The Deglaciation of Cumbria: Insights from some Recent Dating Studies

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Introduction

During the last ten years several studies have been published in which numerical ages relating to the deglaciation of Cumbria are reported. Some of these studies were summarised in an earlier paper in these Proceedings (Wilson, 2014) and elsewhere (Wilson & Lord, 2014). Since that time, other ages have been obtained and provide additional insights into the timing of the loss of glacial ice cover in different parts of the county. Some of the recently acquired ages suggest that previous ones, about which an element of doubt had existed because they were single ages from scattered sites, can now be considered as accurate. Together these ages allow statements concerning deglaciation of Lake District valleys to be made with a greater degree of confidence (Wilson et al., 2018). Other recently obtained ages from the coastal/upland fringe of west Cumbria (Chiverrell et al., 2018) give an indication of the timing of land emergence from beneath the Irish Sea/Lake District sector of the last ice sheet and the age of the Scottish Readvance. Additional numerical ages pertaining to deglaciation are now available from Talkin Tarn, near Brampton (Livingstone et al., 2015), and from the bottom sediments of Windermere (Avery et al., 2019).

The Last British-Irish Ice Sheet

The last period of extensive glaciation (hereafter termed the Last Glaciation) in the British and Irish Isles occurred during the Dimlington Stade of the Late Devensian substage (~28-15 ka(thousand of years); Rose, 1985; 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). During that time 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; Clark et al., 2012; Ó Cofaigh et al., 2012, 2019; Peters et al., 2015; Callard et al., 2018; Evans et al., 2019; Bradwell et al., in press). 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 ~250-300 km southwest of the Isles of Scilly to the Celtic Sea shelf edge (Praeg et al., 2015; Scourse et al., 2019; Figure 1).

The surface elevation of the last ice sheet in mountain areas of Britain and Ireland has been deduced from several lines of evidence. Results from cosmogenic nuclide surface exposure-age dating, offshore geomorphological and sedimentological evidence that constrains the lateral extent of the ice, and two and three dimensional models of ice surface configuration along former flowlines, indicate that the ice surface elevation may have been in the range 1000-2000 m (Boulton & Hagdorn, 2006; Evans et al., 2009; Hubbard et al., 2009; Fabel et al., 2012). Assuming the minimum value of this range to be accurate, at ice sheet maximum extent none of the mountain summits in Cumbria would have projected above the ice as nunataks.

