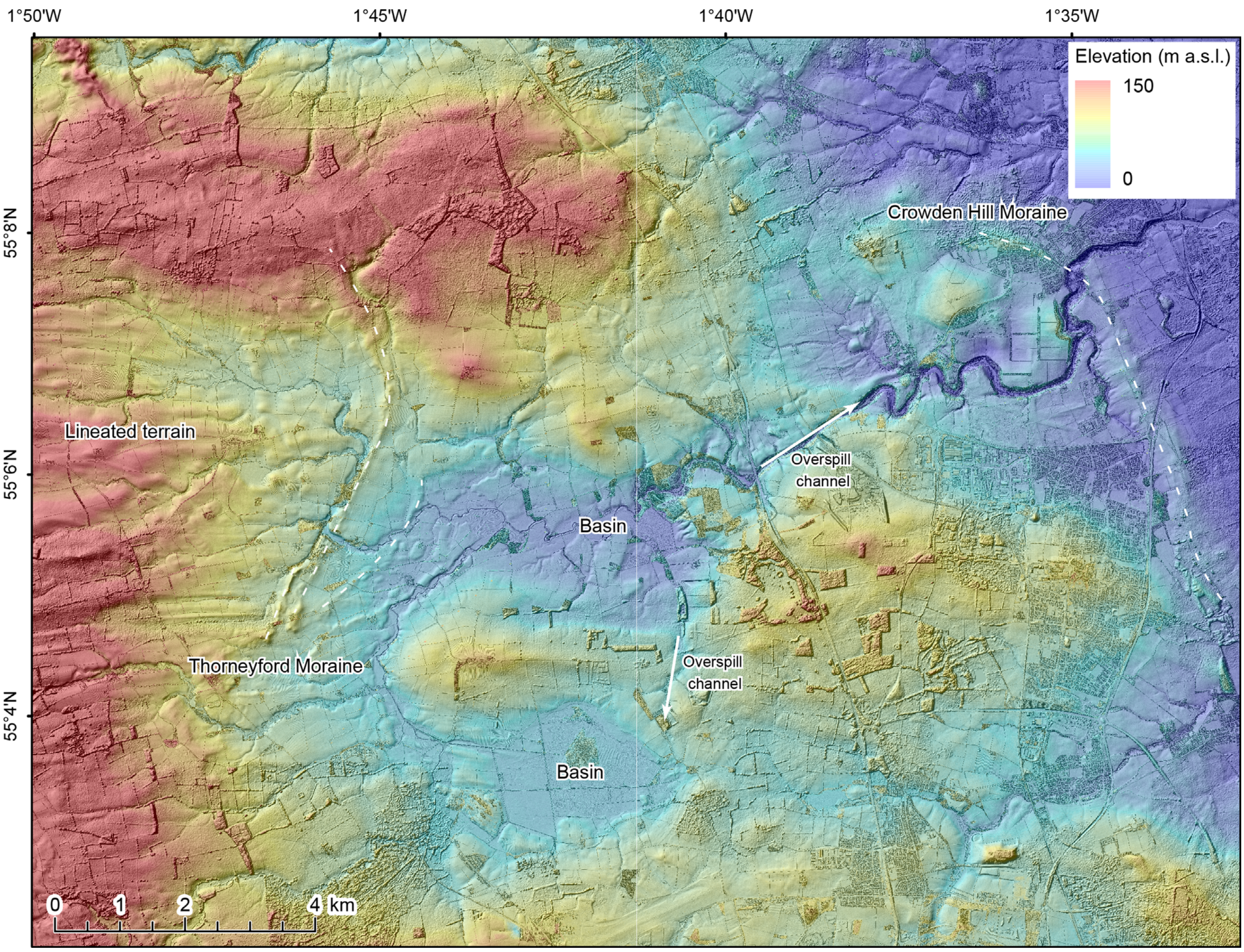

Figure 6. The Crowden Hill and Thorneyford moraine ridges (white dotted lines) (Fig. 4B for locations). The Thorneyford Moraine has a distinctive lobate planform. The terrain to the west of the moraine is lineated, while to the east there are two small basins, with overspill channels at their eastern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

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 ice stream (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 (230 m 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 (221 m 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 (431 m 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 ($\sim 2 \times 2$ m) pedestals. There is some lichen cover and evidence of granular disintegration, spallation and large ($\sim$5 cm) weathering pits.

