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Towards a robust deglacial chronology for the northwest England sector of the last British-Irish Ice Sheet

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Abstract

A number of absolute age determinations that provide a timeframe for the deglaciation of the last ice sheet in northwest England are reviewed. Some of the ages are probably too old and are therefore unreliable; some others have large associated uncertainties and are imprecise estimates for the loss of ice cover. Several ages are minimum ages for deglaciation because they record the timing of sedimentary events made possible by the removal of ice. The tightest age constraints on deglaciation are those derived from cosmogenic nuclide surface exposure dating but for some sites only a single age is available. Nevertheless together these age determinations indicate that between ~18 ka and ~17 ka northwest England began to emerge from its cover of glacial ice. Valley glaciers persisted in the Lake District until ~15 ka but had probably disappeared by 14.7 ka, or shortly after, when climate warmed abruptly. A more detailed picture of the style and rate of deglaciation is likely to come in the next few years as a result of the BRITICE-CHRONO project.

Keywords

Deglaciation, Last Glacial Maximum, British-Irish Ice Sheet, Dating techniques, Northwest England.

Introduction

The idea that glaciers had previously existed in the British and Irish Isles was proposed by Swiss geologist Louis Agassiz, who toured northern England and Scotland in 1840 in the company of the Reverend William Buckland, Professor of Mineralogy and Geology at the University of Oxford (Imbrie & Imbrie, 1979). Through their subsequent lectures and publications both men stimulated and challenged geologists to search for and document the evidence relating to a former widespread cover of glacial ice (Agassiz, 1840; Buckland, 1840). Since then considerable time and energy has been devoted to describing the nature of both erosional and depositional glacial landforms, their areal extent and spatial distribution, and it is now almost universally accepted that glaciers and ice sheets had earlier covered much of Great Britain and Ireland. The temporal aspect of glaciation has also been the focus of much research, with a broad consensus that glaciers have waxed and waned on numerous occasions during the Quaternary era (the last ~2.6 Ma; e.g. Lundberg *et al*., 2010; Lee *et al*., 2012; Thierens *et al*., 2012).

Interest in the glacial geomorphology and sediment stratigraphy of northwest England extends back to the earliest days of glacial study. Buckland (1840) commented on the widespread dispersal of Shap granite erratics, and the drumlins around Kendal (he termed them 'piles of gravel' and 'moraines'). However, other researchers raised objections to the glacial theory, arguing that marine currents were more likely to have been the agents of erratic boulder transport (e.g. Hopkins, 1848). For a number of years in the second half of the nineteenth century a diluvial-glacial theory, in which the glaciers were thought to comprise floating ice masses (e.g. Mackintosh, 1870; Ward, 1873, 1875) competed with a land-based ice theory (e.g. Hughes, 1867; Dakyns, 1872; Tiddeman, 1872) in accounts portraying the rich diversity of surface landforms. As more evidence supporting land-based ice was gained diluvialism was gradually abandoned, and the glacial theory eventually became widely accepted.

Northwest England continued to provide a focus for studies of its glacial past throughout the twentieth century (e.g. Jowett, 1914; Raistrick, 1930; Hollingworth, 1931; Manley, 1959; Boardman, 1982, Longworth, 1985) such that Johnson (1971, 1985a, 1985b), Clark (1990) and Delaney (2003) were able to provide overviews of the last glacial period and highlight, either directly or indirectly, some of the outstanding issues. Since these latter publications the availability and application of dating techniques have increased considerably and a substantial number of absolute age determinations that constrain the glacial and related landform and sediment evidence are now available. These ages are facilitating construction of a timeframe of events associated with the wastage of the last ice sheet.

Presently, the NERC-funded BRITICE-CHRONO project is conducting "a systematic and directed campaign to collect and date material to constrain the timing and rates of change of the collapsing British-Irish Ice Sheet'" (http://www.sheffield.ac.uk/geography/research/britice-chrono/home). This will undoubtedly result in a large number of absolute ages pertaining to the deglaciation of northwest England. However, it is likely to be several years before these ages are available and a more detailed picture emerges. In the meantime this paper presents an outline deglacial chronology based on existing ages. Some of these age determinations, for the Yorkshire Dales, were discussed by Mitchell (2013) and are also considered here along with those from north Lancashire and Cumbria to provide a region-wide outline chronology of the later stages of the last glaciation. A final short-lived episode of glaciation during the Younger Dryas Stadial of 12.9-11.7 ka that affected the uplands of northwest England is not considered here.

