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Glaciation and deglaciation age of the Stump Cross area, Yorkshire Dales, northern England, determined by terrestrial cosmogenic nuclide (^{10}Be) dating

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Abstract: Terrestrial cosmogenic nuclide (^{10}Be) surface-exposure ages are reported for three glacially-transported gritstone boulders and one glacially-scoured exposure of gritstone bedrock in the vicinity of Stump Cross Caverns, North Yorkshire. Although the ages do not form a statistically consistent cluster, three of them nevertheless indicate that the transport and deposition of boulders was by ice of the last (Late Devensian) glaciation. The ages provide evidence for glacier ice at the Wharfe–Nidd interfluve, in contrast to previously held views that these uplands had remained above the level of the last ice sheet. The youngest of the three ages on boulders (~18.5 ka) is taken as the best estimate for deglaciation of the area. This is consistent both with surface-exposure ages from sites elsewhere around the southern margin of the Yorkshire Dales and with uranium-series dated speleothems in Stump Cross Caverns. Together these results reveal that deglaciation of the Dales was most likely well advanced by ~18–16 ka, facilitating the rejuvenation of surface and subsurface karstic processes.

Keywords: Glaciation, deglaciation, terrestrial cosmogenic nuclide dating, uranium-series dating, ice-transported boulders, speleothem.

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Refinement of the timescale regarding the last glacial/deglacial cycle for certain areas of northern England has been advanced in recent years through applications of optically stimulated luminescence (OSL) dating of loessic sediment and glacio-lacustrine/fluvial sediments (Telfer *et al*., 2009; Bateman *et al*., 2015), and terrestrial cosmogenic nuclide (TCN) dating of ice-transported boulders and glacially-scoured bedrock (Vincent *et al*., 2010; Wilson *et al*., 2013; Livingstone *et al*., 2015). In addition, the interpretation of the geomorphological and sedimentological evidence displayed by glacigenic landforms and materials has provided valuable information concerning the pattern and style of glacial events (Livingstone *et al*., 2012; Chiverrell *et al*., 2016). Even so, questions remain over whether some parts of the region were glaciated during the Last Glacial Maximum (LGM: ~26.5–19 ka BP; Clark *et al*., 2009) of the Late Devensian sub-stage, and for other areas there is a paucity of detailed information concerning when they emerged from beneath the ice.

In the Yorkshire Dales National Park, deglaciation of limestone terrain is constrained by ages from four sites, all of which occur close to its southern boundary and are a maximum distance of 41km apart (Sutcliffe *et al*., 1985; Atkinson *et al*., 1986; Telfer *et al*., 2009; Wilson *et al*., 2012). The ages suggest the sites became free of ice ~18–16 ka BP (Wilson and Lord, 2014). However, this apparently consistent picture of deglaciation within a relatively narrow timeframe is undermined by the large 1σ uncertainties of 2–4 ka on two of the ages (speleothems at White Scar Cave: 17±4 ka (Atkinson *et al*., 1986), and Stump Cross: 17±2 ka (Sutcliffe *et al*., 1985)). It is therefore important that additional geochronological data are obtained in order to establish whether certain areas were or were not glaciated and, if glaciated, when deglaciation occurred, and by inference provide a maximum age for the resumption of surface and sub-surface karstic processes.

In this respect the Stump Cross area on the Wharfe–Nidd interfluve was identified as a location about which there is limited information concerning its glacial/deglacial history and where it has even been suggested that the tills there may pre-date the Devensian stage (>115 ka; Smith 1977; Catt, 1991; Baker *et al*., 1996). At present, dated speleothems from Stump Cross Caverns provide the only chronology for Late Devensian events in the area, with U–Th ages of 17±2 ka and 15±1 ka (Sutcliffe *et al*., 1985) indicating the renewal of groundwater flow and calcite deposition following the removal of glacial ice cover and/or permafrost degradation after the LGM. In the vicinity of the Caverns, there are several large ice-transported boulders of coarse-grained Millstone Grit sandstone ("gritstone"). These boulders were targeted for TCN dating with the aims of establishing: (1) whether the last ice-sheet covered the area and was responsible for transporting the boulders, and (2) the timing of deglaciation and associated deposition of the boulders.

