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Early Holocene loessic colluviation in northwest England: new evidence for the 8.2 ka event in the terrestrial record?

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Twelve new samples of loessic silts from widely spaced locations on the karst uplands of northwest England have yielded Optically Stimulated Luminescence (OSL) dates that fall within or overlap with (within uncertainties) the early to mid-Holocene period (11.7–6.0 ka), and support three already-published Holocene ages from similar sediment from this region. Nine of the 15 dates are coincident with the hypothesized climatic deterioration at 8.5–8.0 ka in the North Atlantic region and eight are coincident with the 8.2 ka event. These dates demonstrate that the silts are not primary air-fall loesses of deglacial/Lateglacial age (*c.* 18.0–11.7 ka) but have been reworked and now consist of loess-derived colluvial deposits; we consider the ages to be reliable as there is no compelling evidence to indicate that the samples are partially bleached. There is no substantive archaeological or palynological evidence for Late Mesolithic hunter-gatherers having had a major impact on the landscape, and it is considered highly unlikely that these people triggered colluviation. We estimate that during the 8.2 ka event there was a reduction in mean annual air temperature at these upland locations of ~2.6–4.6°C, and proxy evidence from other sites indicates a shift to wetter conditions. It is inferred that there was greater snow accumulation in winter, that the snowpack survived for longer periods, and that there was an increase in the magnitude and frequency of frost-related processes and meltwater flooding. Together, these changes in climate and their associated (sub)surface processes were responsible for the reworking of the loess. The OSL dates indicate climatically induced landscape dynamism in Great Britain during the latter half of the ninth millennium.

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The most pronounced centennial-scale anomaly in Holocene proxy-climate records in the North Atlantic region is the 8.2 ka event (Alley *et al.* 1997; Alley & Ágústsdóttir 2005; note that throughout this paper dates are given as b2k unless otherwise specified (Rasmussen *et al.* 2007; Wolff 2007)). The event is especially prominent in oxygen isotope records of the Greenland ice cores (Johnsen *et al.* 2001; Muscheler *et al.* 2004; Rasmussen *et al.* 2007; Thomas *et al.* 2007) and in the lithic, petrologic and foraminiferal content of marine sediments (Bond *et al.* 1997; Ellison *et al.* 2006; Kleiven *et al.* 2008), but has also been recorded in numerous terrestrial proxy records (Klitgaard-Kristensen *et al.* 1998; Tinner & Lotter 2001; Magny *et al.* 2003; Nesje *et al.* 2006). The anomaly is characterized by an excursion towards cooler temperatures, peaking sometime between *c.* 8.5 and 8.0 ka, lasting ~70–200 years, and often showing two distinct maxima (Nesje & Dahl 2001; Magny *et al.* 2003; Keigwin *et al.* 2005; Lutz *et al.* 2007). Some records also indicate that the 8.2 ka event punctuated a longer interval of climate downturn variously placed between *c.* 8.6 and 8.0 ka (Rohling & Pälike 2005) and *c.* 9.0 and 8.0 ka (Alley *et al.* 1997; Hu *et al.* 1999; Ellison *et al.* 2006). In northwest England, a phase of marked climate cooling identified in the sedimentary record of Hawes Water, north Lancashire (8 m a.s.l.; Fig. 1) occurred at 8.38 ka and lasted for ~150 years (Marshall *et al.* 2007). A high-resolution (1–2 years) record based on oxygen isotope data along with speleothem ages from several caves in northwest England have confirmed the regional occurrence of the 8.2 ka event (at 8.2 ka) with a duration of ~150 years (P. Hopley, pers. comm. 2008). There is a general consensus that the most likely cause of the 8.2 ka anomaly is disruption of the Meridional Overturning Circulation in the North Atlantic as a result of freshwater input from the final collapse of the North American ice sheet, with the two-stage nature of the anomaly possibly correlating with the drainage of the proglacial lakes Ojibway and Agassiz (Barber *et al.* 1999; Ellison *et al.* 2006; Wiersma & Renssen 2006; Kleiven *et al.* 2008).

In this paper we report Optically Stimulated Luminescence (OSL) dates from silt deposits at widely spaced (~35–50 km) locations on the outcrop of the Carboniferous Limestone of northwest England. It has been known for some considerable time that thin (<~1 m) deposits of aeolian silt are the parent materials for some of the soils on the limestone (Pigott & Pigott 1963; Bullock 1971; Furness & King 1972; Catt 1977; Vincent & Lee 1981). Bullock (1971), using mineralogical analyses, established that the silt deposits differed from underlying tills and were not weathered tills. On the limestone around Morecambe Bay, Vincent & Lee (1981) employed a variety of techniques

