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Sedimentation during Marine Isotope Stage 3 at the eastern margins of the Glacial Lake Humber basin, England

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ABSTRACT: The stratigraphic sequence at North Cave, on the eastern margins of the Lake Humber basin, records the deposition of a fluvioperiglacial fan (LFs 1–4), with early sedimentation (LF1) dating to Marine Isotope Stage (MIS) 3 (optically stimulated luminescence date range 41.8–38.6 ka and ^{14}C dates 41.6–49 ka BP). Three phases of permafrost and ice wedge development during MIS 3 are evident and indicate possible fan abandonment and hence periods of reduced nival runoff. Involution structures dated to 11.1 ka with large boulders and fine-grained sorted circles in LF4b are interpreted as periglacially cryoturbated littoral deposits with boulders derived from anchor ice, initially deposited at the margins of Lake Humber up to an altitude of 8 m OD during MIS 2. The style and age of fluvioperiglacial fan deposition at North Cave is compatible with several mid-Devensian sites around Britain characterized by significant nival melt and run-off from steeply incised valleys in permafrozen cuesta landscapes. This phase of fluvioperiglacial fan aggradation to near or below 0 m OD is recorded around the glacial lakes Humber and Fenland basins and indicates that no glacial lakes existed at that time.

KEYWORDS: fluvioperiglacial fan; Glacial Lake Humber; MIS 3; OSL dating; permafrost.

Introduction

During Marine Isotope Stage (MIS) 2 (29–11.7 ka, Late Devensian) the British and Irish Ice Sheet (BIIS) expanded considerably to cover large parts of Ireland, Scotland, Wales and England as well as the Irish Sea and parts of the North Sea. With extensive marine margins, located in a maritime driven climatic system and extensive ice at low altitudes, the BIIS appears to have been highly dynamic. This is well illustrated with the significant advances that have been made recently in the reconstruction of glacial limits and associated ice-dammed lakes in eastern England during the last glaciation (Catt, 2007; Murton *et al.*, 2009; Evans and Thomson, 2010; Livingstone *et al.*, 2012; Evans *et al.*, 2017; Bateman *et al.*, 2018). The glacial lakes have been proposed as important in understanding the dynamism of the BIIS in the North Sea and adjacent areas through ice draw down and increasing basal lubrication/lower basal shear stress (Bateman *et al.*, 2018).

Less is known about environmental conditions and the extent of glaciation during the earlier parts of the last glacial stage. An MIS 4–3 (71–57 and 57–29 ka; Mid Devensian) glacier margin was originally proposed by Straw (1979; Fig. 1). This proposed glacial advance featured ice extending slightly further than the MIS 2 limit (Late Devensian). Separating glacial advances where ice has picked up similar sediment and hence forms similar diamictons (tills) is notoriously difficult, especially when marginal exposures are limited and undated. Straw envisaged a solution to this problem in identifying that ice advances would have dammed regional fluvial drainage to form Lake Humber. When this lake filled to over 30 m Ordnance Datum (OD) (cf. Lewis, 1894; Edwards, 1936; Gaunt, 1976, 1994; Gaunt *et al.*, 1992) it connected, via the Lincoln Gap, to a larger expanse of water named Lake Fenland (West, 1993; West *et al.*, 1999). The coexistence of the lakes would have required the damming of both the Humber Estuary and The Wash by the BIIS moving onshore from the North Sea (Fig. 1). Later, lower levels of Lake Humber may have only been dammed by the North Sea Lobe and/or a significant moraine dam plugging the Humber Estuary. Thus, the key evidence to understanding BIIS advances during MIS 3/4 could relate to the formation and levels of Lake Humber. Although it is apparent that the Lake completely emptied at least once based on subaerial exposure of the lake floor (Gaunt *et al.*, 1970; Gaunt, 1974), opinions are divided as to whether Lake Humber existed only during MIS 2 (e.g. Gaunt *et al.*, 1992; Bateman *et al.*, 2015; Fairburn and Bateman, 2016) or an initial Lake phase dates to an earlier glacial advance as proposed by Straw (1979; *cf.* Murton *et al.*, 2009; Murton and Murton, 2012).

The potential MIS 2 age for Lake Humber is related to a complex pattern of ice-marginal dynamics of both the Vale of York Lobe and North Sea Lobe (NSL) of the BIIS by Gaunt (1974, 1981). Gaunt originally proposed that Lake Humber was initiated by the penetration of the NSL up the Humber Estuary to a stabilization point demarcated by landform–sediment associations at North Ferriby and South Ferriby. Ice is now known to have reached this position at least by 22.5 ± 1.6 ka (Shfd13071; Bateman *et al.*, 2018). Shortly thereafter, the lake attained water levels up to 33 m OD; this upper level is marked by the Older Littoral Sand and Gravel and '100 foot' strandline of Edwards (1936), deposited on the west-facing scarp of the Yorkshire Wolds. The 33 m OD lake level has been variously dated to <26 163 ± 2046 cal BP based on a bone found at Brantingham (Gaunt, 1974), 22.7 ± 1.4 ka, which was not *in situ*, and from low-lying

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Figure 1. The proposed extents of Devensian glaciation and the glacial Lake Humber/Fenland high-level (ca. 30 m OD) phase during the early Devensian (MIS 4) as proposed by Straw (1979). Red arrow represents the proposed spillway along the Waveney valley. The 'low level fan' at Tattershall is incised into the MIS 6 Kirkby Moor Sands and emerges from the mouth of the lower Bain valley, Lincolnshire. Contours are shown at 50 and 100 m, and at 100-m intervals thereafter. Adapted from Straw (1979) and Murton and Murton (2012). Locations cited in the text are: B – Brantingham; E/B – Elloughton/Brough; F – Ferrybridge; H – Hemingbrough; NC – North Cave; NF – North Ferriby.

sediments presumed to relate to the 33 m OD lake at Caistor (Bateman *et al.*, 2000), and a 16.6 ± 1.2 ka age from a beach deposit found at ~30 m OD at Ferrybridge (Bateman *et al.*, 2008). The Vale of York lobe of the BIIS is then hypothesized by Gaunt to have surged southwards to Wroot and then rapidly receded to stabilize at the Escrick and York moraines. Based on deposits at Lindholme this is thought to have occurred ~18–19 ka (Bateman *et al.*, 2015). A low level lake

Table 1. Stratigraphic nomenclature for the southern Vale of York/ Humber Estuary area.

Stratigraphic unit		Depositional environment/age
Holocene alluvium	Breighton Sand Formation	Alluvial deposits (postglacial)
Bielby Sand Member		Glacilacustrine – littoral (MIS 2)
Hemingbrough Formation		Glacilacustrine – distal (MIS 2)
Pocklington Gravel Formation		Cold climate alluvial fan (MIS 3–2)

phase of 8 m OD ('25 Foot Drifts'; Edwards, 1936) is then thought to have been related to moraine damming at North and South Ferriby after local deglaciation (Gaunt *et al.*, 1970; Gaunt, 1974; *cf.* de Boer *et al.*, 1957).

The occurrence of Lake Humber is clearly recorded by up to 24 m of glacilacustrine deposits of the Park House Clay and Lawns House Farm Sand members of the Hemingbrough Formation (Table 1; e.g. Thomas, 1999; Ford *et al.*, 2008). The former have been variously dated to 20–24 ka and the latter to 16–17 ka (Murton *et al.*, 2009; Bateman *et al.*, 2015). These deposits cannot be unequivocally associated with any lake level above 8 m OD, being the height to which they occur. This is supported by the presence of sand ripples within the Park House Clay Member, which indicate shallow water formation at least at times (Bateman *et al.*, 2015). Indeed, the only low-level phase evidence that can be verified stratigraphically in association with the MIS 2 ice margin is at South Ferriby and the Horkstow Moraine in the Humber Gap (Frederick *et al.*, 2001). These moraines are undated but are presumed to be of similar age to the North Ferriby moraine, dated to at least 22.5 ± 1.6 ka (Bateman *et al.*, 2018) and directly related to lake damming. In the Vale of York, the Hemingbrough Formation lies directly above either bedrock or the Basal Glaciofluvial Deposits (Ford *et al.*, 2008) and has been associated with the ice advance which occurred around 21.6 ka (Bateman *et al.*, 2018, table 2). At higher elevations on the western slopes of the Yorkshire Wolds, the dominant surface materials are chalk and flint gravels and are contained within coalescing alluvial fans, collectively named the Pocklington Gravel Formation (Ford *et al.*, 2008; *cf.* Fairburn, 2011). These have been subdivided by Fairburn and Bateman (2016) into two bodies of cold climate alluvial fan deposits and named the Younger and Older Alluvial Fans. According to Fairburn and Bateman (2016), the Older Alluvial Fans are cross-cut by 25, 30 and 33 m OD lake terraces; the Younger Alluvial Fans outcrop between their 25 and 20 m OD terraces. Fairburn and Bateman (2016) dated the formation of their 20 m OD terrace to $\sim$16 ka.

The surface deposits along the eastern side of the Vale of York, stretching from the Escrick Moraine to the Humber, form an extensive cover of clayey to slightly silty sand with local fine-grained flint and chert gravels and named the Bielby Sands Member (Table 1). Originally assigned to the '25 Foot Drifts' of Edwards (1936), it locally overlies either the Pocklington Gravel Formation or the Hemingbrough Formation and is somewhat loosely assigned to 'Late Devensian drainage' by the British Geological Survey (BGS) because it is part of their predominantly Holocene-aged Breighton Sand Formation. However, its tendency to drape the west Wold slopes up to 35 m OD suggests that the Bielby Sands Member potentially represents some of the rare depositional evidence for the high-level phase of Lake Humber as well as deposition during later, lower lake levels.

The overview presented above identifies a significant gap in our knowledge of the depositional events that took place during the last glacial cycle, particularly the extent and duration of any NSL glaciations during the earlier parts of the last glacial stage and their relationship to Lake Humber. Critical to this is a better appreciation of the stratigraphic evidence for potential glacilacustrine versus alluvial sedimentation in the area and the relationship between that sedimentation and former ice sheet margins. Important stratigraphic evidence pertinent to this knowledge gap was found at North Cave, where extensive quarrying has exposed sands and gravels on the lower slopes of the Yorkshire Wolds chalk escarpment. We present the stratigraphy and sedimentology of North Cave, a site located at the proposed former margins of Glacial Lake Humber in the south Vale of York (Fig. 2) and hence critical to the reconstruction of depositional events in the area. We also present the results of dating of the North Cave deposits and thereby erect the first chronology of depositional events at the eastern margins of the Lake Humber basin immediately before MIS 2 or Dimlington Stadial glaciation.

Methods

Sediments and stratigraphy were analysed on a 300-m-long working face at the Breedon Group's Crosslands Lane quarry, North Cave, in spring 2013 (section centre at 53° 46′52.85″N, 0°40′52.85″W; SE877324) and recorded on scaled photomontages and vertical profile logs. These include information on primary sedimentary structures, bed contacts, sediment body geometry, sorting and texture, and secondary structures, as well as data on clast form and lithology and palaeocurrents. These data were then used to characterize lithofacies types and to allocate facies codes following the procedures of Evans and Benn (2004). Clast form analysis was undertaken on samples of 50 chalk clasts and involved assessments of Powers roundness and clast shape following procedures outlined by Benn (2004) and Lukas *et al.* (2013).

Three units were sampled for optically stimulated luminescence (OSL) dating. Quartz grains of size 180–250 μm were extracted and cleaned from each sample under controlled light conditions as per Bateman and Catt (1996).