Cosmogenic nuclides are formed *in situ* when a rock surface is bombarded by high-energy neutrons and subatomic particles known as cosmic-rays. This interaction alters elements contained in the minerals of the rock and new nuclei are created (cosmogenic nuclides). The most commonly used nuclides, beryllium-10 (^{10}Be), aluminium-26 (^{26}Al) and chlorine-36 (^{36}Cl) accumulate in rock over time, depending upon the half-life of the nuclide, the rate of rock surface erosion, the composition of the rock and the intensity of the bombardment. Measurement of the concentration of a nuclide and knowing its rate of production and half-life, enables the determination of how long a rock surface has been exposed to cosmic radiation (Gosse and Phillips, 2001; Phillips, 2001; Cockburn and Summerfield, 2004). Implicit in the meaningful interpretation of surface exposure ages relating to glaciation/deglaciation is that the rock surface must have been exposed continuously and without disturbance since the loss of ice cover. Furthermore, cosmogenic nuclides that accumulated during a previous period of exposure (i.e. inherited nuclides) should not be present.

Stump Cross

The Stump Cross area (360m OD; National Grid Reference SE 089 635; Figs 1 and 2) is on the broad interfluve between the valleys of Wharfedale, to the west, and Nidderdale, to the east, and is ~30–35km inside (i.e. north of) the LGM ice limit (Clark *et al*., 2004). The bedrock consists of Dinantian limestones overlain to the north by rocks of the Namurian Millstone Grit Group (specifically the Grassington Grit Formation) (Dunham and Stubblefield, 1945).

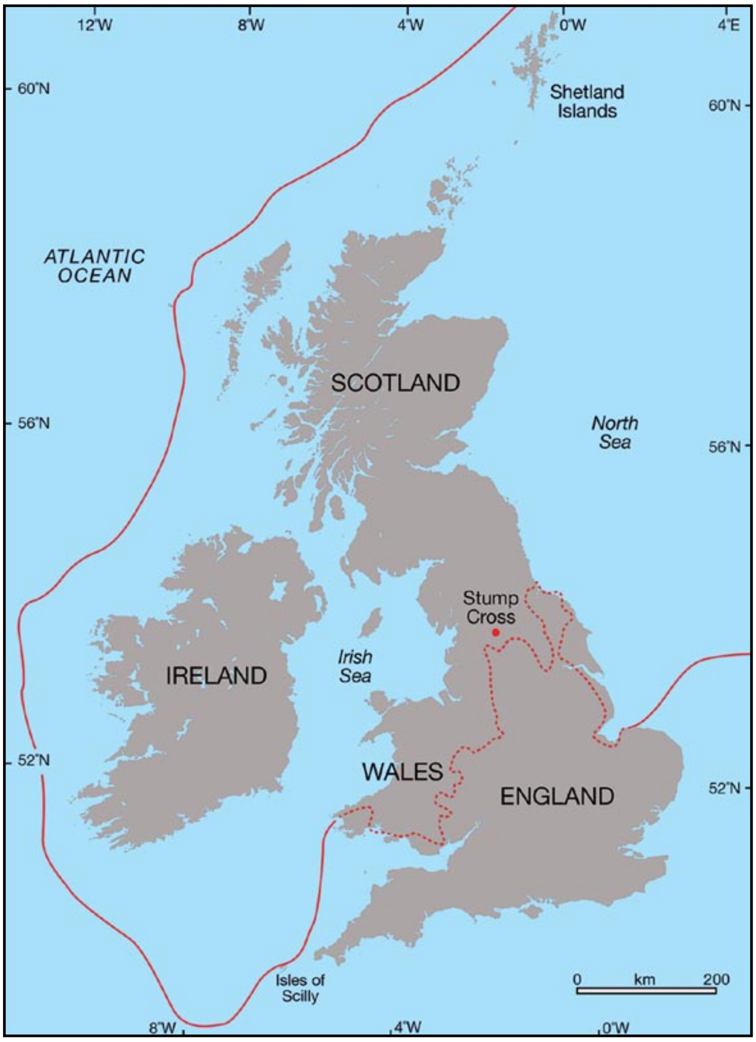

Figure 1: *The location of Stump Cross in relation to the maximum extent of the British–Irish Ice Sheet during the Last Glacial Maximum (after Scourse and Furze, 2001; Clark et al., 2004; Sejrup et al., 2005; Bradwell et al., 2008; McCarroll et al., 2010; Ó Cofaigh et al., 2012).*