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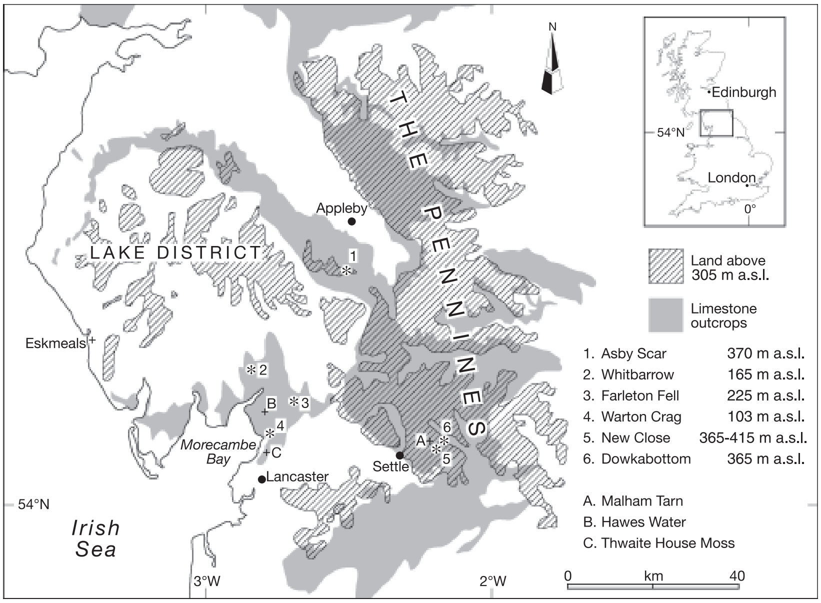

Fig. 1. Map showing locations (1–6) from where 15 OSL dates that fall within or overlap with (within uncertainties) the early to mid-Holocene period (11.7–6.0 ka) were obtained from loess-derived colluvium on the Carboniferous limestone of northwest England. Also shown are the locations of Malham Tarn, Hawes Water and Thwaite House Moss. Little Hawes Water is adjacent to Hawes Water.

(grain size, scanning electron microscope analysis of quartz grains, clay mineralogy and sediment stratigraphy) and demonstrated that the silts were distinctly different from the local tills and limestone weathering products. They regarded the silts as loess derived from the deflation of glacigenic sediments in Morecambe Bay as Lake District and Irish Sea ice wasted following the Last Glacial Maximum (LGM: *c.* 21±2 ka). Initial dating work by Wilson *et al.* (2008) provided age estimates for the loess that ranged from the early to mid-Holocene period, refuting the hypothesis that these sediments were primary air-fall loesses of deglacial/Lateglacial age (*c.* 18.0–11.7 ka), during this latter period environmental conditions were periodically conducive to loess formation (Wintle 1981; Gibbard *et al.* 1987; Parks & Rendell 1992; Murton *et al.* 2003; Clarke *et al.* 2007). It was therefore proposed that the dated samples were not primary loesses (cf. Vincent & Lee 1981) but consisted of loess-derived colluvium that had been reworked from adjacent areas of limestone pavement (Wilson *et al.* 2008). The presence of abundant exposed rundkarren in the vicinity, which require soil cover for their development (Sweeting 1972; Ford & Williams 2007), supports the idea of localized soil erosion. Further dating work on silts from the region (Telfer *et al.* 2009) has provided not only deglacial ages (*c.* 19–16 ka), but also ages (*c.* 27 ka) pre-dating the LGM ice extent in northwest England, suggesting that in small isolated basins in locations protected from ice-scour, primary loessic deposits may indeed still exist. These pre-LGM and deglacial ages are not considered further in this paper as they are not considered directly relevant to the Holocene silt reworking discussed below.

In order to test and refine the spatial and temporal/stratigraphic aspects of loessic and colluvial sediments on the karst of northwest England, we have obtained and dated samples from a number of new locations. We present 12 new ages from widely spaced locations that fall within or overlap with (within uncertainties) the early to mid-Holocene period (11.7–6.0 ka) and also consider the only three previously published ages from similar sediment in this region (Wilson *et al.* 2008). Nine of these 15 ages are coincident with the hypothesized climatic deterioration at 8.5–8.0 ka, and eight ages are coincident with the 8.2 ka event. The implications of these ages for the cause(s) of loess reworking and environmental changes are the focus of this paper.

Sites and methods

The locations from which the 15 samples have been obtained are shown in Fig. 1. All but one of the sites are in shallow (< 5 m deep) karstic depressions adjacent to areas of exposed limestone pavement with rundkarren. The New Close–Abbot Hills site is located a short distance downslope from the highest point (415 m a.s.l.) of the hill. At each site a pit was excavated to bedrock. The loessic materials consist of structureless, yellowish-brown (10YR5/4) sandy silt loam and silt loam up to 1.4 m in depth. The Farleton Fell pit contained a few small (*b* axes < 5 cm) angular clasts of limestone in the lowermost 20 cm, and elsewhere the pits were clast-free. The homogeneous, well-sorted nature of the silts and their occurrence in topographic depressions, and the demonstrated presence of LGM-aged loess in this region (Telfer *et al.* 2009) have led us to conclude that these sediments are either primary loess or reworked loess (loess-derived colluvium).