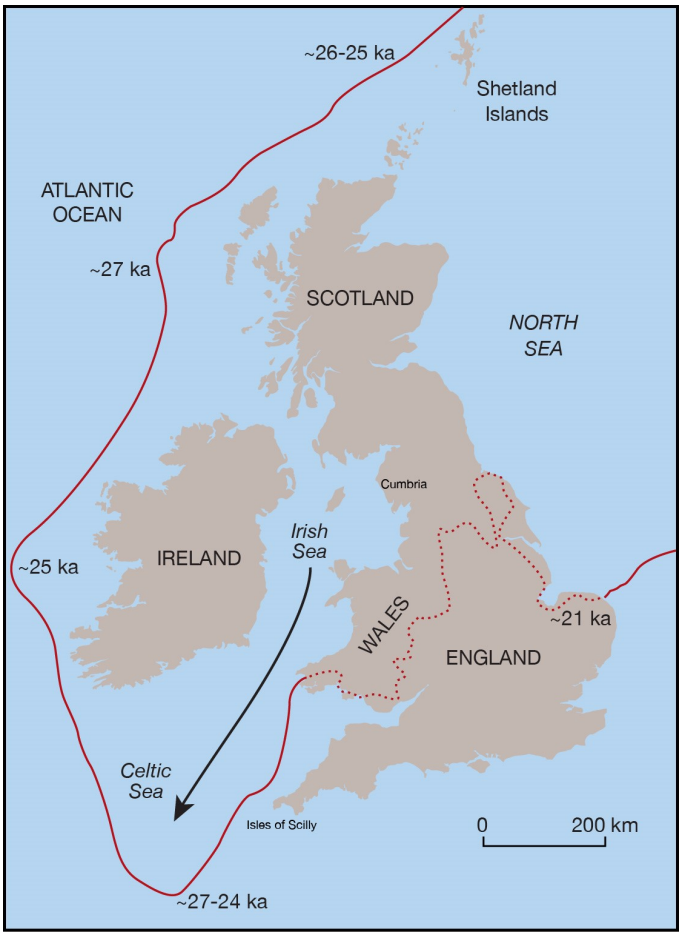


Figure 1. Maximum extent and timing of the last British -Irish Ice Sheet shown by solid red line offshore and red dots onshore (based on Sejrup et al., 2005; Clark et al., 2012; Ó Cofaigh et al., 2012, 2019; Peters et al., 2015; Praeg et al., 2015; Callard et al., 2018; Evans et al., 2019; Scourse et al., 2019; Bradwell et al., in press).

Dating evidence indicates that the last ice sheet reached its maximum extent at different times in different sectors. For example, radiocarbon (^{14}C) ages reveal the limit attained by the Irish Sea Ice

Stream at the Celtic Sea shelf edge occurred at~ 27-24 cal.(calibrated) ka BP (Scourse et al., 2019), the maximum extent to the west of Ireland was at ~25 cal. ka BP (Peters et al., 2015; Ó Cofaigh et al., 2019), at ~27 cal. ka BP to the west of the Hebrides (Callard et al., 2018) and at ~26-25 ka to the west of Shetland (Bradwell et al., in press). In contrast, optically stimulated luminescence (OSL) ages suggest the North Sea Lobe of the last ice sheet reached its southernmost limit, on the coast of north Norfolk, at ~21 ka (Evans et al., 2019).

Dating evidence also shows that rates of ice retreat from maximum limits varied between different sectors of the ice sheet. The most rapid rates of retreat were from sectors with marine-terminating ice margins, such as from the Celtic Sea shelf edge and the shelf edge to the west of Ireland and Scotland, although retreat was episodic and punctuated by several stillstands or readvances. The causes of rapid retreat along the southern sector of the Irish Sea Basin have been linked to the geometry (size, shape, and bed slope and orientation) of the basin and the width of the calving ice margin rather than with ocean-climate forcing (Chiverrell et al., 2013; Smedley et al., 2017; Small et al., 2018). In contrast, ice retreat from marine -terminating margins to the west of Ireland and Scotland is associated with glacial isostatic crustal depression that caused high relative sea level and ice losses by calving, rather than by increases in ocean-atmosphere temperatures (Callard et al., 2018; Benetti et al., 2019; Ó Cofaigh et al., 2019).

Cumbria

During the Last Glaciation the mountains of Cumbria were one source of ice for the Irish Sea Ice Stream but they also supplied ice that flowed north and east into the Tyne Gap, east across Stainmore Pass and south across Lancashire and into the Cheshire-Shropshire lowlands (Clark, 1990; Chiverrell & Thomas, 2010; Livingstone et al., 2010c). The pattern and retreat of the ice margin from its maximum limits in the various ice sheet sectors has been subjected to detailed investigation in recent years through the BRITICE-CHRONO project (http://www.sheffield.ac.uk/ geography/research/britice-chrono/home). Although terrestrial upland regions were not the focus of the project, deglaciation of the coastal fringe of Cumbria was included because it borders the northern Irish Sea Basin and it falls within the area considered to have been influenced by a late readvance of ice from southwest Scotland (the Scottish Readvance) first identified by Trotter (1929) and since subjected to much investigation and debate.