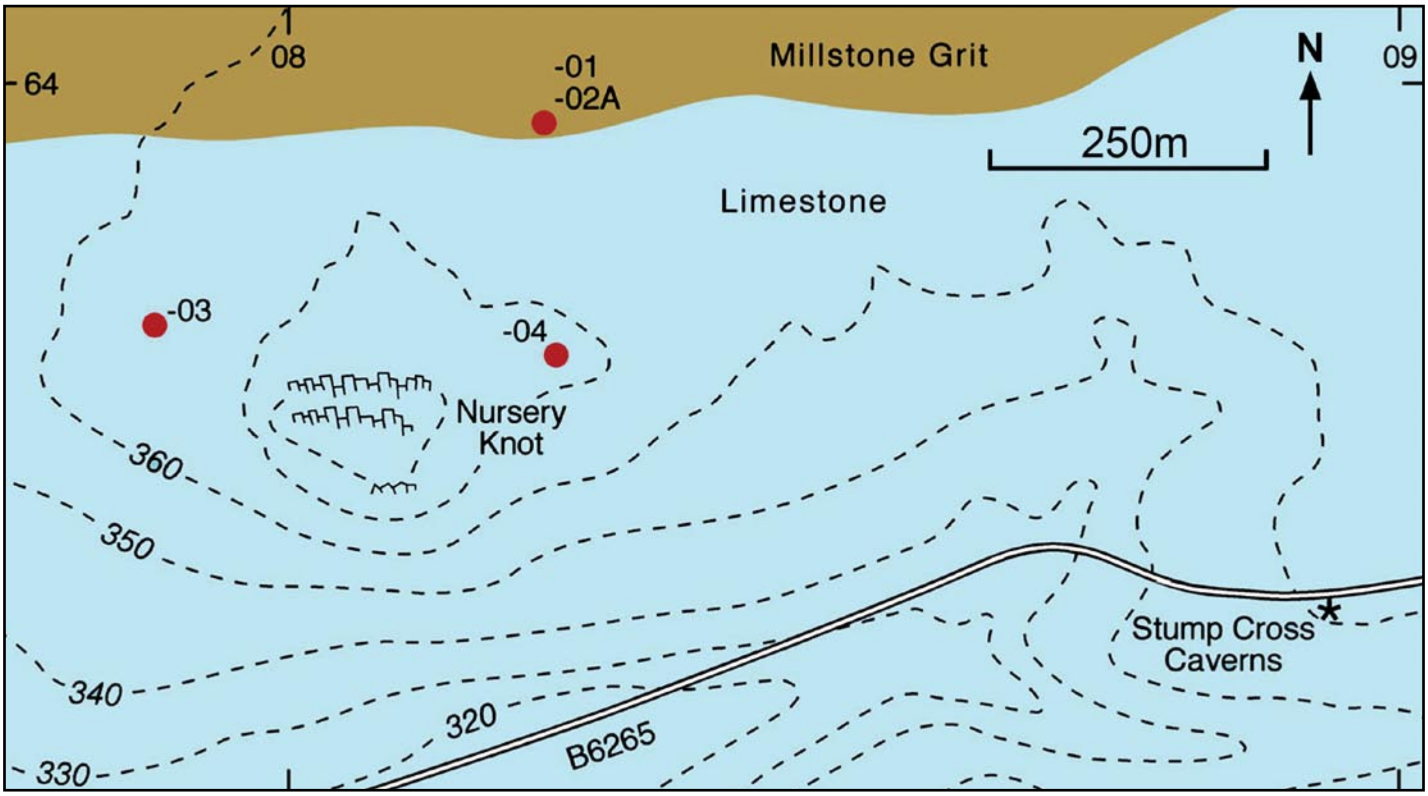

Figure 2: *Locations of Stump Cross Caverns, Nursery Knott, and the boulders (red dots) sampled for TCN dating. The geological boundary is based upon Dunham and Stubblefield (1945).*

Sample code	Grid reference	Latitude (°N)	Longitude (°W)	Altitude (m OD)	Thickness (cm)	Density (g cm^{-3})	Topographic shielding
NK-01	SE 08229 63970	54.07142	1.87424	365	1.5	2.32	1.0000
NK-02A	SE 08224 63974	54.07145	1.87430	363	3.0	2.35	0.9663
NK-03	SE 07884 63783	54.06975	1.87950	360	1.5	2.38	0.9980
NK-04	SE 08255 63761	54.06954	1.87384	370	1.5	2.41	0.9993