Samples for OSL dating were collected by inserting light-tight plastic tubes horizontally into the walls of the pits at depths of between 20 and 110 cm. All samples were from at least 25 cm above bedrock. At Asby Scar, Farelton Fell, Dowkabottom and New Close, *in situ* field gamma spectrometry was conducted, and for the Warton Crag and Whitbarrow samples, Inductively-Coupled Plasma Mass Spectrometry/Atomic-Emission Spectrometry (ICP-MS/-AES) was used for dosimetry (as the field gamma spectrometer was not available for fieldwork). For one sample at New Close East, interpolation of *in situ* gamma spectrometry data from a sample within 20 cm (not presented here) was used, as variance between adjacent samples was low. We believe that the variability in dose rates (values ranging from ~1 Gy/ka to ~3 Gy/ka) between sites reflects true variability in the concentrations of radioisotopes rather than its being an artefact of the different methodologies at different sites; geological reference standards run in tandem with the ICP analyses produced coherent results, and the gamma spectrometer had been recently calibrated on doped concrete reference blocks at the University of Oxford.

The samples were predominantly silts, and hence the 4–11 μm fraction was isolated by settling, and was treated with standard preparation for fine-grained luminescence samples using HCl, H_2O_2 and H_2SiF_6. All samples were measured at the Oxford Luminescence Dating laboratories with the Single Aliquot Regeneration (SAR) protocols of Murray & Wintle (2000, 2003) and were analysed with the equipment and experimental parameters as described for silts from this region by Wilson *et al.* (2008). Measured moisture contents have been used, with conservative uncertainties applied to account for time-averaged variance in the water content of the sediments.

Most samples show a relatively dim luminescence response (Fig. 2A shows a typical response, for OxL-1801), but all aliquots demonstrated reasonable growth characteristics (Fig. 2B). Overdispersion (σ, *sensu* Galbraith *et al.* 1999) is <10% for all samples (e.g. Fig. 2C), and probably arises from the difficulty of fitting growth curves to samples with poor signal-to-noise ratios. A few samples showed evidence of persistent feldspar contamination despite the H_2SiF_6 treatment, and thus an IR bleach was used prior to each blue OSL stimulation (Banerjee *et al.* 2001; Roberts & Wintle 2001; Wintle & Murray 2006; Roberts 2008). Fast-component-derived D_e (equivalent dose) estimates of the post-IR blue decay curve (assumed to represent the quartz fast component; Li & Li 2006) on the limited number of aliquots that were sufficiently bright to allow signal deconvolution were consistent with those from the bulk post-IR blue signal, and it is thus concluded that the post-IR blue method is appropriate in this instance (Roberts 2008).