The Last Glaciation

The most recent period of extensive glaciation in the British and Irish Isles occurred during the Dimlington Stade of the Late Devensian substage (~28-15 ka; Rose, 1985; Scourse *et al*., 2009; Chiverrell & Thomas, 2010), approximately equivalent to Greenland Stades 3 and 2 of the Greenland NGRIP Ice Core Chronology (Lowe *et al*., 2008) and Marine Isotope Stage 2 of the marine isotope record (Ehlers & Gibbard, 2013). It is now believed that the ice sheet extended west to the continental shelf edge, north to beyond the Shetland Islands, and was confluent with Scandinavian ice in the northern half of the North Sea basin (Sejrup *et al*., 2005; Bradwell *et al*., 2008; O'Cofaigh *et al*., 2012). Much of the Midlands and south of England lay beyond the ice margin, but the Irish Sea Ice Stream, fed by ice from Scotland, the Lake District, Ireland and Wales extended ~150 km southwest of the Isles of Scilly (Scourse & Furze, 2001; McCarroll *et al*., 2010; Fig. 1).

Various lines of evidence have been used to estimate the thickness of the last ice sheet. During the 1990s and early 2000s several researchers proposed that weathering limits on mountain slopes in parts of the Scottish Highlands, the Lake District, Snowdonia, and southwest Ireland represented the upper limit of the last ice sheet on those mountains (Ballantyne, 1997; Lamb & Ballantyne, 1998; McCarroll & Ballantyne, 2000; Rae *et al*., 2004). Above the weathering limit evidence for glacial erosion was said to be absent, with summits characterised by shattered bedrock, blockfields and tors; these features were taken to indicate that the summits had remained above the ice as nunataks. Below the weathering limit abundant striations, roches moutonnées, ice-moulded bedrock and perched glacially-transported boulders were regarded as demonstrating a former cover of erosive ice. The weathering limit was regarded as a periglacial trimline marking the maximum altitude reached by the last ice sheet and the level to which it had eroded or 'trimmed' pre-existing frost-weathered debris.

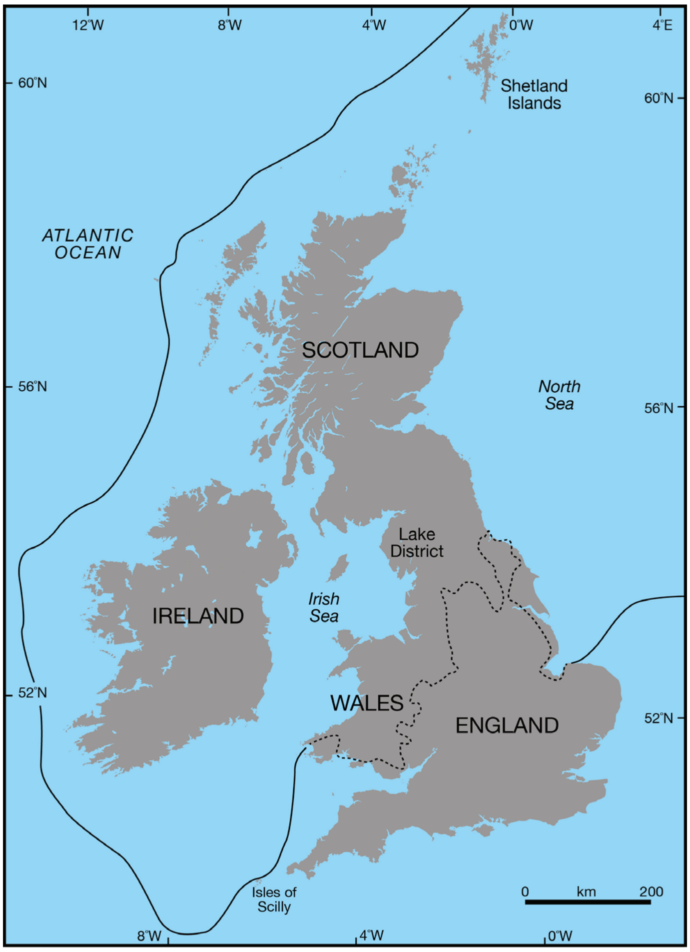

Figure 1. The maximum extent of the British-Irish Ice Sheet during the Last Glacial Maximum (after Scourse & Furze, 2001; Sejrup et al., 2005; Bradwell et al., 2008; McCarroll et al., 2010; O'Cofaigh et al., 2012).