Table 1: *Details of samples for TCN dating from Nursery Knott.*

Stump Cross Caverns are one of the most intensively dated cave systems in the UK, with 55 age determinations, ranging from ~225 ka to ~8 ka, pertaining to phases of flowstone development in, and faunal occupation of, the Caverns (Sutcliffe *et al*., 1985; Baker *et al*., 1996; Gilmour *et al*., 2007; Caseldine *et al*., 2008; O'Connor and Lord, 2013). In spite of this wealth of sub-surface information there is little detail concerning the geochronology of surface processes, materials and events. Both Raistrick (1931) and Tillotson (1934) inferred the former presence of glacier ice in the Stump Cross area, but their chronology was hampered by the absence of an established dating framework. In contrast, Smith (1977) thought that the local glacial drift was of Wolstonian (~300–130 ka) or earlier age, implying that the area had not been inundated by Devensian (~115–13 ka) ice, including at the LGM. O'Connor and Lord (2013) suggested that the area was not covered by warm-based ice during Quaternary cold (glacial) stages because Stump Cross Caverns lack the laminated clays that characterise glacial events in the Victoria Cave sedimentary record, 25 km to the west (Lundberg *et al*., 2010). However, the presence of ice-transported gritstone boulders on the limestone north and west of Stump Cross indicates the former presence of south-going glacier ice, but hitherto the age of this glacial event has not been established conclusively. Even though the area is regarded as within the limit of the last ice sheet at the LGM (Clark *et al*., 2004) it has not been proven that the high ground in this area was ice covered at that time.

Methods

Samples for TCN (^{10}Be) dating were collected from three ice-transported boulders and one exposure of coarse-grained Millstone Grit sandstone in the vicinity of Nursery Knott, ~1km northwest of Stump Cross Caverns (Fig.2, Table 1). Sample NK-01 was from the top of a 2m-high boulder (Figs 3A and B) that appears to have been pushed or dragged southwards by about two metres, presumably by glacier ice, from the underlying bedrock that now forms a plinth immediately north the boulder. The plinth stands <0.5m above the surrounding vegetated ground and the boulder rests partly on its southern edge; sample NK-02A was obtained from the centre of the plinth (Figs 3C and D). The other two samples (NK-03 and -04) were from the uppermost surfaces of 1m-high boulders that had been transported minimum distances of ~200m from the gritstone outcrop to their current positions on the limestone (Figs 3E and F). Samples were collected from these surfaces using hammer and chisels. A compass and clinometer were used to record the geometry of the sampled surfaces and the surrounding topography, and locations and altitudes were determined with a hand-held GPS unit cross-referenced to a 1:25,000 topographic map (Table 1).

All samples were crushed and sieved to 250–500µm and preparation for ^{10}Be analysis followed the procedures described in Wilson *et al*. (2008), as modified in Glasser *et al*. (2009). Measurement of ^{10}Be by accelerator mass spectrometry (AMS) is described in detail by Xu *et al*. (2010). The ^{10}Be/^{9}Be isotope ratios were normalized to the National Institute of Standards and Technology Standard Reference Material corresponding to a ^{10}Be/^{9}Be nominal value of 2.79 x 10^{-11} for a ^{10}Be half-life of 1.36 Ma (Nishiizumi *et al*., 2007). This standard agrees with standards prepared by K. Nishiizumi, which were used as secondary standards. Procedural blank corrections were in the range 3–9.6%. The standard uncertainties of the cosmogenic nuclide concentrations include the AMS counting statistics and scatter uncertainties from sample and blank measurements, which includes the long-term AMS and chemical preparation uncertainties.

Exposure age calculation and results

The ^{10}Be surface exposure ages were calculated using the two methods adopted by the BRITICE-CHRONO project (D. Small *pers. comm*., 2016). This enables the Nursery Knott ages to be related directly to results from other areas in northern England deriving from that project.