Equivalent doses were estimated based on the OSL signal of small multigrain aliquots (containing $\sim$20 quartz grains each), which has been shown to be appropriate to measure samples potentially affected by incomplete bleaching as it provides similar resolution to single grain measurement (Evans *et al.*, 2017). All luminescence measurements were carried out using an automated Risø TL/OSL DA-15 luminescence reader (Bøtter-Jensen *et al.*, 2000, 2010) and the SAR protocol of Murray and Wintle (2000, 2003), with an additional second recycling, including infrared (IR) stimulation before OSL measurement, to detect any feldspar contamination. Within the SAR protocol a preheat of 200 °C for 10 s was used based on a dose recovery preheat temperature test performed on Shfd13059, which recovered to a given ratio consistent with unity. Around 80 small multigrain aliquots were measured for each sample to have a representative dose distribution. Equivalent dose (D_e) estimates were accepted only if the relative uncertainty on the natural test-dose response was <20%, the recycling and the IR depletion ratio including uncertainties were within

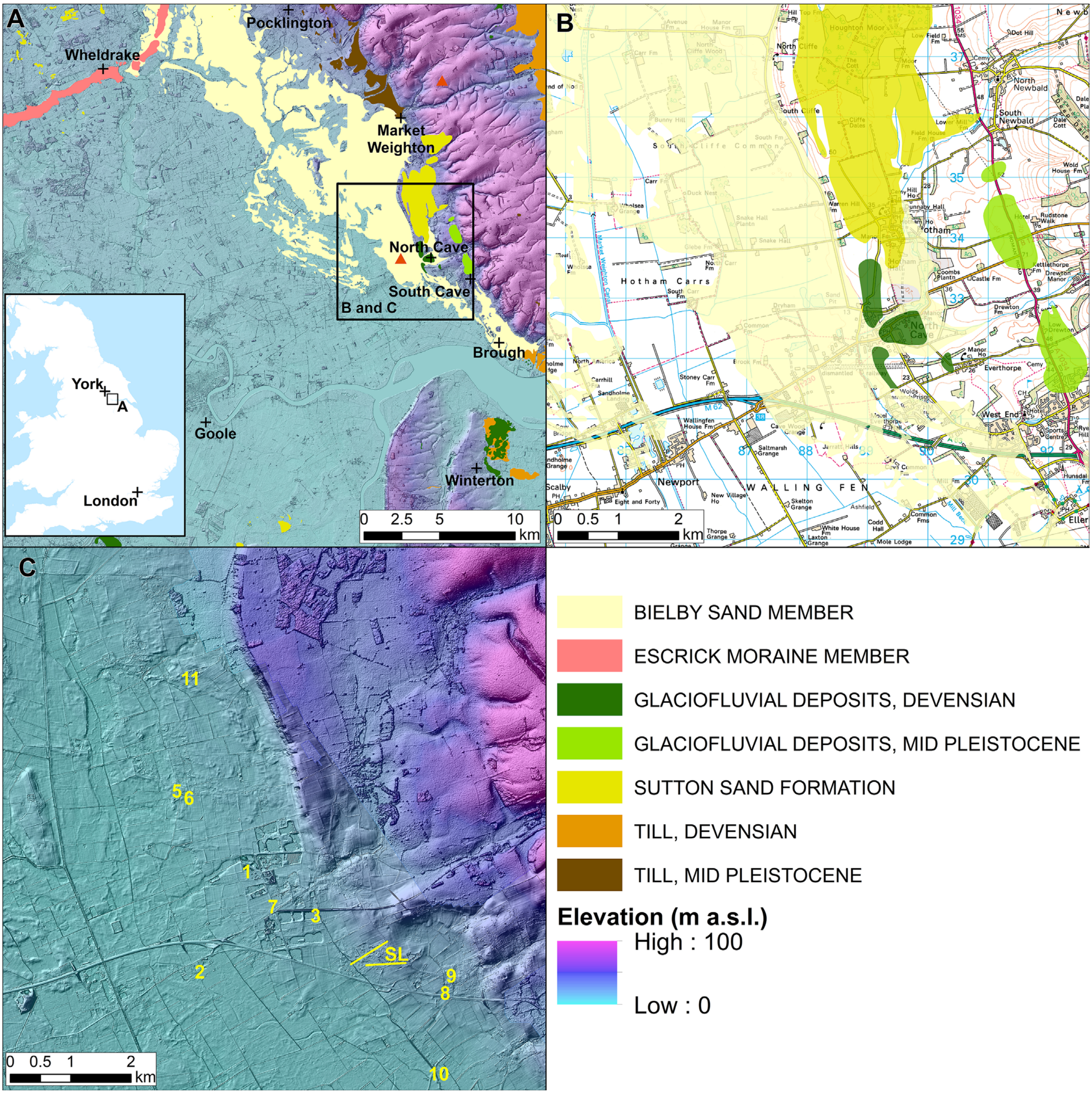

Figure 2. Location maps (derived from Digimap) showing (A) the distribution of the main surficial geology units and LiDAR images for the south-east corner of the Vale of York and adjacent Humber lowlands and Yorkshire Wolds. (B) Enlargement of geological units in the study area. (C) LiDAR and borehole log locations (marked in yellow) and North Cave quarry (red triangle) in the study area.

20% of unity and the recuperation was <5%. These criteria led to dose distributions containing ~60 independent dose values.

The beta contribution to dose rates was based on the concentration of U, Th and K measured using inductively coupled plasma mass spectroscopy (ICP-MS) at SGS Laboratories Ontario, Canada. Gamma dose rates are based on the average radionuclide activities measured using an EG & G MicroNomad gamma field spectrometer. Appropriate conversion factors (Guérin *et al*., 2011) were then used to calculate the dose rate. A linear accumulation of deposits has been assumed to calculate the contribution of cosmic radiation according to a varying burial depth (based on Prescott and Hutton, 1994). The total dose rates were calculated according to attenuation caused by moisture and grain size. Uncertainty of 5% on all water contents has been adopted. Sampling depths, assumed water contents, beta, gamma and cosmic dose rates, and derived total dose rates to an infinite matrix are summarized in Table 2.

Two radiocarbon dates were secured from an organic-rich sandy horizon from within the stratigraphy at North Cave and were digested in 2 m HCl (80 °C, 8 h), washed free from mineral acid with deionized water, dried and homogenized. The total carbon in a known weight of the pre-treated sample was recovered as CO_2 by combustion with CuO in a sealed quartz tube. The gas was converted to graphite by Fe/Zn reduction. Results are reported as conventional radiocarbon years before present (bp; where 0 BP = AD 1950) and further details are provided in Table 3. The $\delta^{13}C$ value was measured on a dual inlet stable isotope mass spectrometer (Thermo Fisher Delta V) and is representative of $\delta^{13}C$ in the pre-treated sample material.

Table 2. Summary of OSL estimated ages (to 1σ error) and associated information for three samples from North Cave. Depth, water content and the calculated contribution to the total dose rates are summarized. The table also includes information on the total number of aliquots measured with OSL which passed the acceptance criteria and the overdispersion (OD) of the resulting dose distribution.

Lab. code	Depth (m)	Water content (%)	β dose rate (Gy ka^{-1})	γ dose rate (Gy ka^{-1})	Cosmic dose rate (Gy ka^{-1})	Total dose rate (Gy ka^{-1})	Aliquots accepted (measured)	OD (%)	Equivalent dose (Gy)	Age (ka)
Shfd13060	0.8	23	0.52 ± 0.04	0.25 ± 0.02	0.19 ± 0.01	0.97 ± 0.05	62 (74)	38	10.8 ± 0.6	11.1 ± 0.8
Shfd13059	6.4	23	0.76 ± 0.07	0.43 ± 0.03	0.09 ± 0.01	1.31 ± 0.07	65 (74)	43	50.4 ± 4.1	41.8 ± 3.7
Shfd13058	8.0	23	0.70 ± 0.07	0.33 ± 0.02	0.08 ± 0.01	1.19 ± 0.07	57 (80)	58	49.8 ± 3.2	38.6 ± 3.3

Table 3. Radiocarbon dates and associated information for the peat samples collected from the top of LF2 at North Cave.

Lab. code	^{14}C enrichment (% modern ± 1σ)	% carbon content	$\delta^{13}C_{VPDB}$ (‰, ± 0.1)	Conventional radiocarbon age (years BP ± 1σ)
SUERC-77600	0.22 ± 0.10	10.6	−29.2	48 981 ± 3582
SUERC-79023	0.56 ± 0.10	Not available	−29.8	41 586 ± 1420

Results are reported as conventional radiocarbon years before present (bp; where 0 bp = AD 1950) and % modern ^{14}C both expressed at the ±1σ level for overall analytical confidence. ^{14}C results have been normalized to $\delta^{13}C_{VPDB}$‰ = −25 using the ^{13}C values in the report. The results are close to background and the calibrated ages are beyond the range of the calibration software (OxCal 4.3).

Stratigraphy, sediments and structures at North Cave

Description

The stratigraphy at North Cave comprises laterally extensive, tabular units of sands and gravels that display significant secondary and syndepositional disturbance structures, especially in the upper part of the sequence (Fig. 3). Both lithology and disturbance structures allow the identification and classification of four major lithofacies (Fig. 4a).

Lying directly on the local Triassic age bedrock of Mercia Mudstone is lithofacies 1 (LF1), which comprises ≤2.2 m of predominantly multiple stacked units of horizontal to low-angle planar cross-bedded coarse to medium sand, containing fine to medium-sized gravel lags (Fig. 5). These sands are separated by discontinuous lenses to beds of massive to horizontally bedded, poorly sorted granule to pebble gravel. Clast forms from the base of LF1 are variable, with a clast shape defined by a C40 of 57% and roundness measures of RA at 35% and average roundness at 1.96 (Fig. 4A). Clast lithologies are dominated by chalk (82%), with minor components of limestone (11%) and sandstone/ironstone, flint and vein quartz (all each <5%; Fig. 4b). Clast forms from the middle of LF1 are similar to those from the base, with a slightly less blocky clast shape defined by a C40 of 72% and less variable roundness, with an RA at 20% and average roundness at 1.98 (Fig. 4).

A relatively thick gravel bed at the top of LF1 passes abruptly into overlying LF2, which is a generally finer sediment package comprising ≤0.8 m of low-angle planar cross-bedded sands with poorly sorted granule to pebble gravel lags (Fig. 6). The lags lie either at the base of individual sand beds, as in LF1, or on the floors of shallow scour fills. Palaeocurrent measurements taken from the dips of downflow-prograding avalanche beds in cross-bedded sands on LF1 and LF2 reveal a wide range of orientations indicative of radial flow from the east (Fig. 4a). Vertically orientated V-shaped secondary structures are developed in the upper 0.5 m of LF2 and are characterized internally by sub-vertically inclined beds of poorly sorted sand and gravel and sub-vertical clast alignments. Finer, sand-rich vertical necks form the central axes of the V-forms. Some of these features extend only to the surface of LF2 (Fig. 6) but others continue upwards through overlying LF3 and LF4a (Fig. 4a). Also at the top of LF2 are discontinuous lenses of organic-rich sand or peat indicative of patchy vegetation establishment at the same time that the V-forms were created.

An erosional contact separates LF2 from overlying LF3 (Fig. 6), the latter comprising ≤0.5 m of crudely horizontally bedded, poorly sorted pebble gravel with a sandy matrix. These gravels are locally cross-cut by vertically orientated V-shaped secondary structures characterized internally by sub-vertically inclined beds of poorly sorted sand and gravel and sand-filled vertical necks; the vertical structures extend both downwards (narrowing) into underlying LF2 and upwards (widening) into LF4 (Fig. 4).

A loaded or deformed contact separates LF3 from overlying LF4 (Figs 4a and 6). The wider tops of vertically orientated V-shaped secondary structures also extend from the base of LF4 into and through LF3 (Fig. 4a). Although it appears heavily deformed or disturbed due to contorted bedding structures, a very crude overall pattern of horizontal bedding is visible in LF4 (Figs 3 and 7). The primary sediments appear to comprise interstratified, horizontally bedded sands and gravels but where they have been more heavily mixed by secondary deformation they occur as poorly sorted pebble gravel within a sandy matrix (matrix-supported gravel; Gms). The horizontal bedding is better preserved in the lower 2.5 m of LF4, where disturbance structures appear to be intraformational and hence do not penetrate through significant thicknesses of sand and gravel beds. Consequently the lower 2.5 m is sub-classified as LF4a. Internally, the crude horizontal bedding in LF4a is better displayed in its upper 0.5–1 m (Fig. 7), contrasting with the relatively more heavily disturbed lower 0.5 m, where large open folds or deformation cells and the upper ends of V-shaped structures are dominant (Fig. 4). The upper 1–1.3 m of LF4 is characterized by significant soft-sediment deformation structures, the latter manifest as the downward penetration of cells of finer-grained silty sand with isolated boulder-sized clasts and the upward penetration of gravel-cored diapirs; these characteristics are used to sub-classify this area of LF4 as LF4b. In places, the finer-grained