These trimlines have since been re-interpreted as englacial thermal boundaries; erosive warm-based ice occurred below the weathering limit while passive cold-based ice existed above the limit and preserved the pre-existing shattered bedrock, blockfields and tors (Ballantyne *et al.*, 2009, 2011; Fabel *et al.*, 2012). If that is correct then all mountain summits were buried beneath the ice sheet, only existing as nunataks during downwastage of the ice. In virtually all cases re-interpretation of trimlines as englacial thermal boundaries has been founded on the application and results of cosmogenic nuclide surface exposure dating, offshore geomorphological evidence that constrains the lateral extent of the ice, and/or two-dimensional models of ice surface configuration along former flowlines. Computer-generated three-dimensional models of the ice-sheet indicate that over northwest England ice thickness may have been in the range 1500-2000 m (Boulton & Hagdorn, 2006; Evans *et al.*, 2009; Hubbard *et al.*, 2009).

During recession from maximum limits the ice sheet went through several phases of internal reorganisation that resulted in both regional and local directional flow switching, and the field evidence for this is particularly pronounced in northwest England (Mitchell & Clark, 1994; Evans *et al.*, 2009; Livingstone *et al.*, 2012; Mitchell, 2013). Such changes indicate that the ice sheet was highly dynamic, undergoing marked changes over short periods, between its initial retreat and final disappearance.

Geomorphological evidence for the dynamic nature of the last sheet during its recession has been gained over many years from sites in northwest England: for example the Kirkham moraine across the southern Fylde (Gresswell, 1967), the Raven Ray moraine across the exit of Kingsdale above Ingleton (Waltham *et al.*, 2010), moraines in valleys of the southern Lake District, and throughout the length of the Windermere basin (Gresswell, 1952, 1962; Wilson & Smith, 2012; Pinson *et al.*, 2013), and the varied glacial, glacifluvial and glacilacustrine sediments associated with the Scottish Readvance along the coast of west Cumbria and across the Solway Lowlands (Merritt & Auton, 2000; Livingstone *et al.*, 2010). These landform and sediment sequences testify to a pattern of ice-sheet decay punctuated by stillstands or readvances, but as yet they have not been constrained by absolute ages.

In contrast, ice-sheet fluctuations dated at widely spaced sites from the coasts of northwest and eastern Ireland have enabled J. Clark *et al.* (2012) to propose that readvances occurred between ~18.2 ka and ~17.1 ka, during the Clogher Head Stadial, and between ~17.1 ka and ~16.0 ka, during the Killard Point Stadial. These readvances have been linked to abrupt climatic changes in the North Atlantic region and demonstrate that a robust chronology is essential in order to understand the dynamic nature of the last ice-sheet.

Dating techniques

Four dating techniques have been utilised in order to obtain age estimates for deglaciation in northwest England. These are radiocarbon (^{14}C) dating, optically stimulated luminescence (OSL) dating, uranium-thorium (U-Th) dating and surface exposure dating using cosmogenic nuclides (CN). Short descriptions of each method are provided below.

Radiocarbon (^{14}C) dating

Radioactive carbon (^{14}C) is created in the upper atmosphere and enters the global carbon cycle. All organisms accumulate and retain a small amount of ^{14}C. When an organism dies ^{14}C no longer accumulates; exchange ceases and the stored ^{14}C undergoes decay at a known rate. Comparing the amount of ^{14}C remaining in fossil material with that present in modern material enables an age of death to be determined for the organism. ^{14}C ages can be obtained on wood, peat, charcoal, shell, coral, bone and soil organic matter. Because there have been long-term variations in the production rate of ^{14}C, the age obtained is not measured in calendar years but in ^{14}C years. To convert from ^{14}C years to calendar years a 'calibration' is applied and for the last 12,000 years this is done using tree rings. Beyond this limit, a combination of fossil corals, laminated marine sediments, and U-Th dating has been used to extend the calibration to 50,000 years. ^{14}C dating has a range from about 250 years to 60,000 years.

Optically Stimulated Luminescence (OSL) dating

When mineral grains (such as quartz and feldspar) are buried in sediment they receive ionising radiation from naturally occurring isotopes of potassium, uranium and thorium. This radiation strips some electrons from the outer shells of the mineral atoms. The electrons become trapped temporarily within defects in the mineral crystal lattice but can be released by directing a beam of light onto the sample: the amount of light emitted (luminescence signal) by the illuminated mineral grain is proportional to the total absorbed radiation dose. The amount of trapped electrons is related to both the duration and intensity of radiation exposure. When mineral grains are exposed to natural daylight, their trapped electrons are released thus 'bleaching' the signal – sometimes called 'resetting the clock'. On subsequent reburial, the mineral grains once again start to accumulate trapped electrons. The luminescence signal is a measure of the time elapsed since burial and removal from sunlight. OSL dating has been widely applied to aeolian sediments and has a range from a few hundred years to about 400,000 years.