Sample TY5 was from Brierwood Hill (110 m asl), a W–E trending whaleback towards the southern margin of the ice stream corridor (Livingstone *et al.*, 2010a). 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).

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 and 7). Sample TY4 (431 m asl) yielded an age of 47 ± 1.9 ^{10}Be ka BP, which is anomalously old compared with 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 and 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, while further west sample TY3 was dated to 16.5 ± 0.8 ka BP. With an erosion rate of 1 mm ka^{-1} the ^{10}Be ages become 242–260 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) characterized 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 $\sim$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).

Discussion

Decoupling of the TGIS from the NSL

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; and (3) encroachment of the N–S flowing NSL into the coastal lowlands of Northumbria and Durham (Fig. 4). However, the deglacial dynamics and timing of these competing ice flows are poorly understood.

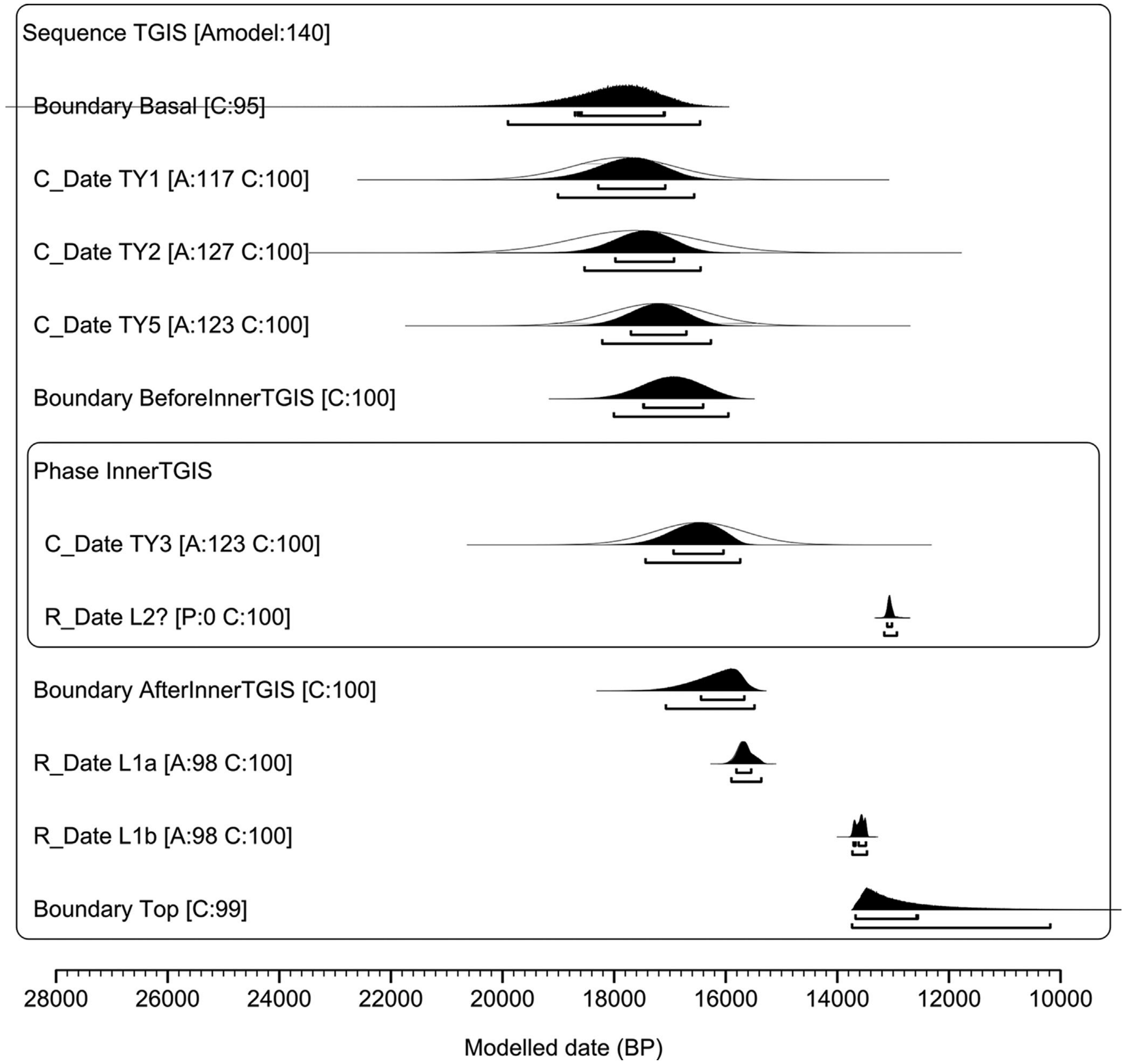

Figure 7. Bayesian sequence model of the dating control for the palaeo-TGIS, showing the OxCal keywords that describe the model (Ramsey, 2009). Each distribution (light grey) represents the relative probability of each age estimate with the posterior density estimate (black) generated by the modelling.

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 probably it relates to the onshore movement of the NSL. This is supported by the 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. 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 near 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.