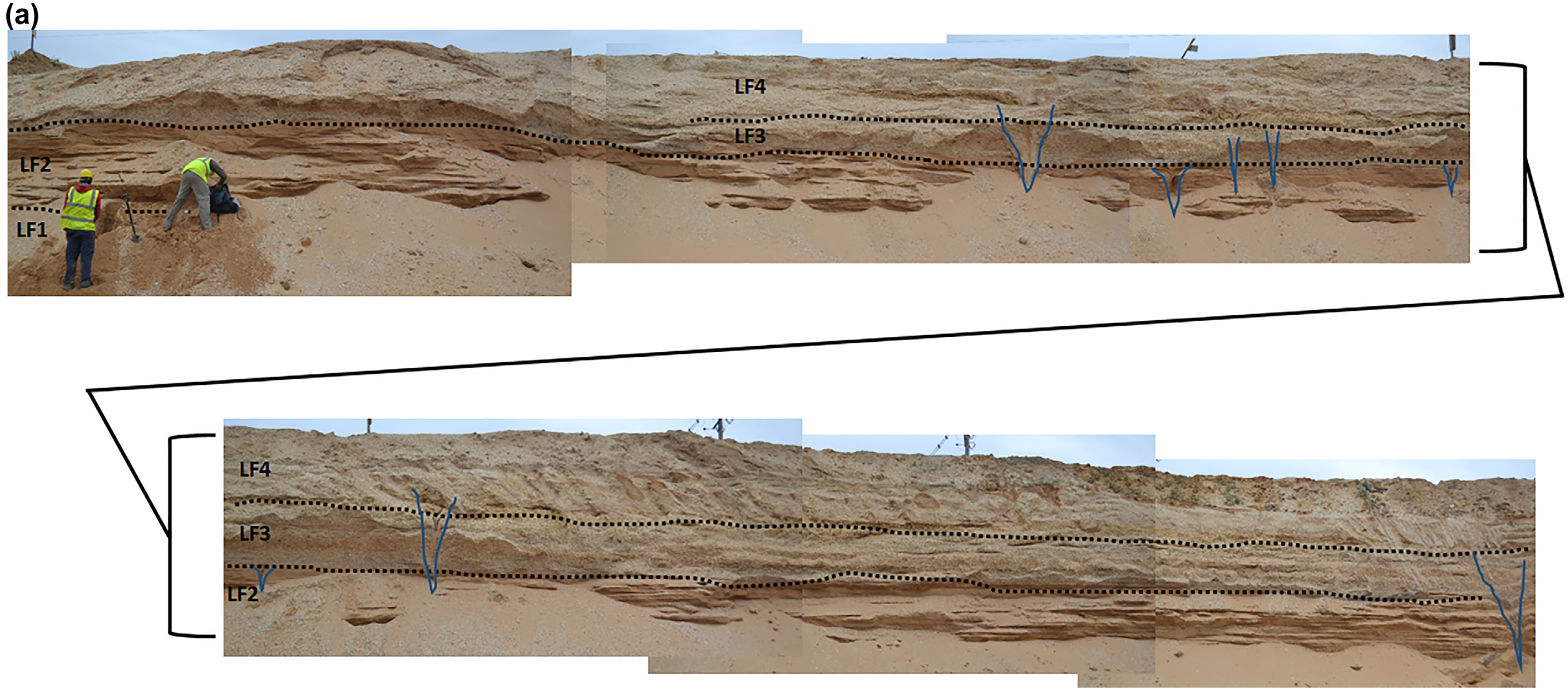

Figure 3. Details of the North Cave stratigraphy. (a) Photomosaic of the main quarry face at North Cave, showing the tabular nature of the lithofacies and the distribution of secondary, vertically aligned structures (ice wedge pseudomorphs) in blue (b) Variety of well-developed periglacial and permafrost features, including: A – simple ice wedge pseudomorph developed in gravels and extending down into sands and sandy gravels in which an earlier ice wedge appears to have been developed, thereby constituting an interformational structure; B – simple ice wedge pseudomorph in gravel extending down to a sand wegde in underlying sandy facies; C – composite wedge pseudomorph extending downwards from LF4a and cross-cutting LFs 3 and 2. Such wedges comprise a primary infill pipe at the centre, here composed of a sand wedge, and a secondary outer zone of normal faults in the host gravel related to secondary infilling in association with the ice wedge; D – multi-layered pendant or tear drop structures/cells of finer-grained sediment and upward penetrating gravel-cored diapirs; E – cryoturbation feature, showing downward loading of gravels and vertical displacement of sandy gravels to form a flame structure.

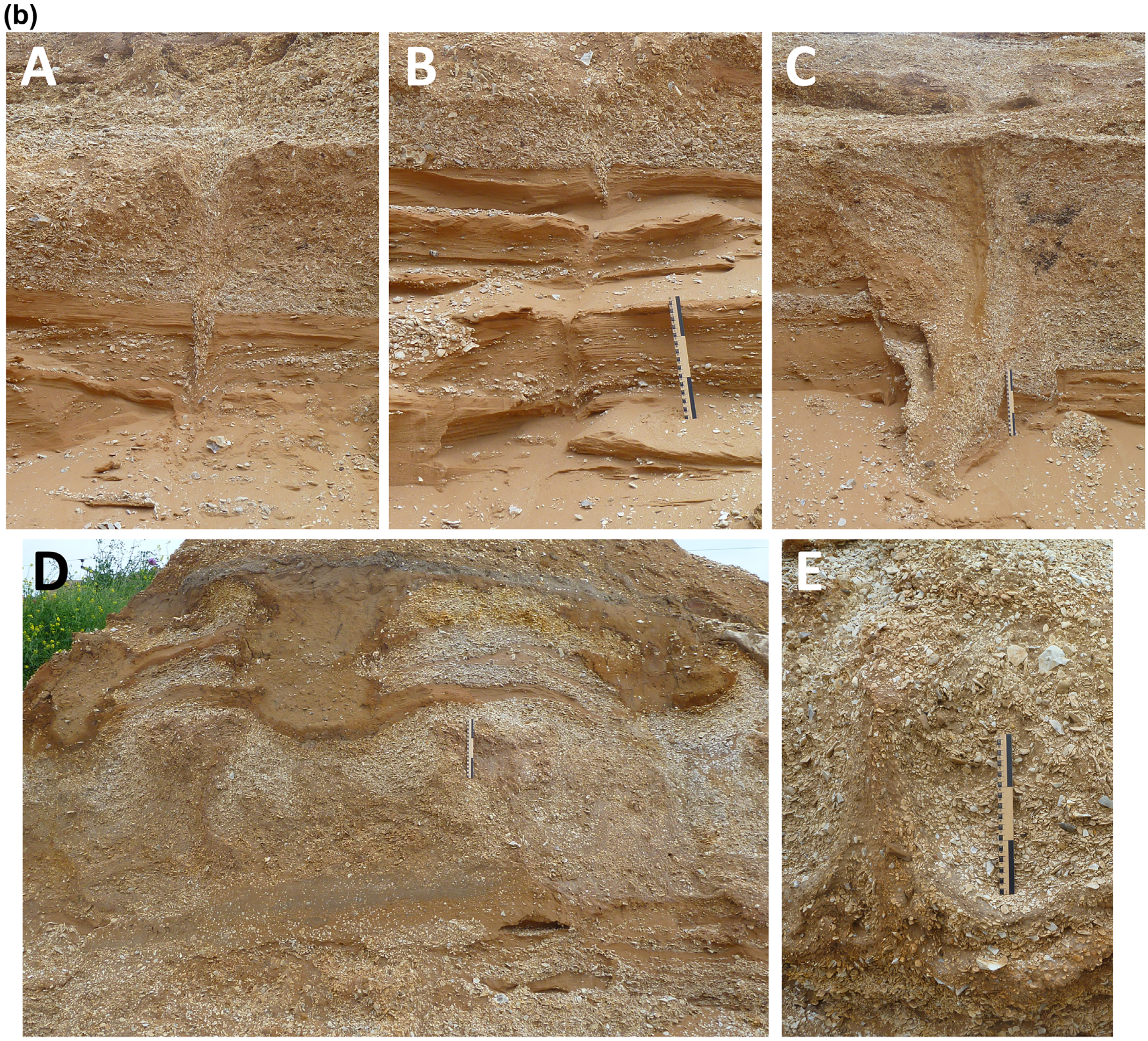

Figure 3. Continued.

cells form multi-layered pendant or tear drop structures that deform around rare angular boulders (Fig. 7) and appear to be locally interdigitated with horizontally bedded gravels and sands towards the top of LF4b. Bedding and clast orientations within the gravels penetrated by the finer-grained cells bend to conform to the cell lower boundaries. Some vertically orientated V-shaped secondary structures have been developed in the base of LF4b and penetrate downwards to the top of LF4a (Fig. 4). Clast forms from the top of LF4a are highly platy with a clast shape defined by a C40 of 90% and roundness measures of RA at 24% and average roundness at 1.5 (Fig. 4a). Clast lithologies from the base of LF4b are dominated by chalk (91.5%) with minor components of sandstone (7%) and limestone (1.5%; Fig. 4b).

Interpretation

The planar cross-bedded nature of the primary sand bedding, with internal clast lags and scour fills, and the occurrence of massive to horizontally bedded gravels in LFs 1 and 2, outcropping over an area of greater than several square kilometres (based on the wider exposures at the various quarries at North Cave), are diagnostic of the aggradation of fluvial bedload in a stream system characterized by fluctuating discharges. A braided fan network is probably represented here by LFs 1 and 2, especially as the palaeocurrents are variable but apparently representative of a general water flow direction fanning out from the east. The vertical facies changes appear to represent lateral accretion macroforms, as defined by Miall's (1985, 1992) architectural element approach, wherein variably orientated sand cross-bedding records the lateral migration of mid-channel bars. The accretion of these macroforms in a sand-dominated system was interrupted by occasional scour infills created by pulses of gravel-charged bedload centred on main channels that developed during phases of relatively high discharge (Church, 1972; Miall, 1977; Bryant, 1983a,b). Predominantly sub-angular and platy to elongate clasts indicate short fluvial transport distances and would not be unusual in permafrost or periglacial, nival-fed rivers (Tomlinson, 1940; Lewin, 1969; Williams, 1971; West and Williams, 2012; Newell *et al.*, 2015; West, 2015), although the dominant chalk lithologies in the region tend to impart a strong control on the slabbiness of clasts in the study area and hence RA and

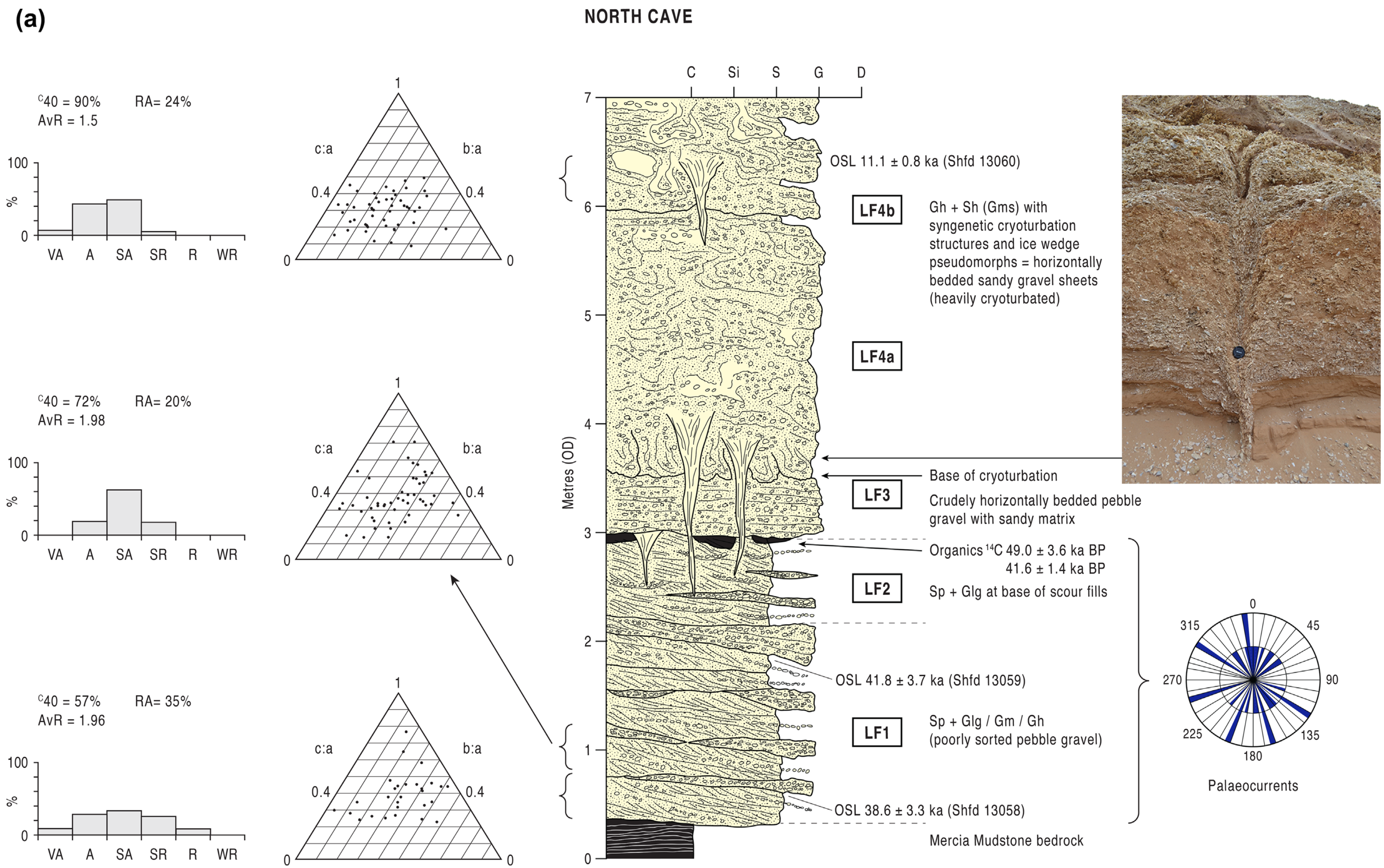

Figure 4. Composite vertical profile log (a) and clast lithologies for selected facies (b) from the exposure at North Cave. The log shows major lithofacies and the internal structures, clast form and palaeocurrent data (based on downflow dip directions of avalanche or lee side beds in cross-bedded sands), and locations of OSL and ^{14}C dates. Inset photograph shows the nature of syngenetic ice wedge pseudomorphs developed in the base of LF4a and extending down into LF3 and LF2.