Uranium-Thorium (U-Th) dating

Uranium-Thorium (U-Th) dating is routinely used for age determination of both marine and terrestrial carbonates. In caves, naturally occurring uranium isotopes transported in solution by groundwater become incorporated in calcite speleothems. The crystals within the speleothem act as a closed system so that as the uranium isotopes undergo radioactive decay to thorium and other daughter isotopes these products remain locked within the calcite. Unlike the parent uranium isotopes, the thorium isotopes are insoluble and in samples of pure calcite must originate from the decay of the parent uranium since crystallisation. Measurements of the ratios of the uranium isotopes to their daughter products enable the speleothem to be dated. U-Th dating has a range from a few hundred years up to about 500,000 years.

Cosmogenic Nuclide (CN) surface exposure dating

Cosmogenic nuclides (or isotopes) are produced when a rock surface is bombarded by high-energy neutrons and other subatomic particles known as cosmic rays. Cosmic rays interact with all elements contained in the minerals of the rock and create new nuclei. The most commonly used nuclides are beryllium-10 (^{10}Be), aluminium-26 (^{26}Al) and chlorine-36 (^{36}Cl) and these accumulate in rock over time depending on the half-life of the isotope, the erosion rate, the rock composition and the intensity of the cosmic rays. By measuring the concentration of an isotope and knowing its rate of production, it is possible to establish how long the rock surface has been exposed to cosmic radiation. CN exposure dating is widely used to date ice-transported boulders and ice-moulded bedrock outcrops, and has a range from a few hundred years up to several million years.

Deglaciation

Chiverrell *et al*. (2013) used geochronological data to document the rapid northward retreat of the Irish Sea Ice Stream from its maximum limit ~150 km southwest of the Isles of Scilly at around ~25-24 ka to a position in the northern sector of the Irish Sea at ~18-17 ka. This latter position was indicated as corresponding to the Kirkham moraine of the Fylde and the Bride moraine in the north of the Isle of Man (Fig. 2). The margin of the ice sheet was not shown east of the Kirkham moraine but it can be inferred that north Lancashire, the Yorkshire Dales, and Cumbria still retained much of their ice cover at that time. Whilst this may be true, the dating evidence from these areas indicates that they too were undergoing dramatic environmental changes associated with the rapidly decaying ice sheet.

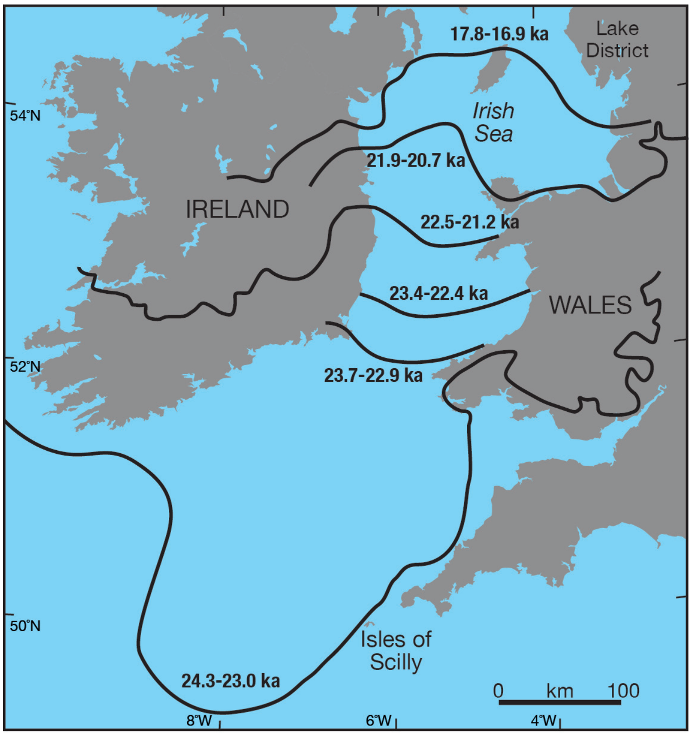

Figure 2. Retreat stages of the last British-Irish Ice Sheet in the Irish Sea basin and on adjacent land areas (after Chiverrell et al., 2013).