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

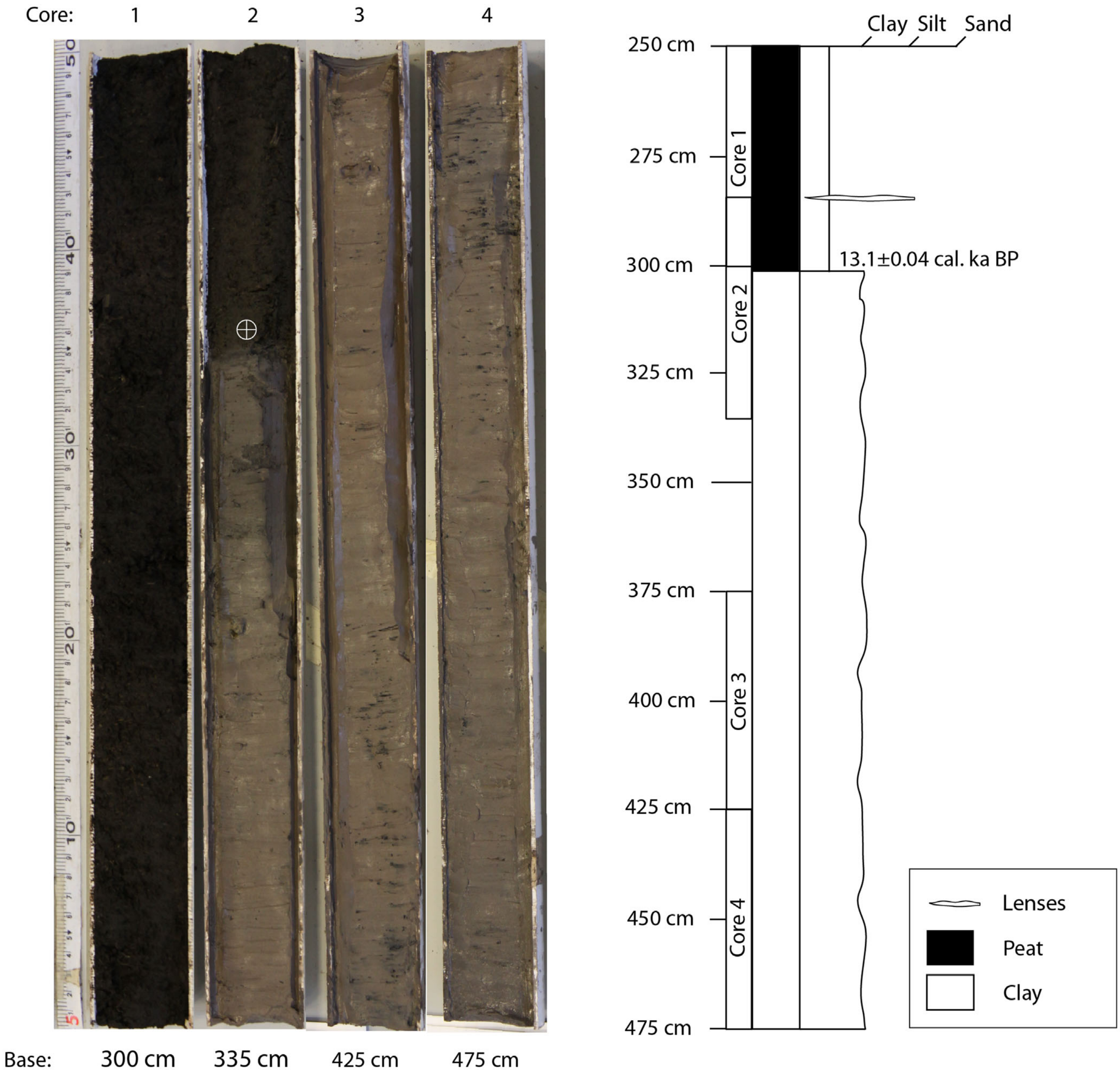

Figure 8. Log and photograph of the 2.0-m Crag Lough cores. The numbered photographs relate to cores 1–4, which are shown in a general log with the radiocarbon age.

located subparallel 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 2, which constrains the formation of Glacial Lake Wear to a period before 18.7–17.1 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).

Retreat of the TGIS

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 to 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 reorganization 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.*,