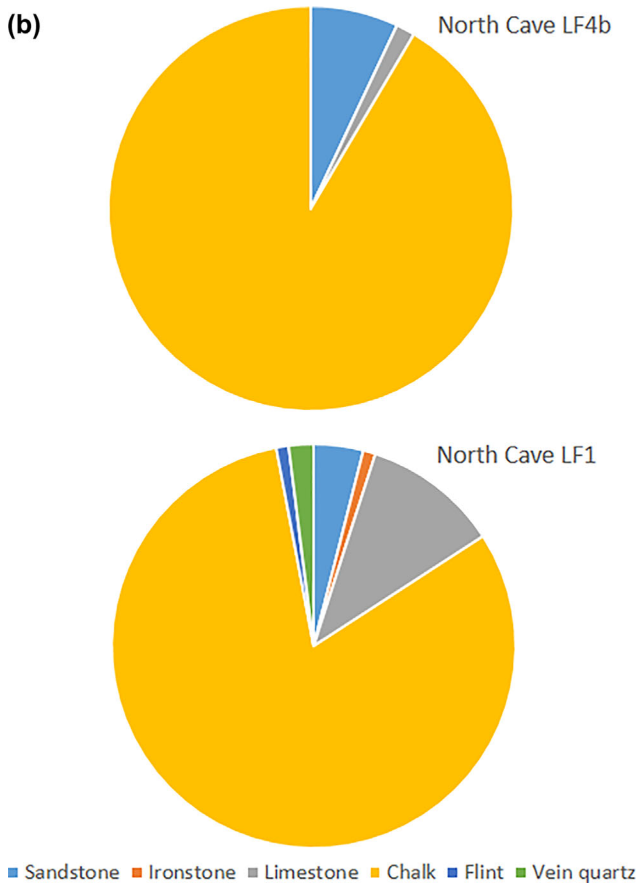

Figure 4. Continued.

average roundness rather than C40 values are the best discriminators for clast modification. Very little data are available on clast form in periglaciated and glaciated limestone and chalk catchments but the slabbiness and elevated C40 of argillaceous rocks identified by Lukas *et al*. (2013) makes them a suitable comparator for the analysis of the North Cave data. Hence, the Type II covariance plot of Lukas *et al*. (2013) indicates a fluvial signature for the clasts of LF1 (Fig. 8), even though the elevated C40 values indicate unusually high levels of slabs and elongates controlled by the local chalk macrostructure. Clast lithologies, being dominated by chalk but including also minor components of limestone, sandstone and flint, indicate entirely local derivation, specifically from the Wolds scarp valleys where all these bedrock types outcrop but with chalk being the most extensive surface material. An increase in the dominance of chalk and decrease in lithological variety between LF1 and LF4b potentially records the backfilling of the lower stretches of the Wolds valleys by fan aggradation, which would have sealed in the non-chalk outcrops at the base of scarp succession. Overall, a periglacial alluvial fan environment appears the most likely scenario for LFs 1 and 2, considering both the lithofacies characteristics, lateral extent of deposits, local derivation of clasts/lack of erratics and the widely dispersed (fan-like) westerly directed palaeocurrents (i.e. flow inland towards the Vale of York).

The characteristics of LF3 indicate that the predominantly sandy fluvioperiglacial environment recorded by LFs 1 and 2 was replaced by a stream system characterized by relatively higher and more sustained discharges. Specifically, the crudely horizontally bedded, poorly sorted pebble gravel with sandy matrix indicates sedimentation by aggradation and migration of gravel bars in braided streams with high debris loads (Miall, 1978, 1985, 1992). The primary sedimentary characteristics of overlying LF4, even though they are significantly modified by secondary structures, indicate that a similar high-discharge fluvial environment persisted at the site, evolving gradually into a gravel and sand interbedded sequence typical of more channellized flows (Miall, 1985,

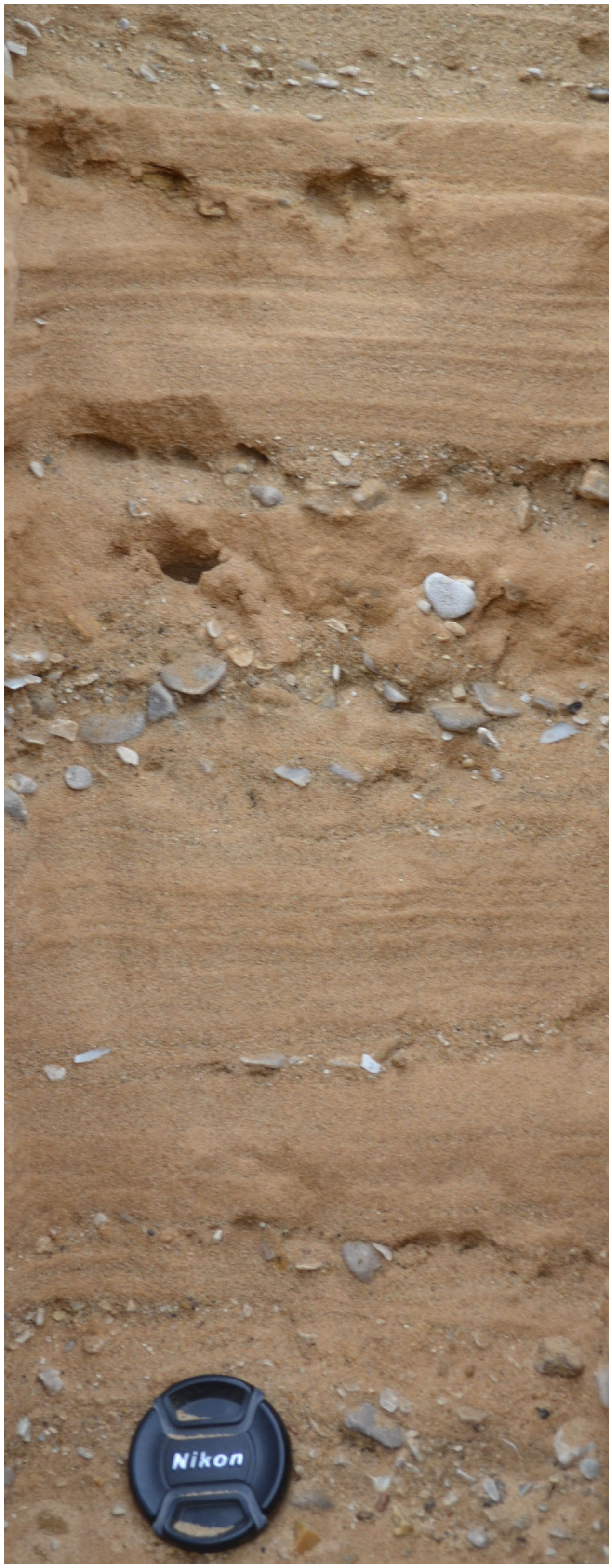

Figure 5. Details of LF1, showing horizontal to low angle planar cross-bedded sand with lags, separated by discontinuous lenses to beds of massive to horizontally bedded gravel.

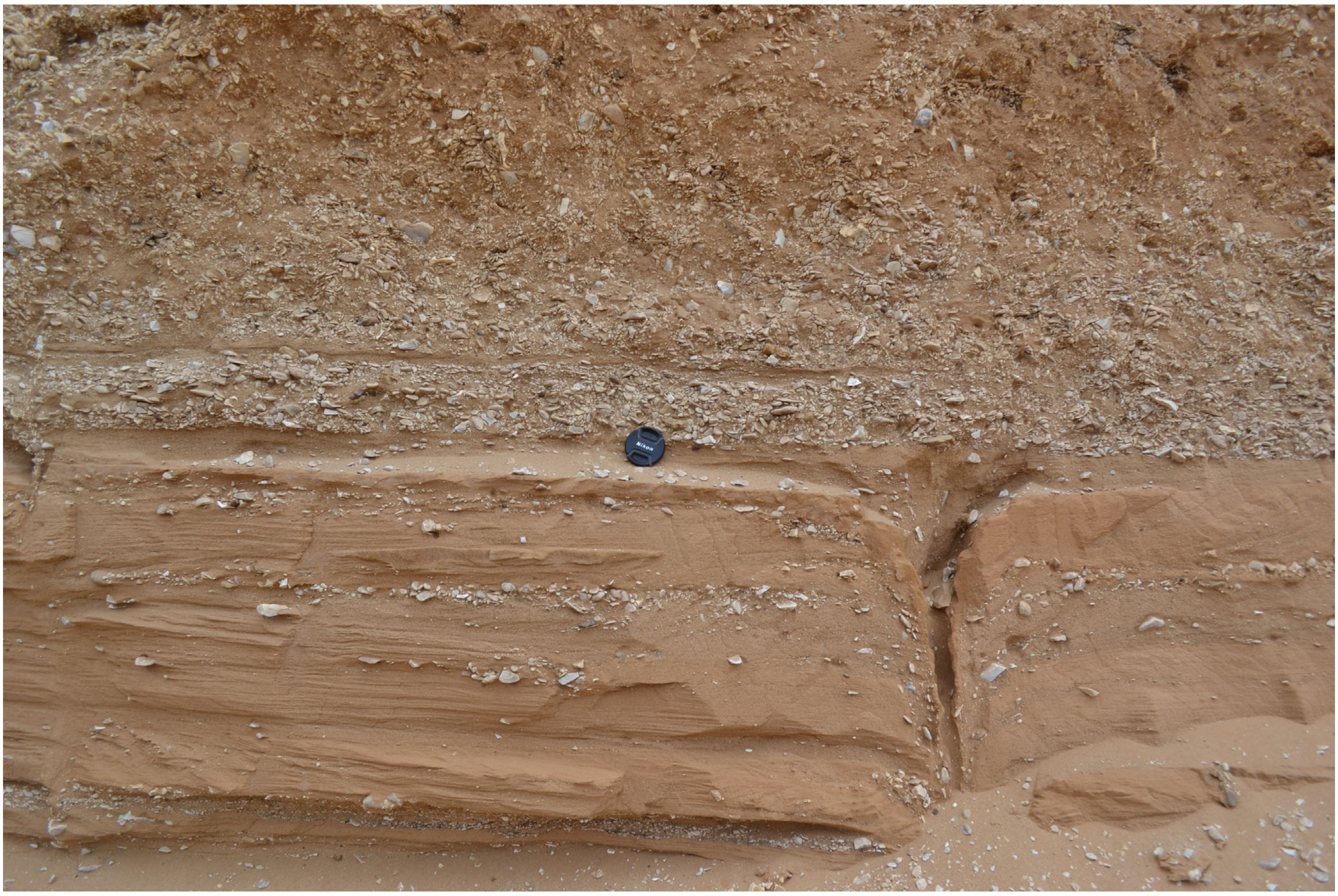

Figure 6. Details of LFs 2 and 3 and the base of LF4a. At the base, LF2 displays low-angle planar cross-bedded sands with poorly sorted granule to pebble gravel lags at planar bed bases or in shallow scour fills and ice wedge pseudomorph. In the centre, LF3 displays horizontally bedded pebble gravel with a sandy matrix but its upper bedding has been disturbed by cryoturbation cells.