In using the existing ages to outline the deglacial chronology of northwest England it must be recognised that some of them might be less reliable than others and should therefore be treated with caution. For most of the 15 dated sites (Fig. 3) the age is derived from a single sample and age reliability can only be judged against other similarly dated sites, the wider geomorphological evidence, and/or proxy climate data from the NGRIP ice core. At least two of the ages indicated on Fig. 3 and detailed in Table 1 may be too old (Low Wray Bay and Hallsenna Moor – discussed later), and further dating at these sites would be appropriate. Furthermore another two ages have large uncertainty values (White Scar Cave ±4 ka and Warton Crag ±2.6 ka) rendering them less precise estimates for the dated sedimentary events. The tightest constraints on the loss of ice cover are provided by the CN ages; all other ages (^{14}C, OSL and U-Th) do not directly relate to retreat of the ice, rather they record sedimentary events made possible by the removal of ice, (i.e. the ice had to have gone from these sites in order for the sediments to accumulate), and in these cases the temporal lag cannot be quantified. Therefore these ages are *minimum* ages for deglaciation.

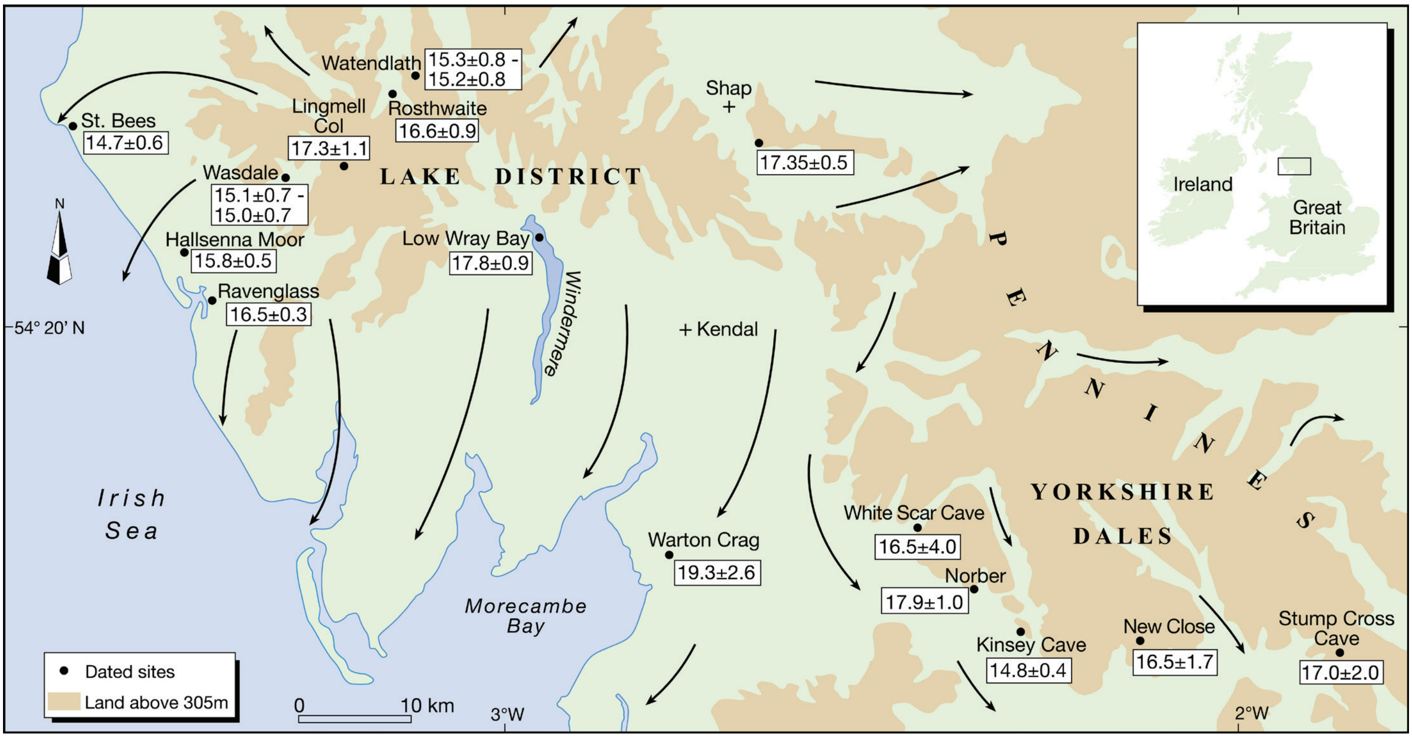

Figure 3. Northwest England, as defined for the purposes of this paper, showing locations of sites with age estimates pertaining to deglaciation. Arrows indicate generalised directions of ice flow during the Last Glacial Maximum. For clarity the only lake shown in the Lake District is Windermere. Details of all the age estimates are given in Table 1.