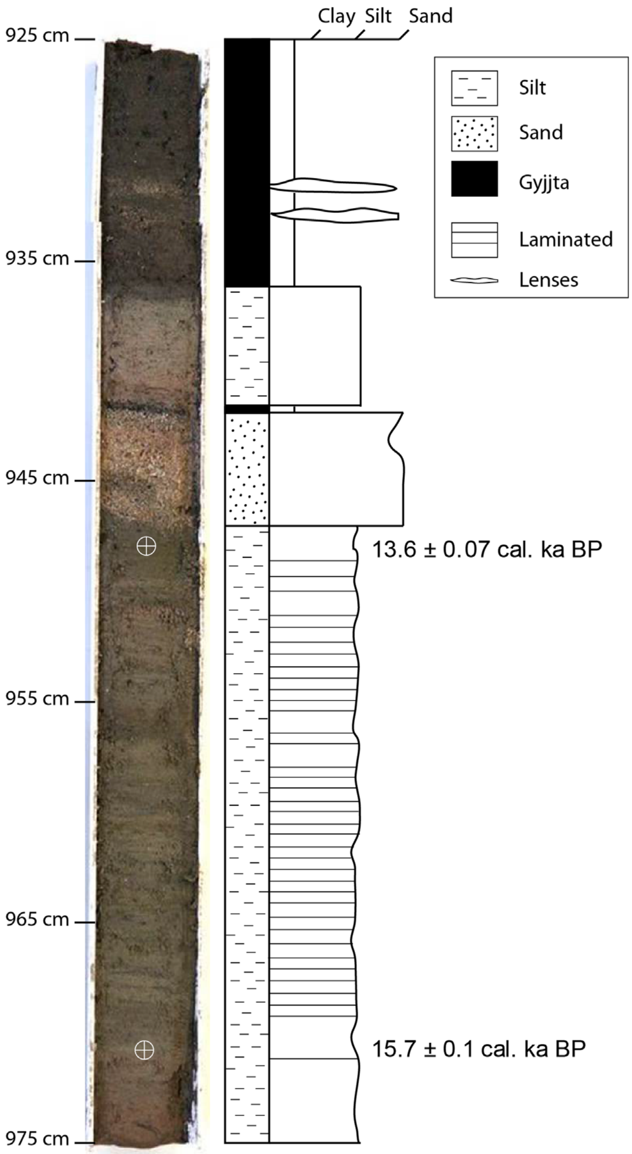

Figure 9. Log and photograph of the 0.5-m Talkin Tarn core.

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.

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 reorganization.

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 and 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 both the NSL and the ISIS were 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, north-east 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 to 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).

Conclusions

There is considerable uncertainty over the timing and rate of retreat and complex flow-phase switching in the central