Figure 7. Details of LF4, showing the better preserved primary interstratified, horizontally bedded sands and gravels of LF4a at the base of the exposure and the more heavily mixed and deformed structures of LF4b at the top. Clearly visible in LF4b are downward penetrating, multi-layered pendant or tear drop structures/cells of finer grained silty sand with isolated clasts and upward penetrating gravel-cored diapirs (see also Fig. 3b, panel D). Note the 0.25-m-wide angular boulder at the upper right, around which downward penetrating, fine-grained pendant-shaped cells have deformed.

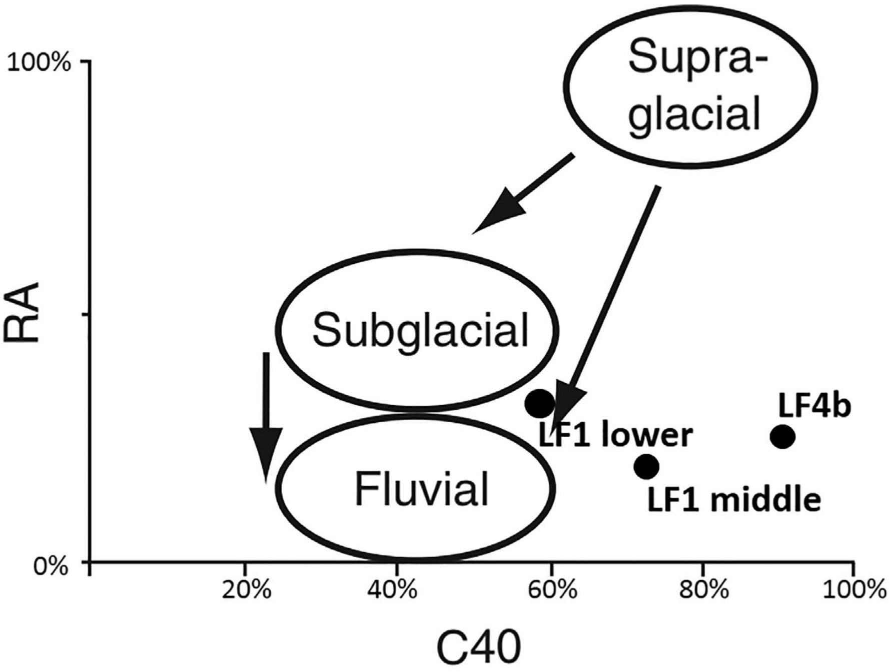

Figure 8. Covariance plot for RA/C40 containing envelopes for samples of known transport origins where clast lithology strongly controls the C40 index to produce abnormally high slabiness/platiness (from the Type II plot of Lukas *et al.*, 2013).

1992). The increase in clast slabbiness (C40 = 90%) and angularity (average roundness = 1.5) potentially indicates faster delivery of material from the frost-weathered western slopes of the west-draining Wolds valleys to the aggrading fluvial sequence; a strong inheritance of bedrock structure is probably reflected in the elevated C40 value for LF4b clasts and hence the RA value is again a better discriminator for clast modification and indicates a fluvial origin using the Type II covariance plots of Lukas *et al.* (2013; Fig. 8). The introduction of rare large boulders into LF4b is incompatible with the apparent fluvial discharge regime indicated by the enclosing medium to fine gravels and sands. However, on a relatively flat terrain such as that around the North Cave area, and in the absence of any evidence for direct glacigenic debris emplacement, these boulders must have been transported to the site by non-glacial processes. Their origins are assessed below in relation to the significance of secondary structures.

Previously reported observations on the deposits along the east side of the Vale of York can be used here to further refine a periglacial alluvial origin for the North Cave stratigraphy. Melmore (1935) reported on a boring and a section near Market Weighton in the area mapped by Fairburn and Bateman (2016) as their 25-, 30- and 33-m terraces, between their Younger and Older Alluvial Fan assemblages. Here the stratigraphy comprised up to 10 m of flint and chalk gravel overlain by brown loamy sand with dispersed clasts (and very rare erratics) and displaying involutions. Melmore (1934, 1935) also describes an extensive 6-m-thick exposure of stratified sands coarsening upwards into locally sourced gravels and displaying large-scale clinoforms, located as far west as Holme-upon-Spalding. Melmore (1935) goes on to explain how similar exposures were found further south, all the way to South Cave, and that the gravel lithologies varied locally but were always indicative of very short transport distances, especially as they were angular and platey in shape.

A further assessment of the thickness and distribution of these locally sourced gravels and sands and their relationship to glacial deposits can be achieved through the study of borehole logs archived by the BGS, located on Fig. 2 and reproduced here in Fig. 9. The maximum mapped extent of the Dimlington Stadial of the last glaciation has traditionally been located at a morainic assemblage around the villages of Elloughton and Brough, located 5 km to the south-east of North Cave and recording the incursion of the North Sea Lobe up the Humber Estuary (Bateman *et al.*, 2018). Beyond this margin, a north–south-trending elongate assemblage of glacifluvial deposits lying between 15 and 40 m OD on the lower Wolds scarp, directly east of North Cave, has been equated by the BGS to Devensian age glaciation (Fig. 2). Borehole log 4 from the Brough area contains a clear stratigraphic record of glacier advance in the form of a 2-m-thick diamicton (till) lying beneath the Bielby Sand Member and overlying sands and clays with a minor chalk gravel unit, all of unknown age. To the west and north of this location, the only borehole records that contain any potential evidence of direct glaciation are logs SL3 and SL7 at Sand Lane, 2.5 km south-east of North Cave, where records describe gravelly clay or clay with gravel; these units are presumed to be diamictons forming the base of a stratigraphic sequence that drapes the Wolds lower slopes but their age is unknown.

With the exception of only three logs (nos. 7, SL17 and SL20), the Bielby Sand Member occurs at the top of all borehole records where it invariably caps sandy gravel or gravelly sand. Because the latter deposits are recorded throughout log 7, which is located at the North Cave quarry, they are regarded as the equivalent of LFs 1–4a reported in this study. As the regional stratigraphy reveals that the Bielby Sand Member overlies either the Hemingbrough Formation or the Pocklington Gravel Formation, we consider LFs 1–4a to constitute a local outcrop of the Pocklington Gravel Formation. In this area, these deposits represent part of the Younger Alluvial Fans of Fairburn and Bateman (2016), who reported an OSL age of 58.4 ± 3.3 ka (Shfd12069) for them from the North Cave quarry and therefore proposed that they recorded fluvial reworking of older sediment during late MIS 2 periglaciation. We will discuss below our re-assessment of this proposed late MIS 2 age for LFs 1–4a, which appears to be too young. Evidence of the Bielby Sand Member being separated from the Pocklington Gravel Formation by a clay unit occurs in logs 5 and 6, and clay also underlies a thick unit of Bielby Sand Member in log 11. These logs importantly lie at greater distances from the main dry valleys of the Wolds

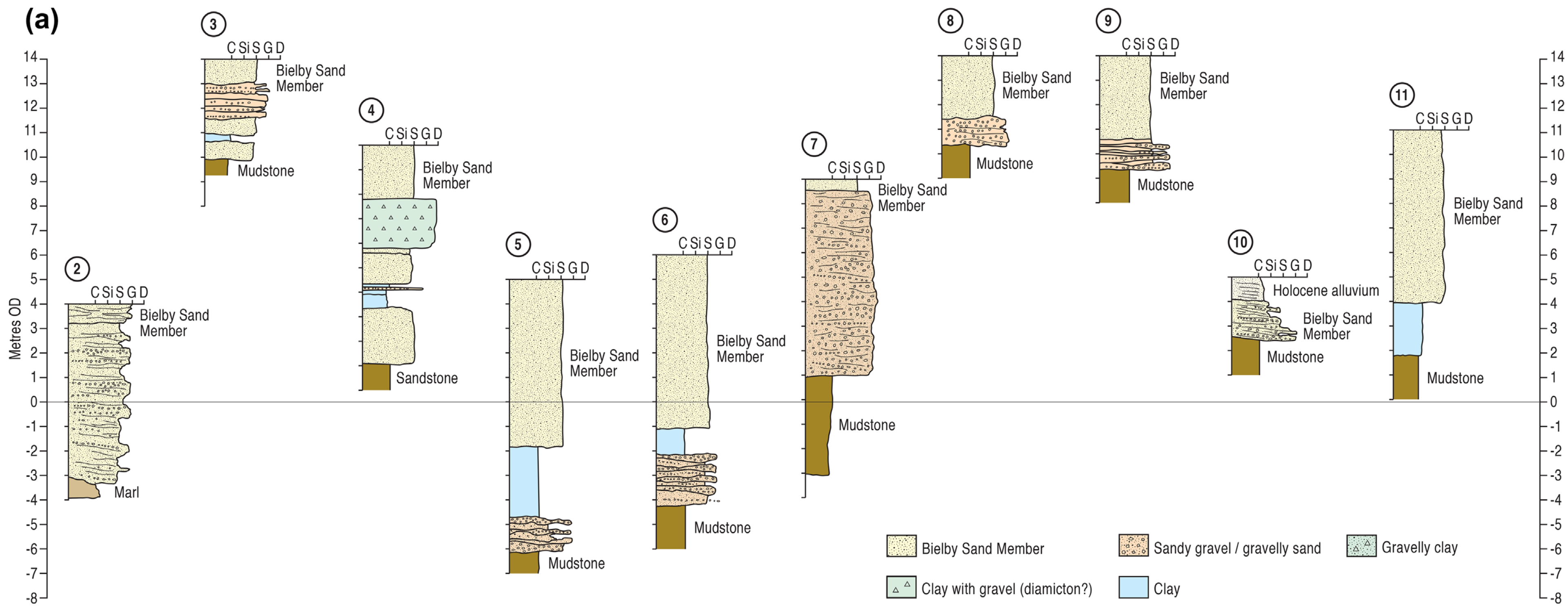

Figure 9. Borehole logs extracted from the BGS borehole data archive and located on Fig. 2C (except site 4 which is near Brough on Fig. 2A): (a) individual logs from around the study area; (b) logs from intensively sampled site at Sand Lane, immediately south-east of North Cave and arranged along two transects as identified in Fig. 2 by the label SL; (c) correlation of stratigraphic units along a transect from the Wolds scarp slope to the head of the Humber Estuary using selected borehole logs, BGS mapping and employing the formation and member nomenclature of the BGS.

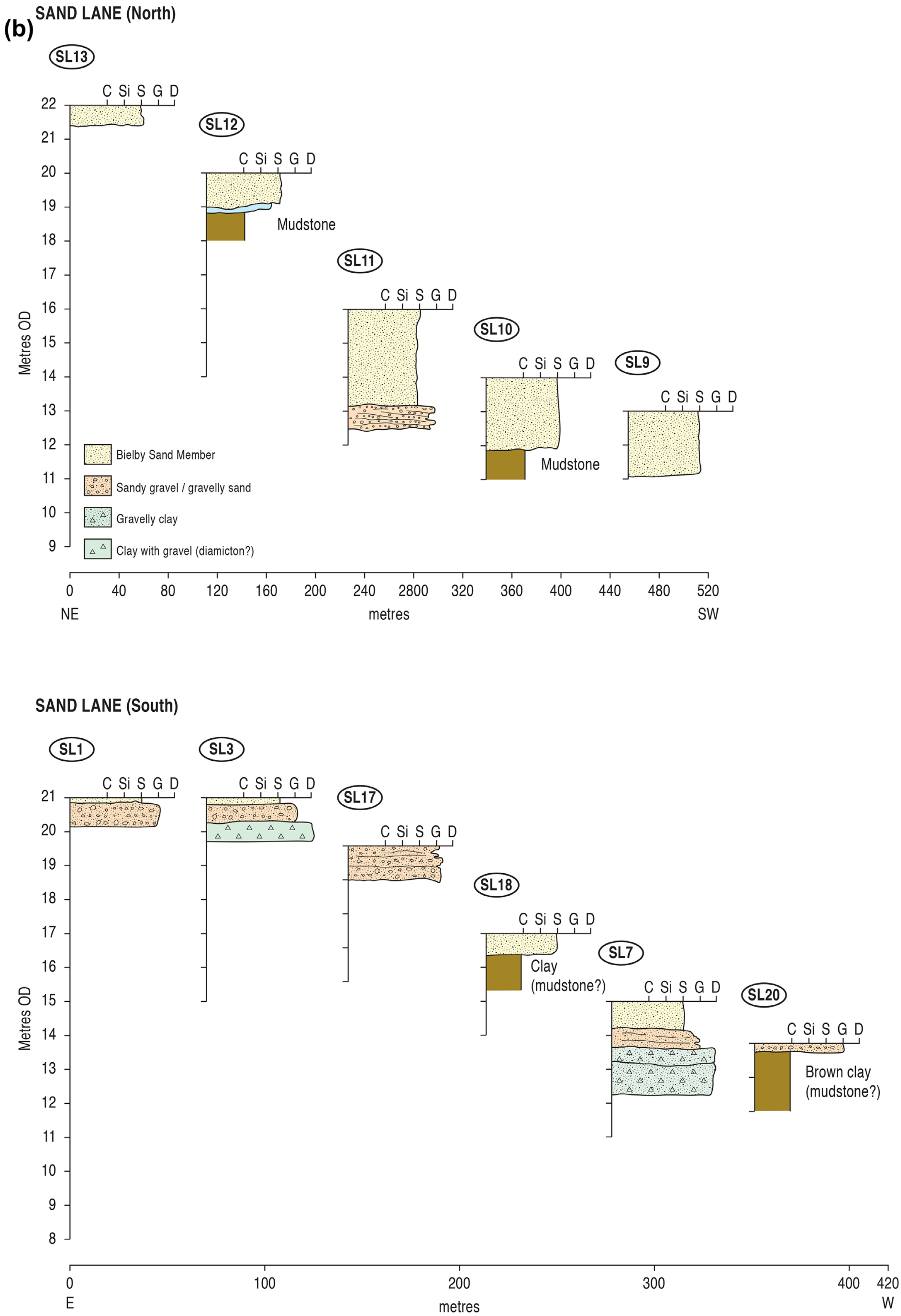

Figure 9. Continued.