Table 1. Age estimates (ordered by area and year of publication) relating to loss of glacial ice cover following the Last Glacial Maximum in northwest England. ^{14}C ages are reported at 2σ, ^{10}Be, ^{36}Cl, U/Th and OSL ages are reported at 1σ.

Source	Location	Material dated	Context	Method	Age (ka)
North Lancashire					
Telfer *et al*. (2009)	Warton Crag	Loess	Doline infill	OSL	19.3±2.6
Yorkshire Dales					
Sutcliffe *et al*. (1985)	Stump Cross Cave	Speleothem	Cave deposit	U/Th	17.0±2.0
Atkinson *et al*. (1986)	White Scar Cave	Speleothem	Cave deposit	U/Th	16.5±4.0
Lord *et al*. (2007)	Kinsey Cave	Bone	Cave deposit	^{14}C	14.8±0.4 [a]
Telfer *et al*. (2009)	New Close	Loess	Doline infill	OSL	16.5±1.7
Wilson *et al*. (2012)	Norber	Rock	Erratic boulders	^{36}Cl	17.9±1.0 [b]
Lake District					
Coope & Pennington (1977)	Low Wray Bay	Organic silt	Lake sediment	^{14}C	17.8±0.9 [a]
Coope & Joachim (1980)	St. Bees	Wood fragments	Kettle hole infill	^{14}C	14.7±0.6 [a]
Walker (2004)	Hallsenna Moor	Organic mud/silt	Lake sediment	^{14}C	15.8±0.5 [a]
Ballantyne *et al*. (2009)	Lingmell Col	Bedrock	Ice-moulded rock	^{36}Cl	17.3±1.1
McCarroll *et al*. (2010)	Wasdale	Bedrock	Roche moutonnée	^{10}Be	15.1±0.7 – 15.0±0.7 [c]
Lloyd *et al*. (2013)	Ravenglass	Organic clay	Estuarine sediment	^{14}C	16.5±0.3 [a]
Wilson *et al*. (2013a)	Shap	Rock	Erratic boulders	^{10}Be	17.35±0.5 [d]
Wilson *et al*. (2013b)	Watendlath	Rock	Erratic boulder	^{10}Be	15.3±0.8 – 15.2±0.8 [c]
	Rosthwaite	Rock	Erratic boulder	^{36}Cl	16.6±0.9

a: calibrated using OxCal v4.2 (Bronk Ramsey, 2009) and the IntCal 13 calibration curve (Reimer *et al*., 2013).
b: mean of age determinations on three boulders, not corrected for temporal variations in production rate.
c: calibrated using CRONUS Earth online calculator with northwest Highlands local production rate (12.2±0.3 ka) assuming 1 mm/ka erosion. Ages represent oldest and youngest of four different scaling schemes.
d: calibrated using CRONUS Earth online calculator with northwest Highlands local production rate (12.2±0.3 ka) assuming 1 mm/ka erosion. Mean of age determinations on three boulders.

North Lancashire and Yorkshire Dales

For these areas of northwest England five ages provide constraints on deglaciation and another indicates the timing of re-colonisation of the landscape by large carnivorous mammals and, by inference, their prey. The earliest age (19.3±2.6 ka) is an OSL age from loess at 103 m OD on the southern side of Warton Crag in north Lancashire (Telfer *et al.*, 2009). Loess is aeolian silt and has a thin and patchy distribution on the limestone uplands around Morecambe Bay and in the Yorkshire Dales (Bullock, 1971; Vincent & Lee, 1981). The loess is thought to have accumulated as a result of the deflation of glacigenic sediments soon after the ice had vacated these areas. The uncertainty value of ±2.6 ka associated with this age means that loess deposition could have occurred at any time between 21.9 ka and 16.7 ka. If Chiverrell *et al.* (2013) are correct in their assignment of an age of ~18-17 ka for the Kirkham moraine, then deposition of the Warton Crag loess is likely to have been towards the latter part of the 5 ka range, i.e. at ~17 ka.; if they are not correct and if loess deposition occurred between ~22 ka and ~18 ka then a large swathe of northwest England was free of ice earlier than previously envisaged.

In contrast to Warton Crag, which was inundated by ice from the north, including the Shap area (Strahan, 1888; Standing, 2012), the Yorkshire Dales were affected by ice generated within the west Pennine uplands (Mitchell & Hughes, 2012; Mitchell, 2013). Four dates from sites close to the western and southern margins of the Dales indicate that deglaciation at those sites had occurred by ~18-16.5 ka. However, because of the large uncertainty value associated with the White Scar Cave age (±4 ka) this apparently narrow age range of 1.5 ka expands to 8 ka (20.5-12.5 ka) when the uncertainty on this single sample is taken into account. This sample and that from Stump Cross Cave are U-Th ages from speleothems and indicate that groundwater flow had become re-established following the loss of glacial ice and/or permafrost degradation, facilitating calcite deposition (Sutcliffe *et al.*, 1985; Atkinson *et al.*, 1986). However, both ages are sufficiently imprecise to be anything other than 'ballpark' estimates for deglaciation.