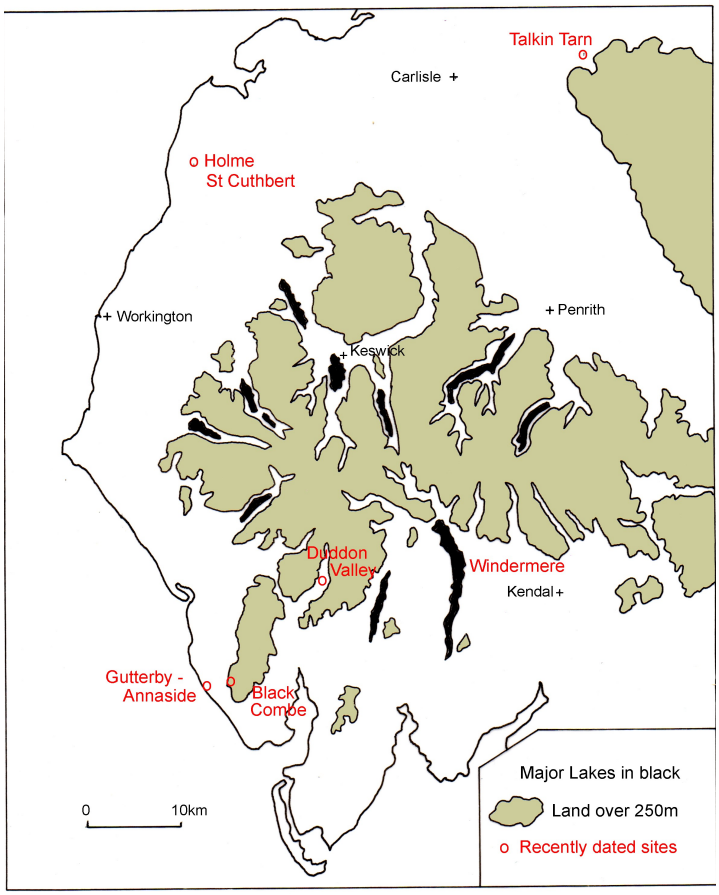
Deglaciation of Coastal Cumbria

The paper by Chiverrell et al. (2018) presents a new chronology that constrains ice-margin retreat in the northern basin of the Irish Sea. The work extends a deglacial chronology established by Chiverrell et al. (2013) by using terrestrial evidence for geomorphology, landform-sediment assemblages and ice-flow indicators from the Isle of Man and coast of Cumbria. In addition, the new chronology utilises offshore geomorphological, sedimentological and geophysical data obtained during cruise JC106 of the RRS James Cook in July 2014.

Previously, three ^{14}C (Carbon 14) ages pertaining to the loss of ice cover from the coast of Cumbria had been published. These were ages of 14.7±0.6 cal ka BP on wood fragments from sediments filling a kettle hole at St. Bees (Coope & Joachim, 1980), 15.8±0.5 cal ka BP on organic mud from lake sediments at Hallsenna Moor (Walker, 2004) and 16.5±0.3 cal ka BP from organic clay within estuarine sediments near Ravenglass (Lloyd et al., 2013). These ages represent minimum ages for deglaciation at the respective sites, i.e. the ice had to have gone in order for the organic materials to accumulate. Although it is not possible to know the time lag involved between ice loss and organic accumulation, the ages are unlikely to be close estimates for deglaciation. Moreover, Walker (2004) considered the Hallsenna Moor age as too old, probably because of contamination by mineral carbon.

Chiverrell et al. (2018) reported: (1) terrestrial cosmogenic nuclide (TCN) 10Be surface-exposure ages from four erratic boulders of Eskdale granite at ~255 m above sea level on the western flank of Black Combe, southwest Cumbria; (2) two OSL ages from glaciolacustrine sands and outwash sands, respectively, from coastal exposures in the ice-marginal ridges at Gutterby-Annaside, 2-3 km west of the Black Combe TCN site; and (3) two OSL ages from outwash sands at Aldoth Quarry within the Holme St. Cuthbert glaciolacustrine delta at 45 m above sea level, northwest Cumbria (Figure 2, Table 1).

The four ^{10}Be surface-exposure ages from erratic boulders of Eskdale granite on Black Combe are within the range 17.7±1.0 - 24.4±1.3 ka. However, the four ages do not form a statistically coherent group and taking the simple average is unwarranted. Only two of the ages are statistically inseparable (T3BC05 – 21.7±1.2 ka and T3BC06 – 22.4±1.3 ka; Figure 3A and 3B) and these average at 22.1 ka. This value can be regarded as providing an age estimate



for downwasting (surface lowering) of the Irish Sea Ice Stream to a height of ~255 m above sea level on the south-western margin of the Lake District. With the summit of Black Combe at 600 m above sea level and the ice surface at an unknown height above this level at ice sheet maximum extent (27-24 ka), downwasting of over 350 m occurred during a period of ~2-5 ka. With current maximum water depths in the eastern sector of the northern Irish Sea of ~35 m, the ice thickness at the time of boulder exposure likely exceeded 300 m. Based on typical ice stream surface gradients, Chiverrell et al. (2018) estimated that when the ice surface had lowered to ~255 m on the flanks of Black Combe, the southern margin of the Irish Sea Ice Stream had retreated to north of the Llŷn Peninsula in North Wales. Dates from the Llŷn Peninsula confirm this to be the case (Smedley et al., 2017). The Black Combe ages along with ages from Wales, Ireland and the Isle of Man indicate that retreat and decay of the Irish Sea Ice Stream and adjacent mountain-based ice centres was rapid.