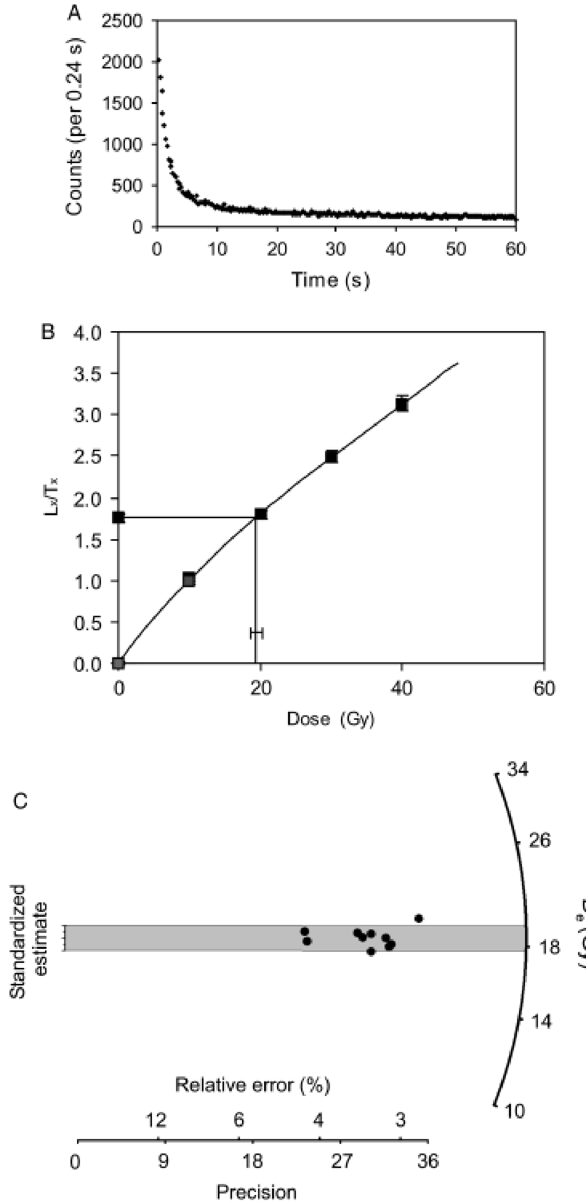

Fig. 2. A. Typical shine-down curve (sample OxL-1801), showing the relatively low intensity of the blue-stimulated luminescence of these samples. B. Growth curve derived from same aliquot. C. Resultant dose distribution from sample OxL-1801.

Results

The 15 luminescence ages are presented in Fig. 3 and Table 1. Partial bleaching (that is, the incomplete resetting of the luminescence signal owing to inadequate exposure to daylight during the last cycle of sediment mobilization) is a potential problem for sediments hypothesized to have been deposited via soil transport processes such as colluviation, and there is thus a risk of age overestimation (Alexanderson & Murray 2007). Furthermore, partial bleaching is difficult to detect in fine-grained samples, because analysing the D_e of such a large number of grains simultaneously tends to average out any variability between individual D_e estimates (Duller 2008).

'D_e(t) plots' of resultant equivalent dose against signal integration time have been suggested to provide a good indication of partial bleaching, particularly

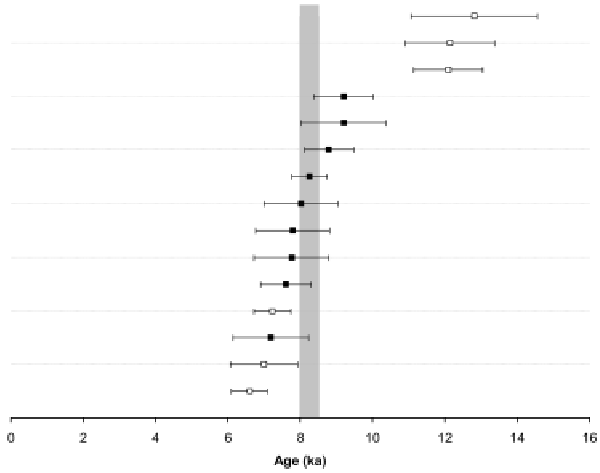

Fig. 3. Ranked age plot of OSL dates for 15 silt samples of early to mid-Holocene age (within age uncertainties) from northwest England, including the three ages presented by Wilson *et al.* (2008). The shaded region indicates the climatic deterioration reported for the North Atlantic region from 8.5 to 8.0 ka, and at its most intense during the 8.2 ka event. Samples coincident with the interval 8.5–8.0 ka are highlighted with solid markers.

for relatively young (≪*c.* 20 ka) samples such as those discussed in this paper (Bailey 2000; Bailey *et al.* 2003). No strongly rising D_e(t) forms, suggestive of partial bleaching, were observed for any of the samples. Although the samples are predominantly silts, the fine sand fraction (90–125 μm) of a limited number of samples was also prepared and analysed as small (~3 mm diameter) aliquots, which might be expected to have yielded more overdispersed and positively skewed dose distributions if partial bleaching were a problem for these samples. Results of these analyses have been given in Wilson *et al.* (2008), and although overdispersion is indeed greater, this is due to the presence of a population of lower D_e estimates, which cannot be readily attributed to partial bleaching. Furthermore, most of the ages presented here are part of dated profiles, and, in each case, all ages are stratigraphically sensible. There is, in short, no compelling evidence to indicate that the samples analysed in this study are partially bleached.

Nine of the dates are coincident with the broader definition of the climatic event at 8.5 to 8.0 ka (with a further two lying just outside this period), and eight of these are coincident with 8.2 ka. If these data are tested with a finite-mixture density model (Galbraith & Green 1990) to attempt to discern discrete populations, the best fit (based on an overdispersion derived from the entire data set, and using Bayesian Information Criteria to determine goodness of fit) is for two populations; the more recent at 7.8±0.2 ka, and an older population at 12.1±0.2 ka. These samples were obtained from six sites spread across the region and from an elevation range of ~310 m (Fig. 1), and this is taken to imply a region-wide cause for loess reworking in the Mesolithic period rather than being an artefact of our sampling strategy.