An OSL age of 16.5±1.7 ka was reported by Telfer *et al.* (2009) for loess at New Close, near Malham. As with Warton Crag, the New Close loess must have accumulated on ground vacated by the ice, and initial deposition may have been slightly earlier than indicated by the OSL age because the dated sample was collected ~25 cm above the base of the loess in the excavated pit.

The mean ^{36}Cl CN exposure age from three of the greywacke erratic boulders at Norber provides the first, and so far only, direct age estimate for deglaciation of the Dales. This age, first reported by Vincent *et al.* (2010) as 18.0±1.6 ka and revised by Wilson *et al.* (2012) to 17.9±1.0 ka, gives the best indication to-date for the timing of deglaciation. However, the age only informs us that the Norber site had lost its cover of glacial ice, large amounts of ice must have still existed elsewhere in the Dales, for example in upper Ribblesdale from where the Norber ice was sourced. Only by CN exposure dating of many more sites in the Dales will the detailed chronology of deglaciation emerge.

From Kinsey Cave (Fig. 3) and also Victoria Cave, both near Settle, ^{14}C ages of 14.8-14.7±0.4 ka have been obtained on the remains of *Ursus arctos* (brown bear) (Lord *et al.*, 2007; O'Connor & Lord, 2013). Although these ages post-date deglaciation of the Dales landscape by up to 2-3 ka they are important because they inform us that marked environmental changes had occurred such that bears were able to colonise the area. The ^{14}C ages correspond with the abrupt warming signal at 14.7 ka, defining the start of the Lateglacial Interstadial, identified in the NGRIP ice core (Andersen *et al.*, 2006; Lowe *et al.*, 2008), suggesting that bears and other animals responded rapidly to climatic amelioration. By implication the landscape supported and was able to supply sufficient food resources to maintain a population of these carnivores. To date these remains represent the earliest known examples of large mammals in northwest England following the retreat of the last ice sheet.

Cumbria

For some time the ^{14}C age of 17.8±0.9 ka from the organic muds of Low Wray Bay, Windermere, (Fig. 3; Coope & Pennington, 1977) was the only absolute age constraint relating to deglaciation of the mountainous tract of the central Lake District. Tipping (1991) regarded this age as too old because of the likelihood of hard-water contamination; a view later endorsed by M.J.C. Walker, (2007, pers. comm.), but it has continued to be treated as reliable and cited in the literature (e.g. C.D. Clark *et al.*, 2012; Livingstone *et al.*, 2012; Pinson *et al.*, 2013). Because it is difficult to reconcile this age with more recent CN exposure ages from the Cumbrian uplands and because there is no evidence of marked warming in the NGRIP ice core at that time (Andersen *et al.*, 2006; Lowe *et al.*, 2008) that would favour organic sedimentation, it would probably be best if the age was allowed to retire gracefully.

CN exposure ages (^{10}Be and ^{36}Cl) are available for several Cumbrian sites although some ages are clearly too old (i.e. they either pre-date the LGM or are coincident with it) and do not enable a realistic assessment of deglaciation at those locations. However, five CN ages, from Lingmell Col, Shap, Rosthwaite, Watendlath and Wasdale (Fig. 3, Table 1), are presently considered to be reliable and these provide the basic foundation of a deglacial framework.

From Lingmell Col (750 m OD), Ballantyne *et al.* (2009) reported a ^{36}Cl age of 17.3±1.1 ka from ice-moulded bedrock. This age was taken to indicate ice-sheet downwastage and exposure of high ground in the central Lake District, and is largely consistent with CN ages from high level sites in other mountain areas of Britain and Ireland. A mean age of 17.35±0.5 ka from three erratic boulders of Shap granite from limestone terrain in eastern Cumbria at 275-325 m OD was obtained by Wilson *et al.* (2013a). These erratics were 2.5-4.25 km from the margin of the pluton and their mean exposure age gives the first direct indication of when the local landscape emerged from its cover of glacial ice. The Lingmell Col and Shap ages are statistically indistinguishable and taken together demonstrate that as mountain summits were emerging from the downwasting Lake District ice dome the lower ground in eastern Cumbria, and by inference elsewhere in the region, was also emerging as a consequence of backwasting. These ages are broadly consistent with those discussed above from the Yorkshire Dales.