Figure 2. Locations of recently obtained ages relating to the deglaciation of Cumbria.

Source	Location	Material dated	Sample code	^{10}Be ages[1,2] (ka)	OSL ages[1,3] (ka)	^{14}C ages[4] (cal. ka BP)
Chiverrell *et al.* (2018)	Black Combe	Erratic boulder	T3BC02	17.7±1.0 (0.6)		
		Erratic boulder	T3BC03	24.4±1.3 (0.7)		
		Erratic boulder	T3BC05	21.7±1.2 (0.7)		
		Erratic boulder	T3BC06	22.4±1.3 (0.8)		
Chiverrell *et al.* (2018)	Gutterby-Annaside	Sand	T3GUTT01		27.0±3.3	
		Sand	T3GUTT03		21.7±2.6	
Chiverrell *et al.* (2018)	Holme St. Cuthbert	Sand	T3ALDO01		20.2±3.5	
		Sand	T3ALDO02		27.9±4.7	
Wilson *et al.* (2018)	Duddon Valley	Erratic boulder	DUD-01	16.5±0.9 (0.5)		
		Erratic boulder	DUD-02	16.7±0.9 (0.6)		
		Erratic boulder	DUD-05	17.0±0.9 (0.6)		
		Erratic boulder	DUD-06	15.9±0.9 (0.5)		
Avery *et al.* (2019)	Windermere	Organic mud	SUERC-64860			13.5±0.08
Livingstone *et al.* (2015)	Talkin Tarn	Organic mud	BETA-342471			15.7±0.1

[1]Ages are given in thousands of years prior to the year of sampling.

[2]Uncertainties represent total uncertainties at 1σ; analytical uncertainties (1σ) are in parentheses.

[3]Uncertainties represent total uncertainties at 1σ.

[4]Ages are reported as calibrated ages in thousands of years Before Present (i.e. prior to AD 1950).

Table 1. Listing of recently obtained ages (ka) relating to the deglaciation of Cumbria.

The ice-marginal ridges of the Gutterby-Annaside complex yielded OSL ages of 27±3.3 ka and 21.7±2.6 ka from sites 1.2 km apart. Taken at face value, the former age suggests the sands were deposited either prior to the Irish Sea Ice Stream reaching its maximum extent or when it was at its maximum extent (i.e. either ~30-27 ka or 27-24 ka). Both scenarios seem unlikely given that the dated sands forms a component of proximal outwash sediments, and the ridges are ascribed to ice-marginal deposition. Furthermore, the sedimentary sequence has been regarded as reflecting a readvance of the ice, and linked with both the Scottish and Gosforth readvances (Huddart, 1977, 1991; Merritt and Auton, 2000). Therefore the accuracy of this age must be in doubt. The reliability of the latter OSL age is also open to question. When the associated uncertainty is taken into account, an age range of 24.3-19.1 ka results. Given that the ice sheet was >300 m in thickness at 22.1 ka, as determined by the 10Be ages of the Black Combe erratic boulders, it is reasonable to assert that the best estimate for the age of the sands is toward the younger end of this range (i.e. 20-19 ka). It follows therefore that the readvance associated with these sands is of this age.