scarp and at lower elevations and hence probably indicate lake sedimentation immediately after the deposition of the Pocklington Gravel Formation and/or before the emplacement of the Bielby Sand Member; this is compatible with the Bielby Sand Member being of littoral origin, as briefly discussed in the introduction and elaborated upon below.

The borehole logs allow us to reconstruct the altitudinal range of sedimentation and provide further support for a fan

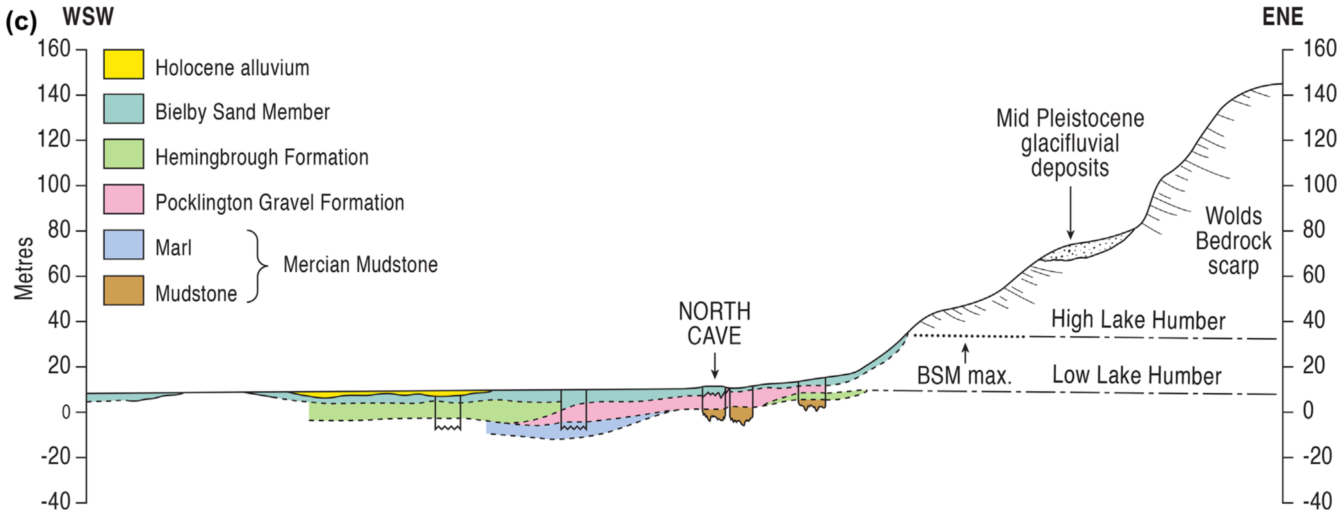

Figure 9. Continued.

origin for the Pocklington Gravel Formation (Fig. 9c). The upper contact of the formation drops from 13 m OD (log 3) at the mouth of the deeply incised Wolds scarp valley of Newbald/Mill Beck (i.e. the fan apex) to 3.25 m OD towards the south-west at Walling Fen (log 2), and through 9 m (log 7), to 6 m (Crosslands Lane) and to −2 m OD and then −4.5 m OD (logs 6 and 5, respectively) towards the north-west. Further north at log 11 there is no Pocklington Gravel Formation present. A similar drop in its upper contact is represented in the south between logs 8/9 (10.5–11.5 m OD) and log 10 (3.2 m OD). The borehole records at Sand Lane (Fig. 9c) indicate that the upper contact of the formation falls from 20.8 to 13.5 m OD in a south-westerly direction. The formation also increases in thickness from the fan *apex* at North Cave, from 2 to 6 m towards the south-west and from 2 m through 6–9 m and then to 1.5–2 m towards the north-west. These altitudinal and architectural characteristics clearly show that the deposits were laid down on a south-westerly, westerly and north-westerly, very gently dipping and aggrading fan surface, fed by runoff from the steeply incised channels and valleys of the Wolds scarp slope and infilling the adjacent lowlands of the eastern Vale of York. Moreover, the fan sands and gravels were initially grading to altitudes approaching 6 m below present sea level, indicating that the area was not inundated by either lake or marine waters at that time and that sea level was lower than those of recent interglacials in the area (i.e. 2 m OD for the MIS 5e beach at Sewerby; Bateman and Catt, 1996). It was only later, when the Bielby Sand Member, and more specifically the clays that underlie it at logs 4, 6 and 11, were deposited that lacustrine littoral depositional processes replaced subaerial fan aggradation.

Although the stratigraphic sequence from LF 1 to LF4 indicates increasingly high-energy sedimentation, the nature of the secondary structures developed in LFs 2–4 provides important information on interruptions to this predominantly periglacial fluvial regime. The vertically orientated V-shaped secondary structures with internal down-turned and vertically aligned bedding and clast sub-horizontal bedding have all the diagnostic characteristics of ice wedge pseudomorphs (Figs 3, 4 and 6) or, more rarely, composite wedge pseudomorphs (Fig. 3b, panel C; Murton, 2013) and hence record the occurrence of permafrost and ground ice at North Cave during the sedimentation of most of the deposits (Harry and Gozdzik, 1988; Mackay, 1990; Mackay and Burn, 2002; Harris and Murton, 2005). Although all wedges appear to be syngenetic and predominantly interformational with evidence of multiple growth phases, separate phases of wedge growth appear to be recorded in the sequence overall, because numerous (intraformational) wedges have been truncated by the emplacement of overlying deposits. For example, at the top of LF2, the tops of ice wedge pseudomorphs display erosional boundaries with the overlying gravels of LF3 (Figs 3 and 6). The upper LF2 ice wedge pseudomorphs are also associated with a discontinuous organic-rich horizon and pockets of peat, indicating that patchy vegetation was established on the periglacial fan surface during the earliest recorded phase of ice wedge growth. Younger, deeper ice wedge and composite wedge pseudomorphs occur in lower LF4a and penetrate down through LF3 and LF2, indicative of a later stage of crack development during the emplacement of LF4a. A later phase of ice wedge development is recorded by the occurrence of ice wedge pseudomorphs in the base of LF4b and extending downwards into the top of LF4a. In summary, three phases of wedge development appear to have taken place during the sedimentation of the fan deposits. Although intraformational ice wedges can develop on the temporarily abandoned surfaces of active fans, the occurrence of wedges at three specific stratigraphic levels at North Cave suggests at least three possible phases of fan abandonment and hence periods of reduced nival runoff.

Some further complexity is apparent in the development of other frozen ground phenomena in the stratigraphic sequence, specifically the deformation or likely involution structures in LF4 (Figs 4 and 7). Many of these features, especially those developed in LF4a, have an outcrop appearance similar to either the more regular dimensions of Type 2 or the more irregular forms of Type 6 cryoturbation structures (Vanderberghe 1988; van Vliet-Lanoe, 1988). Type 2 structures can develop to up to 2 m depth and sometimes greater and hence their development throughout LF4a is not unusual. Their occurrence in LF4a is therefore indicative of significant ground freezing and thawing that appears to have developed after the second phase of ice wedge growth identified above and was probably responsible for the modification of ice wedge pseudomorphs above the basal 0.5 m of the unit. Hence LF4a is probably the upper cryoturbated part of an initially horizontally bedded periglacial fluvial deposit (LF3), and the base of cryoturbation (Fig. 4A) represents the penetration of active layer processes following on from a phase of ground ice development on an abandoned fan surface.

The sedimentary features and permafrost and periglacial structures in LF4b appear to record a later phase of fluvial sedimentation followed by cold climate processes. The preservation of horizontally interbedded gravel and sand typical of channellized fluvial sedimentation, cross-cutting the involutions of upper LF4a, indicates that fluvial processes resumed after LF4a cryoturbation. These deposits (LF4b), like those of LF4a, have been cross-cut and superimposed, respectively, by ice wedge pseudomorphs and cryoturbation structures, again indicative of ground ice development (third phase of fan abandonment) followed by active layer freezing and thawing. The involution structures towards the top of LF4b are, however, distinct from those of lower deposits and are associated with rare large boulders. These involutions are sorted in that they comprise finer-grained cells that appear to have loaded underlying gravels and sands (Fig. 7) and hence resemble the deposits of sorted circles (Hallet and Prestrud, 1986; Washburn, 1989; Hallet, 1990, 1998; Krantz, 1990; Hallet and Waddington, 1992; Kessler and Werner, 2003), potentially related to multiple surfaces (i.e. interdigitated lateral margins) and hence could be intraformational. The origins of the fine-grained material in the downward loading cells as well as the rare large boulders are difficult to speculate upon with great confidence, as they have been consumed within the periglacial structures. However, Ford *et al.* (2008) indicate that surface materials should be the Bielby Sand Member, and its characteristics of 1–2 m (maximum 6 m) thickness, yellow to pale brown and reddish yellow, slightly clayey to slightly silty sand with local fine-grained gravels are indeed compatible with the load cells in upper LF4b.

The Bielby Sand Member, and more generally the Breighton Sand Formation of which the Bielby Sand Member is a part, is traditionally regarded as an alluvial deposit that can be traced over large parts of the Vale of York but, as we briefly discussed in the introduction, its occurrence on the west Wold slopes up to 35 m OD suggests that it could, at least partially, represent some of the rare depositional evidence for the high level and later phases of Lake Humber. Significantly, the North Cave site lies between the 5- and 15-m terraces of the Vale of York and below the final, 10-m Glacial Lake Humber stage of Fairburn and Bateman (2016). Therefore, a possible Bielby Sand Member derivation of the material in the load structures in upper LF4b is entirely compatible with both altitudinal location and lithofacies characteristics. Lake shoreline or littoral sedimentation is also compatible with the introduction of large angular boulders to the upper deposits at North Cave, because they can be explained by anchor ice production, which could have reworked coarser materials from upper shorelines located closer to the Wolds scarp slope to the east (Dionne, 1973; Reimnitz *et al.*, 1987; Heron and Woo, 1994; Smith, 2000). Lake level lowering could conceivably have resulted in the gradual reworking of large boulders to lower elevations, to be reworked into periglacial involution structures after lake drainage.

Chronology of sedimentation at North Cave

With respect to the OSL chronology, the OSL equivalent dose (D_e) distributions of the deepest samples, Shfd13059 and Shfd13058, taken at 6 and 8 m, respectively, are widely scattered (overdispersion 43 and 58%) and skewed (Fig. 10). Given the sampled depths and unit bedding, bioturbation can be ruled out for this D_e scatter (e.g. Bateman *et al.*, 2007) and its magnitude is too great to be attributable to beta heterogeneity. It is instead interpreted that these sedimentary units were affected by incomplete bleaching with a significant number of grains having doses accumulated before the time they were last buried. A minimum age approach using the Internal-External-Consistency Criterion (IEU; Thomsen *et al.*, 2003, 2007) and conditions from well-bleached sediment in the region (IEU model parameter $a = 0.19$, $b = 1.5$ as determined for Evans *et al.*, 2017) was therefore applied to derive the most well-bleached (best reset) grains. As shown in Fig. 10, the D_e distribution of the upper most sample, Shfd13060, is very different. It is unimodal, non-skewed and only moderately scattered (overdispersion 38%), the latter being perhaps due to this sample's association with cryoturbation structures. In this instance, it was therefore decided to base the age estimation on a value derived using the Central Age Model (Galbraith and Green, 1990).