Single CN exposure ages from ice-transported boulders at both Watendlath (15.3-15.2±0.8 ka) and Rosthwaite (16.6±0.9 ka) (Wilson *et al.*, 2013b), and a roche moutonnée at Wasdale (15.1-15.0±0.7 ka) (McCarroll *et al.*, 2010) indicate that valley glaciers were present in the Lake District between ~17 ka and ~15 ka in at least three valleys. The ages from Watendlath and Wasdale imply that glaciers persisted in these valleys until just prior to the rapid warming of climate that marks the opening of the Lateglacial Interstadial at 14.7 ka. Similar ages have been reported for Wester Ross, northwest Scotland, (Ballantyne & Stone, 2012) and Galloway, southwest Scotland, (Ballantyne *et al.*, 2013). The persistence of glaciers in the hills of Galloway until ~15.5-15.0 ka is interesting because this area is only 100 km northwest of the Lake District. It is important that additional CN ages are obtained from Watendlath, Rosthwaite and Wasdale, as well as from other Lake District valleys, in order to assess the validity of these initial ages.

Two readvances of the last ice sheet into the north and west of Cumbria during deglaciation of the region were proposed by F.M. Trotter and co-workers during the 1920s and 1930s (Trotter, 1929; Trotter & Hollingworth, 1932; Trotter *et al.*, 1937). The earlier of these events was termed the Gosforth Oscillation and the later one the Scottish Readvance. More recent work has confirmed the presence of landforms and sediments associated with such ice movements, and although tentative provisional ages have been assigned to the events (Gosforth Oscillation ~20-18 ka; Scottish Readvance ~17-16 ka) they await absolute dating constraints (Merritt & Auton, 2000; Livingstone *et al.*, 2010, 2012).

Three post-glacial ^{14}C ages have been reported for west Cumbrian sites, all of which are either within or adjacent to the limit of Scottish Readvance ice. The age of 14.7±0.6 ka from wood fragments within an organic sequence in a kettle hole in the St. Bees push moraine (Coope & Joachim, 1980) is coincident with the abrupt warming that heralded the Lateglacial Interstadial, and is indistinguishable from those of the earliest dated brown bears from caves in the Yorkshire Dales. This can be regarded as confirmation that climatic amelioration was region-wide and that glacial ice had either gone completely or was by then restricted to the upper reaches of upland valleys.

The other two ages, one from organic muds in a former lake basin at Hallsenna Moor (15.8±0.5 ka; Walker, 2004), the other from organic clay in an estuarine sequence 2 km north of Ravenglass (16.5±0.3; Lloyd *et al.*, 2013) suggest, at face value, that organic accumulation was occurring during a period when climate was still severely cold (Andersen *et al.*, 2006; Lowe *et al.*, 2008) and with significant valley glaciers still present in the Lake District (McCarroll *et al.*, 2010; Wilson *et al.*, 2013b). Walker (2004) considered the pollen spectra of the dated Hallsenna Moor muds consistent with a Lateglacial Interstadial assemblage (14.7-12.9 ka) but the ^{14}C age as being too old, probably because of contamination by mineral carbon. The ^{14}C age from near Ravenglass cannot be dismissed as easily; the associated pollen spectra indicates a sedge-tundra vegetation community consistent with sedimentary sequences from elsewhere in Cumbria that are known to pre-date the Lateglacial Interstadial (Lloyd *et al.*, 2013). If the Ravenglass age is reliable it provides a minimum age for deglaciation of Scottish Readvance ice for this area of the Cumbrian coast. Interestingly, the sedimentary sequence from which Lloyd *et al.*, (2013) obtained the ^{14}C age was shown to contain a ~45 cm-thick peat bed below the dated organic-rich clay. Therefore the site has the potential to provide an even tighter constraint on local deglaciation.

Conclusions

Prior to 2009 very few absolute age determinations relating to the deglaciation of northwest England were available. Of these, two are now regarded as too old and another two have large uncertainty values rendering them imprecise age estimates. In the last five years several additional ages have been obtained, providing the basis of an outline deglacial chronology. While some of these ages also have large uncertainty values and a temporal lag applies to others, the indications are that between ~18 ka and ~17 ka both high and low ground throughout northwest England began to emerge from its cover of glacial ice. Valley glaciers were still present in the Lake District at ~15 ka but are unlikely to have persisted much beyond 14.7 ka when rapid warming of climate occurred. In future years a more detailed picture of deglaciation is likely to emerge as a consequence of the on-going BRITICE-CHRONO project.

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