First, ages were determined using version 2.3 of the online calculators formerly known as CRONUS-Earth ^{10}Be–^{26}Al exposure age calculators (http://hess.ess.washington.edu/math/al be v23/al be multiple v23.php Balco *et al*., 2008) using the independently constrained Loch Lomond production rate (LLPR; 3.92±0.18 atoms g^{-1} a^{-1}) (Fabel *et al*., 2012). Production rates have not been determined for the Yorkshire Dales but are unlikely to differ significantly from the LLPR given the relatively short distance (~280km) between Loch Lomond (Scotland) and the Yorkshire Dales. In version 2.3 of the CRONUS-Earth age calculators a value of 4.0±0.17 atoms g^{-1} a^{-1} is used for the LLPR rather than 3.92±0.18 atoms g^{-1} a^{-1}, but the resulting differences in age are not significant (D. Small *pers. comm*., 2016). The LLPR was established from a geochronology provided by radiocarbon dating (MacLeod *et al*., 2011). Exposure ages were based on the time-dependent Lm scaling (Lal, 1991; Stone, 2000) and assume 1mm ka^{-1} of post-depositional surface erosion. This erosion rate is in general use in TCN dating studies across a range of crystalline rock types (cf. André, 2002; Nicholson, 2009; Larsen *et al*., 2012) and for this reason has been adopted here.

Second, exposure ages were calculated using the CRONUScalc program v2.0 (Marrero *et al*., 2016) using the default global production rate of 3.92 atoms g^{-1} a^{-1} for Sa scaling (Borchers *et al*., 2016) and an erosion rate of 1mm ka^{-1}.

Sample code	AMS ID	^{10}Be (10^4 atoms g^{-1})	Blank correction (%)	Exposure Age[1] (LLPR)	Exposure Age[2] (CRONUScalc)
NK-01	SUERCb9963	10.602±0.329	7.5	18.51±1.01 (0.59)	18.4±1.5 (0.6)
NK-02A	SUERCb9966	8.140±0.275	9.6	14.84±0.83 (0.51)	14.8±1.2 (0.5)
NK-03	SUERCb9967	12.087±0.391	6.7	21.31±1.18 (0.71)	21.0±1.7 (0.7)
NK-04	SUERCb9968	26.163±0.574	3.0	46.75±2.39 (1.08)	44.9±3.6 (1.0)

[1] Exposure ages are based on the time-dependent Lm scaling (Lal, 1991; Stone, 2000) and assume 1mm ka^{-1} erosion.
[2] Exposure ages are based on SA scaling and assume 1mm ka^{-1} erosion. CRONUScalc reports ages to one decimal place.

Table 2: *Cosmogenic (^{10}Be) data and surface exposure ages with total uncertainties at 1σ for the Nursery Knott samples. Analytical uncertainties (1σ) are in parentheses.*