Discussion

The early Holocene of northwest England witnessed widespread colonization by tree species and a rapid rise in sea level. By *c.* 9–8 ka, well-developed mixed woodland existed along with more open areas of heath and grassland (Smith 1986; Bartley *et al.* 1990; Atherden 1999; Hodgkinson *et al.* 2000; Walker 2004) and during the same interval sea level in Morecambe Bay (Fig. 1) rose from ~−20 m to ~−4 m a.s.l. (Zong & Tooley 1996). These conditions would have been inimical to loess formation from the glacigenic sediments in Morecambe Bay and across its hinterland (Vincent & Lee 1981); therefore, we consider that the Holocene samples represent loess-derived colluvium rather than primary air-fall loess. Loess reworking probably resulted from overland flow, although aeolian transport and subsoil piping cannot be excluded entirely (Wilson *et al.* 2008).

Wilson *et al.* (2008) considered that human activities and climate shifts were responsible for loess reworking, either separately or in combination, but were unable to provide conclusive information about their relative impacts. We note that vegetation disturbance and the destruction of soil organic horizons were not restricted to those areas that were stripped of their loess cover and now exist as limestone pavements. Some loess erosion also occurred from the karstic depressions that became the receiving sites for the material we have dated. In several of our soil pits the Holocene sediment is underlain by loessic material that returned OSL dates of Lateglacial and pre-LGM age (Telfer *et al.* 2009), but no buried organic horizons were present between the Holocene and earlier deposits. This suggests that organic-rich soil horizons were eroded from these sites prior to sediment accumulation in the Holocene. A weakly developed buried soil was reported from a site on Farleton Fell by Furness & King (1972); this was about 200 m from our soil pit and indicates that buried soils exist locally. With the exception of Hawes Water (Fig. 1), the general climate downturn of the ninth millennium and the associated loess erosion has not been identified in local lake and mire records, but these were obtained before the 8.2 ka event had been identified in ice-core and marine records. In contrast, the pollen and macrofossil data derived from a Danish lake (Rasmussen *et al.* 2008) and analyses of varved lake sediments in Fennoscandia (e.g. Zillén & Snowball 2009) demonstrate a striking increase in erosion in response to the 8.2 ka event. This implies that lake and mire records in northwest England should be reassessed.

Climate shifts of the ninth millennium

During the 8.2 ka event the inferred mean July temperature at Hawes Water was reduced by ~1.5 °C (Marshall *et al.* 2007). This agrees well with July temperature changes for the 8.2 ka event in Great Britain

Table 1. Experimental data and OSL ages for the 15 samples of loess-derived colluvium from northwest England.

Sample location					Dosimetry						D_e estimation		Age (ka)
Site name	Site location		Depth (cm)	Laboratory code	Method	K (%)	U (ppm)	Th (ppm)	Water content (%)	Dose rate (Gy/ka)	Aliquots measured	Equivalent Dose, D_e (Gy)	
Asby		54.4817°N 2.5413°W	50	OxL-1664	ICP	1.32	2.99	9.79	25±5	3.01±0.24	10	23.07±1.02	7.6±0.7*
Dowkabottom	West pit	54.1147°N 2.0751°W	40	OxL-1796	γ spectrometry	0.99	2.57	9.17	20±5	2.38±0.13	16	15.70±0.84	6.6±0.5
			60	OxL-1795	γ spectrometry	0.98	2.76	9.24	23±5	2.32±0.13	16	18.65±2.15	8.0±1.0
			80	OxL-1794	γ spectrometry	1.17	3.14	9.03	21±5	2.62±0.15	16	18.94±0.84	7.2±0.5
Farleton Fell		54.2135°N 2.7008°W	50	OxL-1665	ICP	2.07	2.33	10.33	17±5	3.85±0.28	10	33.83±1.00	8.8±0.7*
New Close	Abbot Hills	54.0838°N 2.1491°W	50	OxL-1803	γ spectrometry	0.27	1.43	5.08	22±5	1.15±0.08	12	13.98±0.61	12.1±1.0
	New Close East	54.0778°N 2.1368°W	40	OxL-1801	Interpolation	0.90	3.15	7.27	23±5	2.23±0.13	10	18.39±0.24	8.3±0.5
			60	OxL-1800	γ spectrometry	1.07	3.49	7.65	17±5	2.68±0.16	10	31.93±2.51	12.0±1.2
	New Close	54.0770°N 2.1412°W	50	OxL-1666	ICP	2.12	2.68	9.81	21±5	3.70±0.26	10	34.16±1.87	9.2±0.8*
Warton Crag	WC1	54.1478°N 2.7758°W	50	OxL-1807	ICP	1.39	2.45	9.56	22±5	2.62±0.33	12	20.33±0.87	7.8±1.0
			50	OxL-1808	ICP	1.32	2.51	9.30	22±5	2.56±0.32	12	23.65±0.45	9.2±1.2
			75	OxL-1805	ICP	1.46	2.60	10.97	17±5	3.02±0.39	12	38.73±1.75	12.8±1.7
	WC3		45	OxL-1809	ICP	1.37	2.51	9.81	20±5	2.71±0.34	12	21.13±0.81	7.8±1.0
			45	OxL-1810	ICP	1.36	2.86	11.79	17±5	3.07±0.40	12	22.12±1.51	7.2±1.1
Whitbarrow	WB1	54.2596°N 2.8584°W	70	OxL-1811	ICP	1.60	3.00	11.12	17±5	2.62±0.33	12	18.43±0.79	7.0±0.9