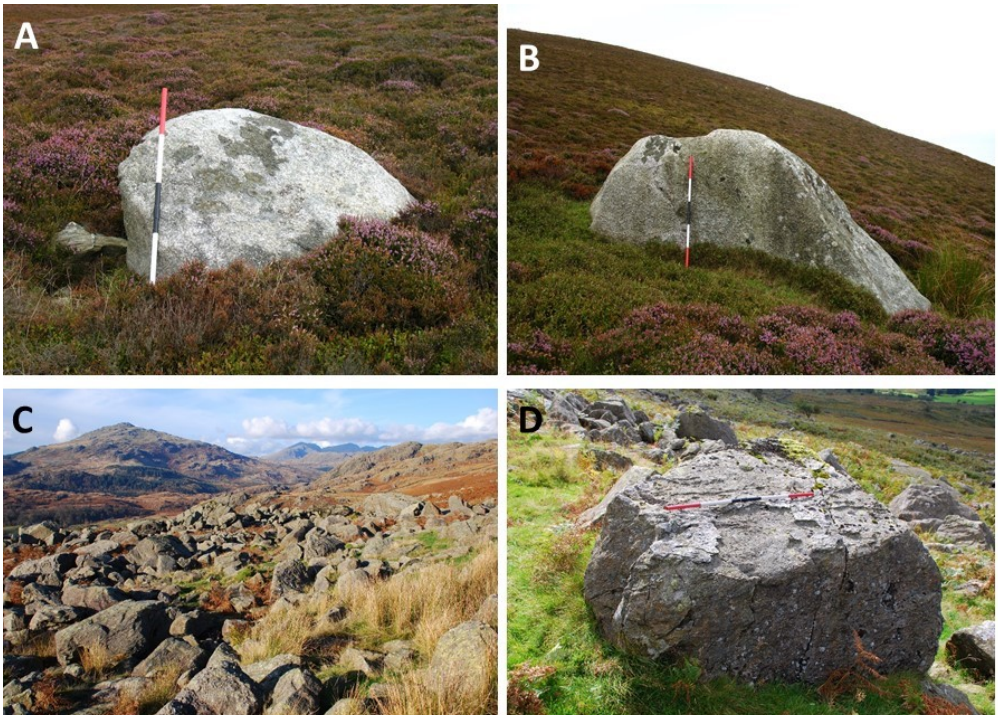


Figure 3. A and B: Granite boulders (TCBC05 and TCBC06) on the flanks of Black Combe sampled for 10Be TCN surface-exposure dating. C: Part of the boulder-dominated lateral moraine near Brock How in the Duddon Valley. D: One of the boulders (DUD-02) from the Duddon Valley moraine sampled for 10Be TCN surface-exposure dating.

Two sand units within the topset beds of the Holme St. Cuthbert delta at Aldoth Quarry returned OSL ages of 20.2±3.5 ka and 27.9±4.7 ka. The delta sands are regarded as evidence for glacial readvance as they overlie drumlinized terrain; the ice that created the drumlins flowed from an easterly direction and must have withdrawn prior to an ice advance from the northwest that impounded a lake into which the delta prograded (Livingstone et al., 2010a). The latter OSL age (range 32.6-23.2 ka) must be considered as unreliable as it spans the period of expansion to, stabilisation at, and initial retreat from maximum ice sheet limits. Chiverrell et al. (2018) regarded this age as anomalous, most likely because the sample was only partially bleached during transport and deposition and probably retained some inherited luminescence signal. The former age of 20.2±3.5 ka, whilst also having a large associated uncertainty value and broad range (23.7-16.7 ka) overlaps with the younger OSL age from Gutterby-Annaside (24.3-19.1 ka) and is less easy to discount.

Chiverrell et al. (2018) used Bayesian statistical models along with ages constraining ice readvance at Jurby, northwest coast Isle of Man, to analyse and interpret this set of OSL ages. The model experiments indicated some synchrony between ice sheet activity at these locations and a best-fit timing for the Scottish Readvance of 19.3±0.8-18.3±1.1 ka. However, although this represents the first attempt to age constrain the readavance, many more (reliable) age estimates are needed to establish the patterns and timings of ice sheet oscillations along the coastal fringe of Cumbria.

Lake District Valleys

Because of their extensive and distinctive moraines the mountain valleys of Lakeland have for long been a focus of interest with respect to establishing a deglaciation chronology. Many of the moraines have been associated with a renewed and short phase of glaciation that occurred during the Loch Lomond (Younger Dryas) Stadial (12.9-11.7 ka) (Manley, 1959;

Pennington, 1977; Sissons, 1980; McDougall, 2001, 2013), although there are few direct age determinations to verify this.

Several valleys have moraine ridges and mounds at locations that are beyond the limits proposed by some researchers for the Loch Lomond glaciers. Age estimates from these features are essential for understanding the pattern and rates of decay of valley glaciers following wastage of the last ice sheet. Single TCN ages, previously reported from three valleys (Wasdale, Borrowdale and Watendlath), indicate that valley glaciers were still present ~16.5-15.4 ka.