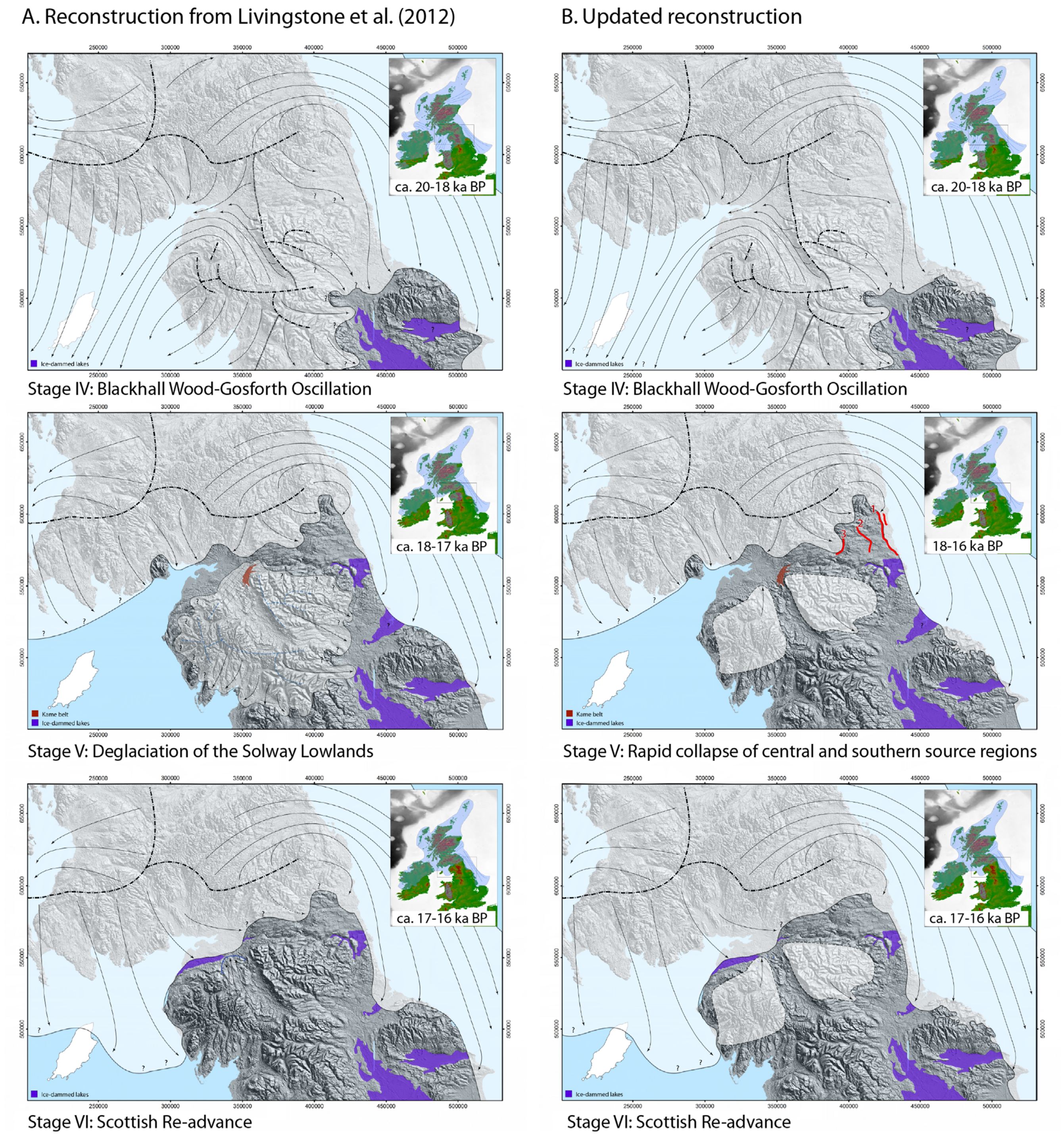

Figure 10. (A) Reconstruction of ice dynamics in the central sector (stages IV–VI) from Livingstone *et al.* (2012). (B) Updated reconstruction based on our new geochronological and geomorphological constraints. Red lines numbered 1–3 refer to the three moraine systems identified in Fig. 4B. In particular, note that the central sector underwent widespread and collapse between 18 and 16 ka BP, while regions sourced from Scottish ice continued to stream a considerable distance south during this time.

sector of the last BIIS 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 a simple chronological model based on single ^{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. Two ^{10}Be ages of 17.8–17.6 ka BP provide maximum bounds on the moraine's formation, and constrain the formation of Glacial Lake Wear to a period before ~18.7–17.1 ka BP 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 reorganization 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 and 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).

Abbreviations. BIIS, British–Irish Ice Sheet; ISIS, Irish Sea Ice Stream; LLPR, Loch Lomond production rate; NSL, North Sea Ice Lobe; NWH LPR, NW Scottish Highlands locally derived production rate; TGIS, Tyne Gap Palaeo-Ice Stream

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