*indicates those samples reported by Wilson *et al.* (2008).

modelled by Wiersma & Renssen (2006), and, coupled with an inferred expansion of sea ice, translates into a mean annual air temperature (MAAT) reduction in excess of 2 °C close to sea level and significantly colder winters (cf. Alley & Ágústsdóttir 2005). Applying an environmental lapse rate of 0.65 °C/100 m (Wheeler & Mayes 1997) reduces the 8.2 ka MAAT at our sites to ~2.6–4.6 °C below modern values. Evidence from ombrotrophic bogs in parts of Great Britain and Ireland (Anderson *et al.* 1998; Hughes *et al.* 2000; Barber *et al.* 2003) indicates a shift to wetter conditions around 8.2 ka, and ^{14}C-dated alluvial units testify to a major flood episode at that time (Macklin & Lewin 2003; Lewin *et al.* 2005).

We infer that this temperature reduction and wet-shift resulted in greater amounts of winter snow accumulation, a longer-lasting snowpack, and increases in the magnitude and frequency of frost-related processes and meltwater flooding in northwest England. A more recent analogue would be with certain decades of the Little Ice Age (AD 1300–1900); although temperature reduction at sea level was not as great (~0.9–1.5 °C; Lamb 1995), there is documentary evidence for greater and more persistent snow cover and for an increase in severe frosts relative to the twentieth century (Manley 1953, 1958). Such conditions during the climate downturn of the ninth millennium, culminating in the 8.2 ka event, are likely to have seriously impacted on vegetation and soils by suppressing growth and disrupting soil organic horizons. The mixed woodland with more open areas of heath and grassland that characterized the uplands of northwest England during the Mesolithic (Smith 1986; Atherden 1999; Hodgkinson *et al.* 2000; Walker 2004) may have functioned in a manner similar to that described from mountain regions by Billings (1969), Holtmeier (2005) and Benedict *et al.* (2008), whereby wind-drifted snow accumulates in clearings and builds up deep drifts where it extends into the woodlands. The overall impact of deep, long-lasting snow cover is to increase the mortality of trees and thus to extend the area occupied by woodland clearings, to encourage a more open ground vegetation, and to supply substantial amounts of meltwater during the thaw. Loess generally has an open structure with little shear strength, and when loaded and wetted collapses easily and flows (Assallay *et al.* 1998). The vulnerability of British loess deposits to disruption and erosion by water has previously been highlighted by Catt (2001).

The northwest of England is an area of moderate to high rainfall with annual precipitation of the order of 1460 mm on the higher ground (Manley 1957). From 1950 to 1975 the average number of days with snow cover (defined as >50% of visible ground covered by snow at 0900 hours) recorded at the meteorological station at Malham Tarn (382 m a.s.l.) was 40 days, and this was estimated to rise to 82 days on ground at ~650 m a.s.l. on the nearby summit of Fountains Fell (Manley 1979). Over the same period the MAAT for Fountains Fell summit was measured as ~4.6 °C compared with 6.4 °C at Malham Tarn, showing that a fall in MAAT of ~1.8 °C doubled the number of days each year with snow cover. Applying similar reasoning to the falls in MAAT suggested for our sites during the 8.2 ka event (~2.6–4.6 °C below modern values) results in a possible two- to four-fold increase in the average number of days each year with snow cover, so that areas with a similar altitude to Malham Tarn, for example, could have had snow cover for >160 days a year. In upland Britain, periods of lying snow are generally terminated by warm air and rainfall generated by Atlantic weather systems, in contrast to areas such as continental inland Europe, where radiation is the main controlling mechanism (Bell & Moore 1999). Thus high rates of snowmelt are characteristic in upland Britain and when associated with heavy rainfall can result in soil saturation and overland flow.

At our sites, exposure of the subjacent loess would, at different times, have rendered it susceptible to frost heave by needle ice and overland flow by meltwater. Examples of sediment redistribution by snowpatch meltwater in Great Britain have been documented by Tufnell (1971) in the northern Pennines, by Vincent & Lee (1982) on the loess of Farleton Fell, near Morecambe Bay, and by Ballantyne (1985) on An Teallach in the Scottish Highlands. In southern England several cases of recent loess colluviation as a result of overland flow, rilling and gullying have been documented by Boardman (1990). Elsewhere, increases in colluviation attributed to the 8.2 ka event have been recorded in Wyoming (Hanson *et al.* 2004), Finland (Ojala & Alenius 2005) and central Europe (Dreibrodt *et al.* 2008), and catchment-scale erosion has been detected through analyses of varved lake sediments in Fennoscandia (e.g. Zillén & Snowball 2009). It is therefore reasonable to suggest that the climate changes brought on by the 8.2 ka event were more than capable of causing the localized reworking of loess deposits on the limestone of northwest England.