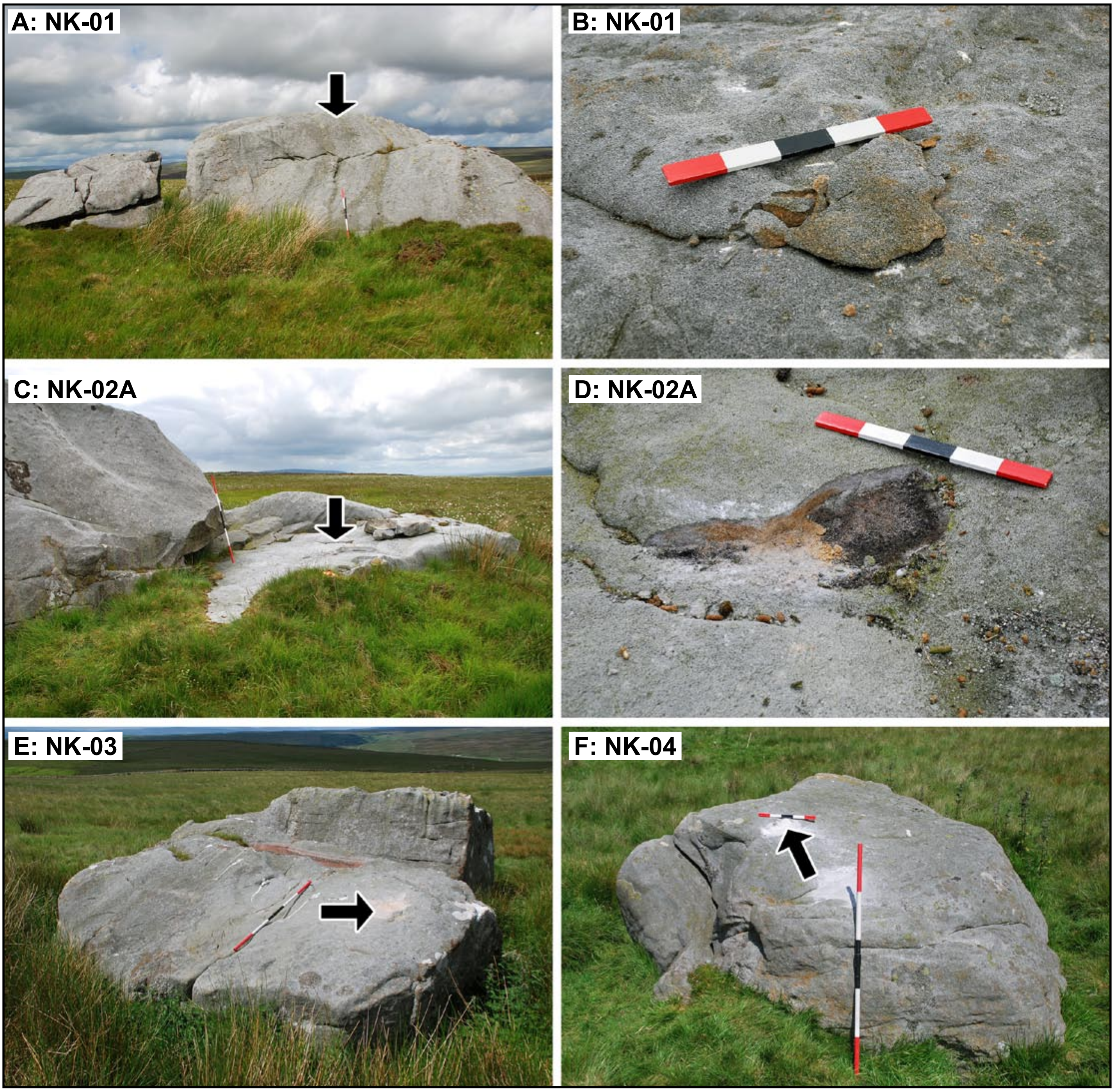

***Figure** 3A: The 2m-high boulder from which sample NK-01 was obtained at the arrowed location. Survey pole divisions are 20cm.*
3B: The piece of rock taken for ^{10}Be surface exposure dating from the arrowed location in A. Scale bar is 30cm in length.
3C: The rear view of Figure 3A showing bedrock surface (plinth) from which the 2m-high boulder (left) was either pushed or dragged. Arrow indicates location of sample NK-02A.
3D: Position of sample NK-02A in the centre of the bedrock plinth.
3E: Boulder and position of sample NK-03 (arrowed).
3F: Boulder and position of sample NK-04 (arrowed).

Both production rates agree within 1σ uncertainties with the range of production rates determined for other high latitude sites in the northern hemisphere (Small and Fabel, 2016). The cosmogenic (^{10}Be) data and exposure ages with uncertainties for each method of calculation applied are given in Table 2. In the following section LLPR ages are reported first followed by CRONUScalc ages.

One boulder sample (NK-04) returned ages of 46.75±2.39 ka and 44.9±3.6 ka, pre-dating the LGM. It is inferred that insufficient erosion of the boulder occurred during glacier transport and that the sample is compromised by the effects of nuclide inheritance. The bedrock sample (NK-02A) returned ages of 14.84±0.83 ka and 14.8±1.2 ka, spanning the terminal stages of the Late Devensian Dimlington Stadial (~28–15 ka) and the Lateglacial Interstadial (14.7–12.9 ka) at 1σ uncertainty, and the Younger Dryas Stadial (12.9–11.7 ka) at 2σ uncertainty, and is significantly younger than previously reported ages for deglaciation of the Yorkshire Dales. Therefore, neither of these samples provide close limiting constraints on the loss of glacial ice cover. Further consideration of these ages is provided below. The other two boulder samples yielded ages of 18.51±1.01 ka and 18.4±1.5 ka (NK-01), and 21.31±1.18 ka and 21.0±1.7 ka (NK-03), consistent within 2σ uncertainties with the range of ages previously obtained for deglaciation of the Yorkshire Dales and other parts of northern England (Wilson *et al*., 2012, 2013). However, NK-01 and NK-03 ages determined by use of the same production rate do not overlap within their 2σ analytical uncertainties (used for comparing samples from the same geological context) and have reduced Chi-square (χ^2_R) values of ~8–9.5, indicating that they do not constitute a single population, for which a χ^2_R <1 is required.

