JOURNAL OF QUATERNARY SCIENCE (2016) **31**(3) 265–280 ISSN 0267-8179. DOI: 10.1002/jqs.2864

Morphological and sedimentary responses to ice mass interaction during the last deglaciation

RICHARD C. CHIVERRELL,* MATTHEW J. BURKE and GEOFFREY S.P. THOMAS
Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Roxby Building, Liverpool L69 7ZT, UK

Received 16 February 2015; Revised 31 March 2016; Accepted 11 April 2016

ABSTRACT: During decline of the last British–Irish Ice Sheet (BIIS) down-wasting of ice meant that local sources played a larger role in regulating ice flow dynamics and driving the sediment and landform record. At the Last Glacial Maximum, glaciers in north-western England interacted with an Irish Sea Ice Stream (ISIS) occupying the eastern Irish Sea basin (ISB) and advanced as a unified ice-mass. During a retreat constrained to 21–17.3 ka, the sediment landform assemblages lain down reflect the progressive unzipping of the ice masses, oscillations of the ice margin during retreat, and then rapid wastage and disintegration. Evacuation of ice from the Ribble valley and Lancashire occurred first while the ISIS occupied the ISB to the west, creating ice-dammed lakes. Deglaciation, complete after 18.6–17.3 ka, was rapid (50–25 m a^{-1}), but slower than rates identified for the western ISIS (550–100 m a^{-1}). The slower pace is interpreted as reflecting the lack of a calving margin and the decline of a terrestrial, grounded glacier. Ice marginal oscillations during retreat were probably forced by ice-sheet dynamics rather than climatic variation. These data demonstrate that large grounded glaciers can display complex uncoupling and realignment during deglaciation, with asynchronous behaviour between adjacent ice lobes generating complex landform records. Copyright © 2016 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons Ltd

KEYWORDS: British Irish Ice Sheet; deglaciation; geomorphology; Last Glacial Maximum (LGM); sedimentology.

Introduction

Given current concerns over accelerated retreat of large ice sheets (Rignot *et al.*, 2014; Thomas *et al.*, 2011), there is a need for well-constrained data on the retreat of former ice masses. It is difficult to directly observe these processes at contemporary ice masses, and so it is only through investigation of former ice sheets that the pattern and conditioning of ice marginal retreat over the timescales (1000s years) of large-scale deglaciation emerges. Over the last two decades the geomorphology and stratigraphy documenting the retreat of major ice streams draining the British–Irish Ice Sheet (BIIS) from its Last Glacial Maximum (LGM) limit has received considerable attention (reviewed in Chiverrell and Thomas, 2010; Clark *et al.*, 2012), and has included investigations around the former ice sheet (e.g. Knight and McCabe, 1997; Scourse and Furze, 2001; Knight, 2004; Jansson and Glasser, 2005; McCabe *et al.*, 2005; Carr *et al.*, 2006; Ó Cofaigh and Evans, 2007; Bradwell *et al.*, 2008; Golledge *et al.*, 2008; Dunlop *et al.*, 2010; Carr and Hiemstra, 2013; Everest *et al.*, 2013). In the Irish Sea sector research has addressed the morphology, stratigraphy and sedimentology of several major moraine systems showing complex ice-marginal oscillations during retreat around the Irish Sea Basin (ISB) (e.g. Huddart, 1971, 1991, 1994; McCabe *et al.*, 1984, 1987; Thomas, 1984b, 1989; Eyles and McCabe, 1989; Merritt and Auton, 2000; Evans and Ó Cofaigh, 2003; Thomas *et al.*, 2004; McCabe and Dunlop, 2006; Thomas and Chiverrell, 2007; Parkes *et al.*, 2009; Livingstone *et al.*, 2010a,b). This paper presents the glacial geomorphology and stratigraphy of lowland Lancashire, which was occupied by ice from three main source areas, the Lake District, the Ribble Valley Glacier and the larger east limb of the ISIS. Our aims are (i) to present the glacial geomorphology of lowland Lancashire; (ii) to identify a set of sediment–landform assemblages that define the primary glacial depositional environments; (iii) to interpret the depositional environments from the sedimentology of available major exposure; (iv) to define the stratigraphical succession through the construction of a series of lithological cross-sections derived from borehole data; (v) to evaluate the impacts of regional ice mass reorganization during deglaciation in producing the sediment and landform record; and (vi) to model the published geochronological data for regional deglaciation.