Support for the presence of valley glaciers at this time is now available from four consistent ^{10}Be TCN ages from a very distinctive, boulder-dominated, lateral moraine to the north and east of Seathwaite in the Duddon Valley (Figures 2, 3C and 3D). The moraine was described briefly by Mackintosh (1871) and Smith (1912), with a more detailed description being provided by Wilson & Smith (2012). The four ages are in the range 15.9±0.88 - 17.0±0.94 ka and the mean value is 16.51±0.78 ka (Wilson et al. (2018). The moraine is ~7 km from the head of the valley and therefore a substantial residual glacier persisted in the Duddon Valley at that time. It is not known for how much longer after 16.5 ka the glacier survived but Wilson et al. (2018) consider a further 500-1000 years. Taken with the single ages previously obtained from Wasdale, Borrowdale and Watendlath, it seems that Lake District valleys may have hosted glaciers until at least the start of the Windermere (Lateglacial) Interstadial (14.7-12.9 ka) and possibly slightly longer.

For several years a ^{14}C age of 17.8±0.9 cal. ka BP from the organic muds of Low Wray Bay, Windermere (Figure 2; Coope & Pennington, 1977), was the only deglacial age constraint relating to the valleys of Lakeland. This age is now considered as too old in view of more recent TCN dating evidence from elsewhere in the area. In a recent investigation of annually laminated sediments (varves) in Windermere, a stratigraphically coherent ^{14}C age of 13.5±0.08 cal. ka BP was reported from organic muds in a core retrieved from the north basin of the lake (Avery et al., 2019). This age indicates that the glacier that occupied the Windermere valley retreated prior to that time. The sample was taken from near the top of the organic muds and represents a minimum age for deglaciation. However, detailed counting of the Windermere varves enabled Avery et al. (2019) to propose that the south basin may have started deglaciating up to 1.5 ka prior to the start of the Windermere Interstadial at 14.7 ka - that is at ~16.2 ka. The varve record for the north basin indicated that the glacier had retreated ~70 varve years before the Interstadial opened but that varves continued to form for another 158 varve years into the early Interstadial as a consequence of remnant glaciers in the upper valleys of the catchment. These findings provide support for the persistence of valley glaciers elsewhere in the area during the interval ~16.5-15.0 ka.

Northeast Cumbria

For a significant part of the Last Glaciation, the Tyne Gap and Valley functioned as a major outlet route for ice from northern and eastern Cumbria, as well as southern Scotland. Three distinctive moraines, each extending in excess of 20 km across the valley, were created during stillstands or readvances of the Tyne Valley Ice Stream, and the Brampton kame belt, situated southeast of the Tyne Gap, is regarded as an upstream subglacial-to-supraglacial extension of the valley's drainage network. The kame belt is envisaged as having formed when ice stagnated during retreat towards the Solway Lowlands (Livingstone et al., 2010b, 2012).

Talkin Tarn occupies an enclosed kettle hole in the kame belt and its basal sediments were cored as part of an investigation into deglaciation of the Tyne Gap Ice Stream (Livingstone et al., 2015). A sample of organic mud from close to the base of the 0.5 m-long core yielded a 14C age of 15.7±0.1 cal. ka BP. As with the age reported from Windermere by Avery et al. (2019), the Talkin Tarn age is also a minimum estimate for deglaciation at the site. Nevertheless, it provides a valuable age constraint on westward retreat of the Tyne Valley Ice Stream into the Solway Lowlands and southward retreat of ice from the lower part of the Vale of Eden. Thus, a substantial area of northeast Cumbria has been ice-free for at least ~16 ka.

Conclusions

Details of recently acquired ages from erratic boulders that are directly associated with deglaciation and other materials that accumulated since the ice vacated their locations have been presented and explained in terms of their geochronological and geomorphological significance. Together with earlier reported ages, a detailed picture of the pattern and rate of ice wastage following the maximum of the Last Glaciation is beginning to emerge for Cumbria. However, there are still some areas of the county for which there are no direct age determinations and until such time as these 'blanks on the map' are eliminated by additional age estimates our knowledge will remain incomplete.

Acknowledgements

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