Discussion

The ^{10}Be ages of the three boulders (NK-01, -03 and -04) indicate that the Stump Cross area was glaciated during the LGM, even though NK-04 has yielded a substantially earlier age than NK-01 and NK-03 (Table 2). Nevertheless, the pre-LGM age of NK-04 is useful in that it indicates that boulder transport and deposition must post-date its exposure ages of ~47–45 ka, and the LGM is the only glacial event in which the boulder could have been moved to its present location. Similar reasoning has been applied to explain boulders with 'old' ages from contexts in which LGM ice was clearly present (e.g. Fabel *et al*., 2012; Ballantyne and Stone, 2015). Therefore, these three ages provide unequivocal evidence for the presence of glacier ice on the Wharfe–Nidd interfluve, rather than the area having been above or beyond the influence of the last ice sheet (cf. Raistrick, 1931; Tillotson, 1934; Smith, 1977; Catt, 1991; Baker *et al*., 1996; O'Connor and Lord, 2013).

Sample NK-02A is problematical in that it returned an age that is younger than expected given its position on the bedrock plinth from which boulder NK-01 was pushed or dragged. We hypothesize that following removal of the boulder the plinth was shielded from cosmic rays, for an unknown period, by a cover of glacial sediment and/or peat that has since been eroded. Walker (1956) noted that the erratic boulders around Nursery Knott are embedded in 'glacial clay'; therefore, a former sediment cover across the plinth is not an unreasonable proposition.

Ages from boulder samples NK-01 and NK-03 are the only two that provide close limiting age constraints for deglaciation of this part of the Wharfe–Nidd interfluve. Depending on the production rate applied and the resulting ages this event is defined as having occurred between 18.51±1.01 ka and 21.31±1.18 ka (LLPR) or between 18.4±1.5 ka and 21.0±1.7 ka (CRONUScalc). Because these sample ages cannot be considered as deriving from the same statistical population they cannot be averaged to produce a best estimate age for deglaciation, and given that the relative accuracy of the LLPR and CRONUScalc methods is unknown it is necessary to consider the merits of the age determinations for both boulders.

Several reconstructions depicting the retreat pattern of the last British Ice Sheet, or parts thereof, based on mapping, geomorphology, sedimentology, geochronology and physical numerical evidence have been produced in recent years (Evans *et al*., 2009; Hubbard *et al*., 2009; Clark *et al*., 2012; Livingstone *et al*., 2012, 2015; Chiverrell *et al*., 2013; Bateman *et al*., 2015; Hughes *et al*., 2016). Each indicates a complex pattern of ice-sheet behaviour but there is a broad consensus that the Stump Cross area of the Yorkshire Dales remained ice covered until ~18 ka, after which there was a rapid loss of ice with the area becoming ice-free by ~17 ka. The exposure ages from boulder sample NK-01 lie closest to this proposed interval of deglaciation and may therefore be preferred, especially as the mean age of three erratics at Norber, 33km to the northwest, is 17.9±1 ka (Wilson *et al*., 2012). Within 2σ total uncertainties the CRONUScalc age for NK-03 also overlaps with the 18–17 ka period. In contrast, the NK-03 LLPR-derived age does not overlap with this interval suggesting that the sample may be compromised by slight nuclide inheritance.

The TCN ages for the Nursery Knott erratics are evidence of their deposition by glacial ice at ~18–17 ka following termination of the LGM and provide the first dated evidence for glaciation on this part of the Wharfe–Nidd interfluve. The results resolve previous uncertainties relating to the age of the tills in the locality which can now be assigned to the LGM. The transport of substantial erratic blocks during the final phase of the LGM implies the presence of a glacier ice cover with the potential to re-activate the hydrology of relict stream passages in Stump Cross Caverns. However, there is no evidence from this cave system of the laminated clay units such as those reported from Victoria Cave, 25 km to the northwest, where they are interpreted as being formed during hydrological rejuvenation associated with warm-based ice during middle and late Pleistocene glaciations (Lundberg *et al*., 2010). Further work is clearly needed to investigate the effects of warm-based ice cover on the cave systems of the Yorkshire Dales, and to explain the variability in the sediments.

Conclusions

Being close to Stump Cross Caverns, the TCN results for the Nursery Knott boulder samples have provided an opportunity to compare surface and sub-surface dating evidence for deglaciation; the results from two boulders in this project and the previously published U–Th dates on speleothems are consistent within their inherent uncertainties and indicate deglaciation by ~17 ka. In the future more precise analysis by, for example, thermal ionization mass spectrometer U–Th dating of speleothems, has the potential to reduce these uncertainties still further.

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