The derived estimated ages are summarized in Table 2 and are included on the vertical profile log for the site in Fig. 4. A date of 38.6 ± 3.3 ka (Shfd13058) relates to the base of the lowest lithofacies (LF1), collected from planar bedded sands with lag gravels, thereby providing an age for the initiation of sedimentation at this site. A date of 41.8 ± 3.7 ka (Shfd13059) from the top of LF1 provides a minimum age for the switch from the relatively more poorly sorted sands and gravels of the base of the North Cave sequence to the better sorted planar bedded sands with lag gravels of LF2. These ages indicate that periglacial fluvial sedimentation was initiated during MIS 3 and that the three phases of ice wedge development at the site post-date ~42 ka, potentially recording increasingly colder and more arid conditions leading up to the Dimlington Stadial. An older date of 58.4 ± 3.3 ka (Shfd 12 069) was reported from sands and gravels sampled from surface augering at North Cave by Fairburn and Bateman (2016), indicating that periglacial fluvial sedimentation could span a significant part of MIS 3. However, as this age estimate was based on large aliquot measurements and the new OSL samples (based on very small aliquots) have demonstrated poor bleaching of this sediment, this age may also be an over-estimate.

The date of 11.1 ± 0.8 ka (Shfd13060) relates to the cryoturbated gravels and sands of LF4b, providing an upper age indicator for both sedimentation and the final phase of frost heave processes at the site. Similar and younger ages have been reported for the Breighton Sand Formation by Fairburn and Bateman (2016), the oldest being 9.13 ± 0.61 ka (Shfd11111). The 11.1 ka date indicates a Younger Dryas age for the upper deposits at North Cave. This is compatible with the well-developed nature of the periglacial and permafrost structures being located at the top of the stratigraphic sequence in LF4 and hence related to the latest phase of cold climate that was severe enough to initiate cryoturbation and ice wedge growth superimposed on Glacial Lake Humber littoral deposits.

Radiocarbon ages of 41 586 ± 1420 ^{14}C a BP (SUERC-79023) and 48 981 ± 3582 ^{14}C a BP (SUERC-77600; Table 3) were obtained for the discontinuous organic-rich horizon and peat in upper LF2, indicating that patchy vegetation was established at 41.6–49 ka BP on the periglacial fan surface during the earliest recorded phase of ice wedge growth. Although the dates are close to background and the calibrated ages are beyond the range of the calibration software (OxCal 4.3), like the OSL ages they indicate an MIS 3 age for the Pocklington Gravel Formation.

Discussion

The Pocklington Gravel Formation in the Vale of York and Humber area of England is described by the BGS as

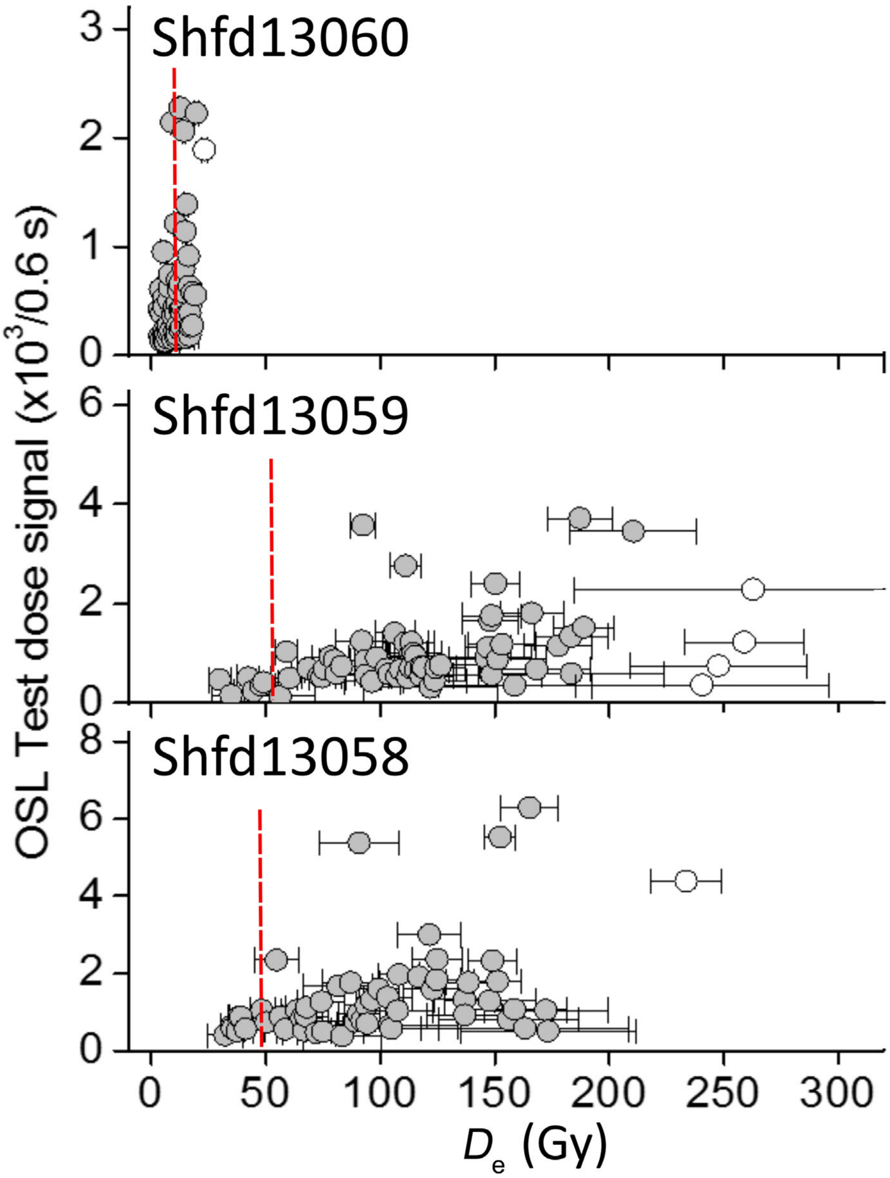

Figure 10. D_e distributions from the three samples. Plots show the OSL natural test dose response as a function of D_e. Each point corresponds to the measurement of an individual multi-grain aliquot. Identified outliers are shown as open circles in the plots. The red dashed line indicates the D_e used for age calculation purposes.

matrix- to clast-supported, clayey sandy medium to coarse gravel with clast lithologies typically dominated by chalk and flint but with some ironstone and oolitic limestone. It exists as a blanket deposit on the eastern edge or higher ground of the Vale of York and lies beneath the Breighton Sand Formation (containing the Bielby Sand Member). Although the BGS include the Pocklington Gravel Formation in their North Pennine Glacigenic Subgroup, this appears inappropriate as it contains no definitive glacigenic material. The sedimentology, stratigraphy and chronology of the Pocklington Gravel Formation at North Cave indicate that it instead probably records fluvioperiglacial fan sedimentation.

Subaerial sedimentation on alluvial fans in a periglacial climate is an interpretation favoured for several sites around the major scarp slopes and mouths of dry valleys of the chalk in Britain, where gelifluction, debris flow, slopewash, fluvial and aeolian processes combined to aggrade significant thicknesses of stratified sands and gravels (e.g. Jukes-Brown, 1887; Straw, 1963, 2015; Alabaster and Straw, 1976; Bateman *et al.*, 2000; Evans *et al.*, 2017), which were subject to ice wedge development and cryoturbation. The deposits in such settings are often classified as fluvioperiglacial, because they are derived from gelifluncted and slopewash materials reworked during nival floods (Tomlinson, 1940; Rowlands and Shotton, 1971; Williams, 1971; McCann *et al.*, 1972; Woo, 1983, 1986, 1990; West and Williams, 2012; West, 2015). Probably the largest of such fluvioperiglacial fans in Britain was aggraded from the base of the western Pennine slopes during the early to mid-Devensian to produce the Chelford Sands in east Cheshire. This deposit records a broad, very shallow fan complex that was dominated by braided streams with a substantial aeolian input of sand (Worsley, 1970, 1985, 2015). The nature of the Pocklington Gravel Formation at North Cave indicates that a fluvioperiglacial fan prograded from the steeply incised valleys of the Wolds scarp slope during MIS 3, towards the end of the period of aggradation of the Chelford Sands, and hence significant nival melt and run-off was operating in the area at that time. Its relatively coarse nature is no doubt dictated by the short travel distances from the scarp slope valleys to the depocentre around North Cave. The grading of the fan toe to altitudes below 0 m OD also indicates that sea level was lower than present and that no Lake Humber existed.

The MIS 3 fluvioperiglacial phase of fan sedimentation appears to be well recorded not just around the glacial Lake Humber basin but also around the margins of glacial Lake Fenland. This is best illustrated by the Tattershall gravels in Lincolnshire, which form a shallow gradient fan that emerges

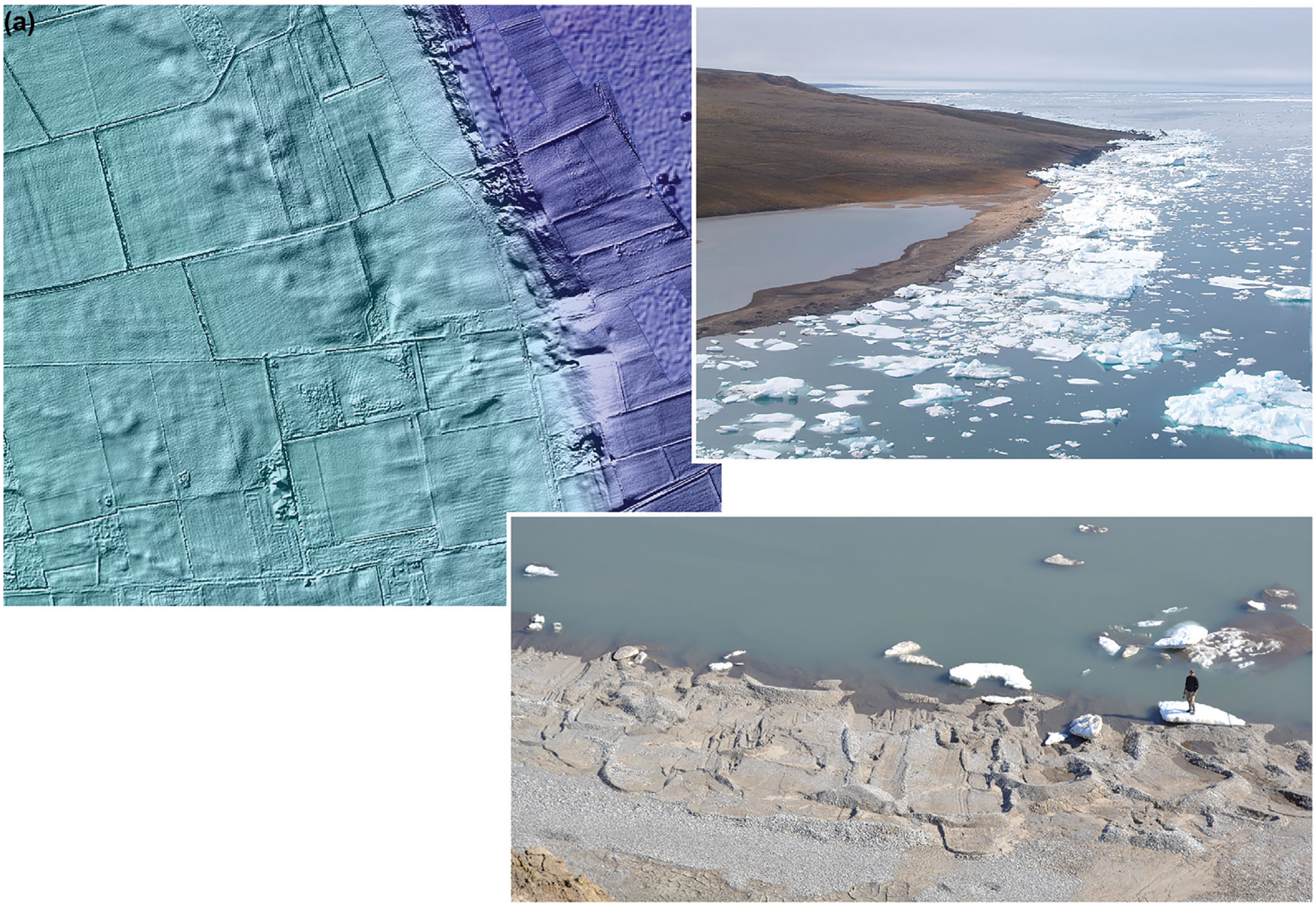

Figure 11. Landforms on the southern Vale of York/Humber lowlands and probable modern analogues: (a) LiDAR image showing overprinted hummocky and arcuate ridges at the Wolds scarp footslope and examples of the most likely modern analogues of floating ice push ridges on the coast of Banks Island, Arctic Canada; (b) LiDAR image showing, at the top, discontinuous sinuous ridges connecting with oval to circular rimmed depressions and, at the base, dual ridged polygonal forms. Examples of modern analogues from recently drained, aggrading permafrost terrains in Arctic Canada are depicted at right, with the upper images showing ice wedge and pingo complexes from Banks Island, and the lower images showing ice wedge landforms from northern Ellesmere Island.