Methods

Geomorphology

The geomorphological mapping of the 4300-km^2 region was undertaken using the NEXTMAP Great Britain and British Geological Survey digital data on bedrock at the surface. Mapping comprised a two-stage process: (i) identifying the breaks in slope together with symbols for primary, non-genetic landform geometries such as flats, ridges, mounds and basins; and (ii) interpretation using sediment landform associations to produce a layered geomorphological ARCGIS geodatabase (Supporting Information 1). Ground-truth of the mapping was carried out in selected areas by conventional field investigation. Interpretation of the geomorphology follows conventional typologies for glacial landforms (e.g. Evans, 2003), and was underpinned by both the morphology and associated sediments.

Lithostratigraphy

The Quaternary stratigraphy in Lancashire is underlain by Permo-Triassic sandstones and mudstones in the west and by Carboniferous sandstones and shales in the east (Earp *et al.*, 1961; Aitkenhead *et al.*, 1992). Exposure of solid rock is limited, but is more frequent to the east against the central upland spine of England (Longworth, 1985). Exposures of the glacial stratigraphy are limited to sand and gravel operations at Lydiate Lane, Hurst Green and Bradley's Quarries (Fig. 1). Exposures were logged using field sketches, vertical lithofacies logs and photo-montages following standard procedures (e.g. Thomas *et al.*, 2004). Characteristics recorded include textural classification, sorting and grain size, palaeocurrent or