Mesolithic human (and animal) activity

Late Mesolithic hunter-gatherers were present over much of Great Britain by *c.* 9.5 cal. ka BP (BP = AD 1950), more than a millennium before the 8.2 ka event (Waddington 2007). The archaeological evidence for the Late Mesolithic in northwest England is mostly limited to scatters of worked pieces of flint and chert (Cowell 1996; Spikins 1999, 2002; Hodgson & Brennand 2006, 2007). These are recorded from coastal and estuarine sites in Cumbria, and from upland areas as far inland as Malham Tarn (Cherry & Cherry 1987, 2007; Williams *et al.* 1987; Hodgkinson *et al.* 2000). Presently there is a dearth of radiocarbon dates for these sites apart from at the Eskmeals foreland in west Cumbria (Fig. 1), where there is a hearth dated to *c.* 7.6 cal. ka BP, and where excavations have led to the suggestion that this area was the focus for year-round occupation during the Late Mesolithic (Bonsall *et al.* 1989; Bonsall 2007).

Although diagnostic stone tools provide widespread evidence for the presence of Late Mesolithic hunter-gatherers across most of Britain, there has been considerable debate about the impact they had on the landscape (e.g. Edwards *et al.* 2007). Palynological investigations at lowland and upland mires in northwest England have revealed evidence suggestive of small-scale woodland clearance by people in the Late Mesolithic (Pigott & Pigott 1959, 1963; Smith 1986; Bartley *et al.* 1990; Taylor *et al.* 1994; Middleton *et al.* 1995; Simmons 1996). Ground flora indicative of open ground have been recognized in Late Mesolithic pollen spectra from lowland mires adjacent to Morecambe Bay, including Little Hawes Water and Thwaite House Moss, as well as from the upland mire of Malham Tarn Moss (Fig. 1). All these mires lie close to karst areas overlain by loessic silts (Wilson *et al.* 2008). At Little Hawes Water, a rise of open-ground indicators including *Plantago* sp., *Pteridium aquilinum* and a band of charcoal is dated to *c.* 9.5–8.6 cal. ka BP (Taylor *et al.* 1994). Late Mesolithic palynological evidence for open ground at Thwaite House Moss is tentatively dated to *c.* 8.5–7.5 cal. ka BP (Middleton *et al.* 1995). At Malham Tarn, increases in open-ground species including *Pteridium*, and seams of charcoal in undated Late Mesolithic horizons (Pigott & Pigott 1959, 1963; Simmons 1996) have been identified.

The explanation for areas of open ground in the karstic landscapes close to these mires during the Late Mesolithic is far from straightforward. Loessic silts have been reported from the karstic region of western Ireland (Vincent 2004). Palynological evidence from Inis Oírr, Aran Islands, off the west coast of Ireland, revealed a karstic landscape with a mosaic of wooded and open areas during the Late Mesolithic, but there is no archaeological evidence for people on the island at this time (Molloy & O'Connell 2004). It seems very likely that the presence of loessic silts is a key and hitherto overlooked factor in the maintenance of spatial diversity in the Early Holocene woodland in these karstic areas. Loessic silts are very free-draining and readily dry out on limestone ground. They are also very variable in depth (Vincent & Lee 1981). Where the silts are thin, stress induced by drought restricts tree growth, and this may explain the persistence of herbaceous flora including *Helianthemum* (rock-rose) in karstic areas during the Holocene (French *et al.* 2005). The tuberous rhizomes of *Pteridium* are very intolerant of wet soils and so are well suited to the free-draining loessic silts. Even the areas of deeper silts are prone to dry out and so favour more drought-tolerant trees such as *Pinus sylvestris* and *Corylus avellana* (Finsinger *et al.* 2006; Edwards *et al.* 2007).

In northwest England the charcoal band at Little Hawes Water and the seams of charcoal at Malham Tarn suggest the presence of Late Mesolithic hunter-gatherers, but the general impression from these mires is that any opening up of the woodland cover attributable to these people was of a fairly limited nature. These findings contrast with those reported from elsewhere in northern England (Simmons *et al.* 1981; Simmons & Innes 1987) and the Isle of Man (Innes *et al.* 2003), where pollen, charcoal and/or archaeological evidence for significant forest disturbance in the later Mesolithic has been found. Even if substantial woodland clearance did occur in the vicinity of our sites in the Mesolithic period, we do not know if this, in turn, resulted in significant degradation of the loessic silts. The limited evidence for mineral inwash into Malham Tarn and nearby mires during the Mesolithic (Pigott & Pigott 1959, 1963) is inclusive, as the Tarn and the mires are fed by karstic springs emerging from the limestone aquifer where underground cavities could have trapped and retained mineral sediments. We failed to see macroscopic charcoal fragments in our soil pits, and there were no microscopic charcoal pieces in the silt samples collected for OSL dating. This suggests that burning is unlikely to have been a significant factor leading to the reworking of the loess during the Mesolithic.