from the lower Bain valley at around 15 m OD and spreads out over the northern lowlands of The Wash. They contain ice wedge pseudomorphs as well as organic remains indicative of short phases of relative warmth and date from $36\,167 \pm 377$ to $>46\,557 \pm 888$ cal BP (Straw, 1966, 1979; Girling, 1974). Morphostratigraphic relationships with the deltaic Kirkby Moor Sands, which lie at altitudes up to 30 m OD above the Bain Valley, indicate that the Tattershall gravels post-date them and hence the 30-m level of Lake Fenland (and Lake Humber due to its connection through the Lincoln Gap) dates to early MIS 3 or MIS 4 (Straw, 1979). Other drainage basins feeding into the Fen basin have also delivered fluvioperiglacial fan gravels to the lowlands surrounding The Wash, probably during MIS 3, and include the Welland, Nene, Ouse, Cam, Wissey and Nar valleys (Lambert *et al.*, 1963; Coope, 1968; Bell, 1970; Sparks and West, 1970; West *et al.*, 1974; Straw, 1979). Like North Cave, these fans appear to have graded to very low elevations, in places to below present sea level. This is compatible with probable low sea level stands of up to −10 m OD minimum during MIS 4–3 (Thom, 1973) and possibly as low as −50 to −80 m based upon global sea level curves. Fan aggradation to such a low sea level stand in the region at that time precludes glacial lake development.

Very little evidence of pre-MIS 3 events is available from North Cave and indeed the wider study area. Fairburn and Bateman (2016) regard the North Cave deposits as part of their Younger Alluvial Fans and report an age of 202.7 ± 11.7 ka (Shfd11115) for a terrace cut into the higher elevation Older Alluvial Fans at 33 m OD. This indicates that the Older Alluvial Fans immediately post-date MIS 7 and pre-date the 33-m terrace (lake shoreline). The sedimentology, stratigraphy and chronology presented here strongly suggests that the younger generation of fans identified by Fairburn and Bateman (2016) aggraded in MIS 3 instead. Indeed, the occurrence of the Bielby Sand Member overlying the Pocklington Gravel Formation and extending up to 20 m OD probably documents littoral sedimentation after fan accumulation and hence glacial lake shoreline production after MIS 3 fluvioperiglacial conditions. A Devensian age and lacustrine origin for the Bielby Sand Member is inherent in its former classification as 'sand of the 25-Foot Drifts' (Edwards, 1936) and its distribution along the eastern side of the Vale of York from the Escrick Moraine in the north to the Humber in the south. Its characteristics are also consistent with a lacustrine origin, such as its lithology of clayey to silty sand with local fine-grained gravels. The BGS also describe the Bielby Sand Member as forming levee-like features, which are clearly shown on the LiDAR imagery in Fig. 11. These <1-m-high, arcuate to sinuous ridges are orientated sub-parallel to contours, giving the impression that they could represent former beach ridges, potentially constructed by lake ice pushing (e.g. Jarvis, 1928; Nichols, 1953; Ward, 1959; Bryan and Marcus, 1972; Davis, 1973; Dionne, 1979); alternatively some ridges could be arcuate dunes developed in the Bielby Sand Member and younger deposits. Nevertheless a range of

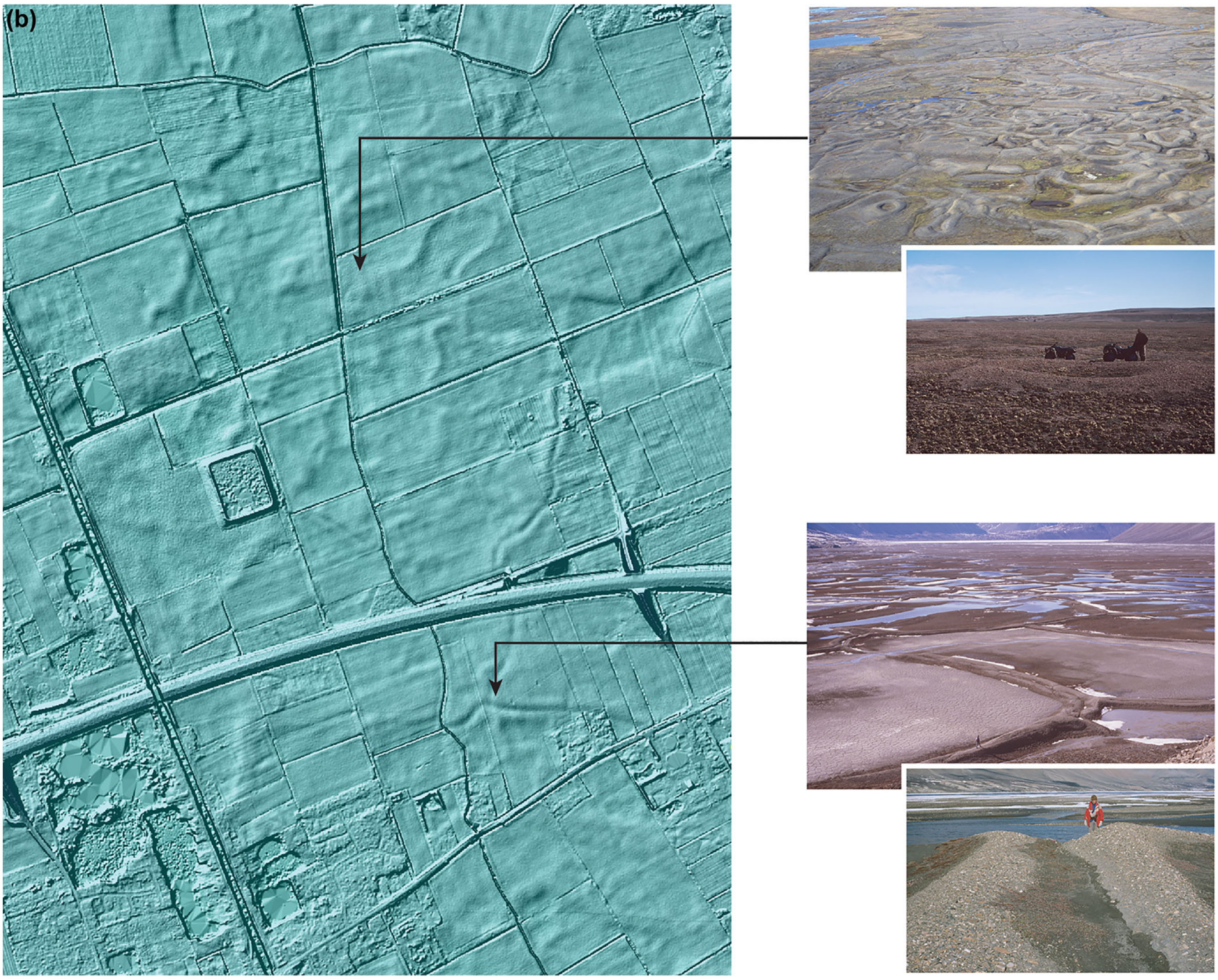

Figure 11. Continued.

features occur in the area in addition to the potential ice push beach ridges, which indicate periglacial and permafrost processes. These include dual ridged polygonal forms, resembling ice wedge landforms, and discontinuous sinuous ridges connecting with oval to circular rimmed depressions, characteristic of combined ice wedge and pingo development in recently drained, aggrading permafrost terrains (Fig. 11b; *cf.* French and Dutkiewicz, 1976; Pissart and French, 1976; Mackay, 1986, 1998, 2000).

Other than the Bielby Sand Member, it is remarkable that no substantial lake sediment is apparent in the North Cave area, especially considering that lakes are purported to have existed over the Vale of York–Humber Estuary during MIS 4 (Straw, 1979; Murton and Murton, 2012) and potentially up to 40 m OD during MIS 2 (Fairburn and Bateman, 2016). Unequivocal evidence of lake waters up to 8 m OD is available in the glacilacustrine deposits of the Hemingbrough Formation (Thomas, 1999; Ford *et al.*, 2008), in addition to, potentially, the Bielby Sand Member. Lake levels up to 30 m have been convincingly dated to MIS 3–4 by Straw (1979) at Tattershall for Lake Fenland, but also to MIS 2 (26.1–22.7 ka) by Gaunt (1974) and Bateman *et al.* (2000) for Lake Humber. Given the fragmentary evidence for the high-level phases of Lakes Humber/Fenland, it is conceivable that Straw's (1979) notion of very ephemeral high lake level stands is applicable and that multiple phases of occupation are possible; for example, deeper lakes may have been difficult for the North Sea Lobe ice to have maintained and hence short-lived high lake phases may have been terminated by catastrophic drainage in response to ice margin floatation. Sedimentary evidence for such substantial changes in water depth, particularly at the end of MIS 3, is not apparent in the Pocklington Gravel Formation, with the exception of the sections reported by Melmore (1934, 1935) at Holme-upon-Spalding, where large-scale clinoforms resemble delta foresets developed in the upper part of the sand and gravel sequence and graded to a water depth of around 15 m OD.

Conclusions

The stratigraphic sequence exposed at North Cave records the deposition of a fluvioperiglacial fan dating to MIS 3 (OSL date range 41.8–38.6 ka and radiocarbon date range 41.6–49.0 ka BP). The deposits are allocated to the Pocklington Gravel Formation and form part of Fairburn and Bateman's (2016) Younger Alluvial Fan assemblage. The increasingly high-energy sedimentation represented by the deposits was interrupted by the development of three phases of ice wedge pseudomorphs and composite wedge pseudomorphs, which record the presence of permafrost and ground ice but also fan abandonment and hence periods of reduced nival runoff. Additionally, the involution structures in the uppermost sediments dating to 11.1 ka (Younger Dryas) record intense cryoturbation at that time, with the occurrence of rare large boulders and fine-grained sorted circles being representative of periglacially disturbed Lake Humber littoral deposits containing anchor ice- derived boulders.

The style and age of fluvioperiglacial fan deposition at North Cave is entirely compatible with several mid-Devensian sites around Britain, indicative of significant nival melt and run-off from steeply incised valleys in permafrozen cuesta landscapes. This phase of fluvioperiglacial fan aggradation to near or below 0 m OD is recorded around the glacial Lake Humber and Lake Fenland basins and indicates that sea level was lower than present and that no glacial lakes existed at that time. Thus, while unequivocal evidence for the lower Lake Humber phases exists with the Hemingbrough Formation and the Bielby Sand Member, no evidence for an MIS 4/3 age glacial Lake Humber has been found. If Straw's proposal for a pre-MIS 2 glaciation is correct, this lack of associated lake evidence may reflect that the high lake Humber/Fenland lakes were ephemeral, being controlled by catastrophic drainage in response to ice margin floatation in the Humber and Wash Estuaries. It also may reflect the lack of ages from basal lacustrine sediments and the erosion of shoreline evidence by the intense periglacial activity apparent in the North Cave stratigraphy. Alternatively, it may indicate that the NSL did not extend down the present-day coastal regions of the North Sea during MIS 4/3 and hence could not have blocked the Humber Gap and Wash area, a scenario consistent with new evidence (Roberts *et al.*, 2018) suggesting that the Devensian Stage NSL did not advance over Dogger until the start of MIS 2.

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Abbreviations. BGS, British Geological Survey; BIIS, British and Irish Ice Sheet; ICP-MS, inductively coupled plasma mass spectroscopy; IR, infrared; LF, lithofacies; MIS, Marine Isotope Stage; NSL, North Sea Lobe; OD, Ordnance Datum; OSL, optically stimulated luminescence.

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