The dominance of deciduous trees in the wooded areas on the limestone of northwest England and the occurrence of *Pteridium* in open areas during the Late Mesolithic are significant. The leaf canopy of deciduous woodland inhibits a closed ground flora, while *Pteridium* with its dense fronds restricts the ground flora of open areas. In winter, after the deciduous trees had shed their leaves and the foliage of *Pteridium* had died back, the open nature of the vegetation mat binding the loessic silts in these areas would offer only limited protection against colluviation triggered by rainfall, snow melt and frost action. These areas might also be more susceptible to disturbance caused by the hooves of large herbivores such as wild cattle and red deer (Evans 1998). *Pteridium* rhizomes might also be attractive to large omnivores such as wild boar and people. The rooting up of *Pteridium* rhizomes by wild boar (Balharry 2006) could have resulted in patches of loessic silts being eroded. While we have no direct archaeological evidence for Late Mesolithic hunter-gatherers digging up *Pteridium* rhizomes for food, ethnographic evidence indicates their use as a calorie-rich food source after careful processing (Dimbleby 1978).

In the Netherlands, Peeters (2009) reported a marked decrease in the number of charcoal-derived ^{14}C dates coincident with the 8.2 ka event and highlighted the possibility that the event impacted on Mesolithic communities. From Germany, Lang (2003) has shown that past phases of climatic deterioration have tended to lower population densities and so decrease human-induced soil erosion. If this is so, we should expect there to have been reduced human activity in the ninth millennium on the karst uplands of northwest England, as documented for some upland areas of Great Britain during the Little Ice Age (cf. Parry 1975; Dodgshon 2005). However, we simply do not know if such population withdrawal during the Late Mesolithic took place. Such issues need resolving in order to disentangle the relative impacts of humans and climate on the landscape of northwest England in the early Holocene (Edwards *et al.* 2007).

We are aware that loess-derived colluvium in parts of Germany has been attributed to human activity (e.g. Lang & Hönscheidt 1999; Kadereit *et al.* 2002), but colluviation is regarded as a consequence of agricultural practices from the Neolithic onwards. In addition, Lang (2003) has argued that the deposition of loess-derived colluvium in southern Germany was associated with phases of more intensive land use. Climatic fluctuations were considered to be of secondary importance and influenced soil erosion through their impact on human activities. Our Holocene OSL data set contrasts markedly with ages obtained by Lang and co-workers in showing that loess-derived colluvium in northwest England is a phenomenon predominantly of the pre-agricultural era.

Conclusions

- OSL dating of loessic silts from widely spaced locations on the karst uplands of northwest England has indicated that substantial amounts of the material have been reworked during the Holocene and therefore no longer constitute primary air-fall loesses of deglacial/Lateglacial age.
- It is inferred that the silts represent loess-derived colluvial deposits.
- Although it is difficult to characterize bleaching characteristics for fine silt samples such as these, analysis of signal integration time, stratigraphic evidence and coarse-grain measurements on samples from the same area all suggest that these samples are adequately bleached. Fifteen OSL dates obtained from these silts fall within or overlap with (within uncertainties) the early to mid-Holocene period (11.7–6.0 ka), nine of these are coincident with the hypothesized climatic deterioration at 8.5–8.0 ka in the North Atlantic region and eight are coincident with the 8.2 ka event.
- Although there is widespread evidence for the presence of Late Mesolithic hunter-gatherers in the uplands of northwest England, their impact on the landscape is considered to have been very limited and highly unlikely to have caused the reworking of primary loess accumulations.
- The estimated sea-level MAAT in northwest England during the 8.2 ka event indicates that our sites in the uplands underwent temperature depressions of ~2.6–4.6 °C below present-day values. Other proxy data indicate a shift to wetter conditions at this time. We infer that there was increased snow accumulation in winter, that the snowpack persisted for longer periods, and that the magnitude and frequency of frost-related processes and meltwater flooding was amplified. It is proposed that these changes in climate together with their associated (sub)surface processes stimulated the reworking of inherently mechanically weak loess deposits.
- Our data complement previously obtained evidence from lacustrine and terrestrial settings in Great Britain for marked climatic deterioration and landscape changes in the latter half of the ninth millennium.

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