---

*Correspondence: R. C. Chiverrell, as above.
E-mail: rchiv@liv.ac.uk

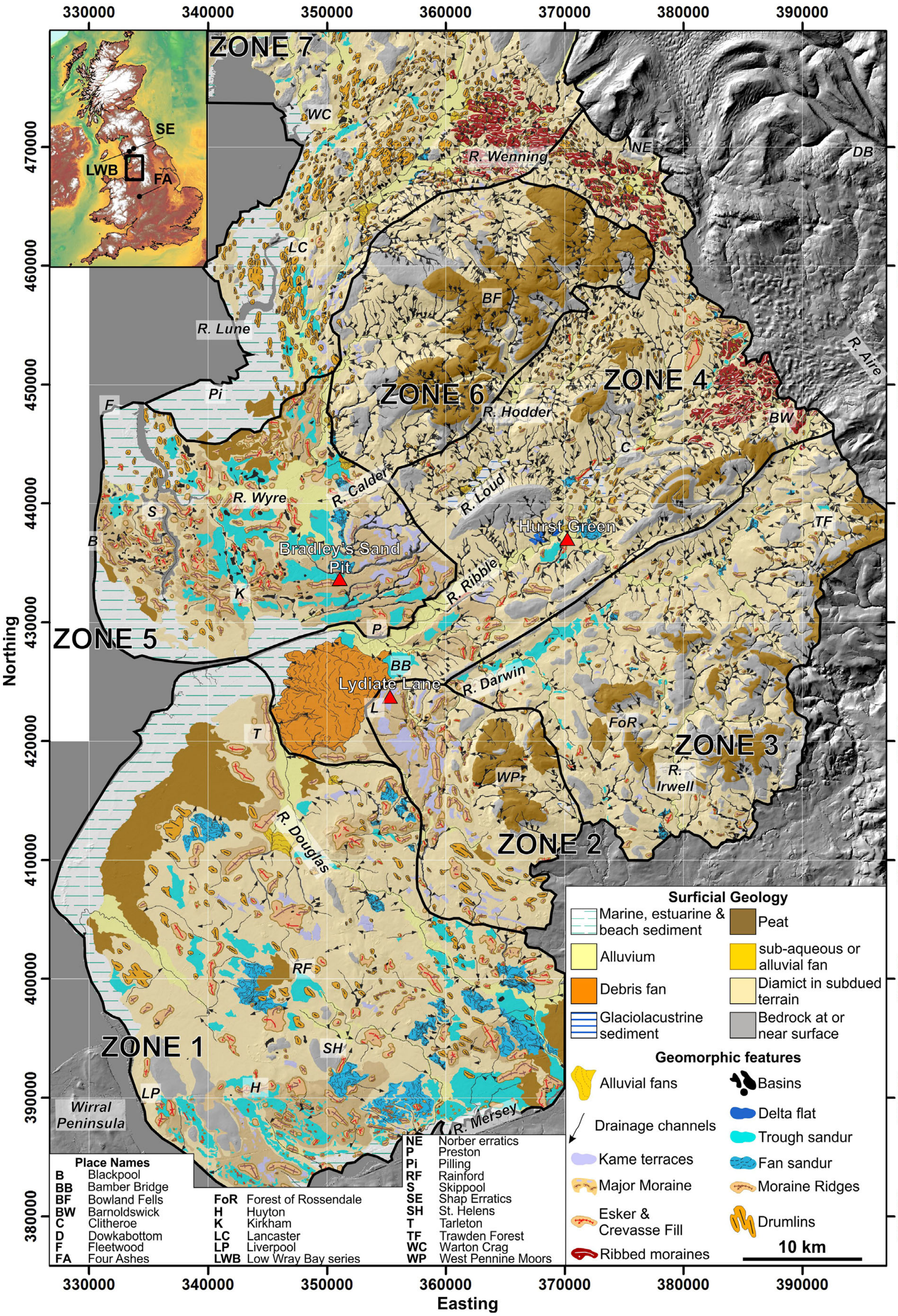

Figure 1. Geomorphic map of Lancashire overlain on a hillshaded elevation model. The map extent is shown by the black box within the inset map (top left). The mapped area has been divided into seven zones that are demarcated by the labelled black polygons. See text for full description. Expanded large-scale version is available as Fig. S1. Locations providing geochronological information are identified on the main panel and inset: SE, Shap erratics; LWB, Low Wray Bay; FA, Four Ashes; D, Dowkabottom; NE, Norber erratics; WC, Warton Crag.

till fabric indicators, sedimentary structures, nature of contacts and the lithofacies.

Boreholes from over 6300 locations were assessed from the British Geological Survey archives, reducing to 1400 sites by excluding the confidential, shallow (<3 m) or uncertain location boreholes. Lithologies were classified from the log descriptions into gravel, sand and gravel, sand, silt/clay, laminated silt/clay and diamicton and used to construct stratigraphical cross-sections. Ground elevations of the sections were interrogated from the NEXTMAP digital elevation model and cross-checked against the borehole log records. Interpretation of the stratigraphical sections is constrained by the limited descriptive information available, especially in older records; imprecision in the definition of clay/silt grain sizes; and the destruction of sedimentary bedforms by percussion drilling. Uncertainties in the interpretation of cross-sections arise from vertical and lateral variability in glacigenic sequences over short distances, limited lithological markers for correlation between boreholes and uncertain origin (e.g. tectonic or cut and fill) for breaks in log profiles. However, combining the regional geomorphology with the borehole stratigraphy gives us confidence in these interpretations.

Bayesian modelling of geochronological data

Following the approaches detailed in Chiverrell *et al.* (2013) all previously published geochronological data constraining the glacial stratigraphy and geomorphology in lowland Lancashire (Morgan, 1973; Telfer *et al.*, 2009; Vincent *et al.*, 2010; Wilson *et al.*, 2013) have been compiled as a hypothetical 'relative-order' model of the expected younging order of events. Geochronological data obtained by ^{14}C, optically stimulated luminescence (OSL) and terrestrial cosmogenic nuclide (TCN) dating approaches have been arranged into a pseudo-stratigraphical order reasoned solely from landform–sediment relationships independent of the geochronological measurements. This 'prior model', using the Bayesian terminology, consists of the events or ice-marginal positions arranged in the order of ice-marginal retreat reasoned from the geomorphology and stratigraphy. Bayesian modelling was implemented using a simple Sequence model in Oxcal (Ramsey, 2009; c14.arch.ox.ac.uk), which merely requires the dated events to be in an order. The model then uses a Markov chain Monte Carlo (MCMC) sampling to build up a distribution of possible solutions that fit the proposed ordering and the available ages in a sequence. To do this the model generates a probability for each sample called a *posterior* density estimate, which is essentially a product of both the *prior* model and likelihood probabilities. Ultimately, the Bayesian modelling approach produces *posterior* density estimates or age ranges, italicized in the text to differentiate them from the prior dating information estimates.

Geomorphology, sedimentology and geochronology

A map of the geomorphological record is presented in Fig. 1 (with greater detail in supplementary Fig. S1). The mapped area has been divided into seven broad zones to facilitate description and interpretation of the landform pattern. Ice flow patterns have been interpreted from the drumlinized and ribbed terrain and comprise 13 flow-sets (Fig. 2a) (Mitchell and Hughes, 2012b). In general, the flow-set orientations identified from the detailed mapping in this paper (Fig. 2a) are similar to those documented by Hughes *et al.* (2014), although here the interpreted sequencing of events differs. Together these flow-sets can be divided into three broad flow phases based on crest-line orientation and elongation ratio (Fig. 2a). Ice-marginal limits have been interpreted from moraine ridges, the ice contact slopes of kame terraces and perpendicular orientations to drumlin crests and eskers (Fig. 2b). These ice limits were subdivided based on interpretations of ice source areas: the Irish Sea (IS), south-eastern Lake District (LD) and Ribble Valley (RV). Figure 2(b) distinguishes between major and minor ice limits draining these ice source areas based on interpretation of ridge continuity and geometry, with larger and more continuous ridges interpreted as major ice limits and smaller, less continuous ridges forming minor ice limits.

Geomorphology

Zone 1 comprises broadly flat low-lying terrain that is punctuated by relatively subdued drumlins, which occur throughout the area and form a NW–SE flow-set (Fs 1: Figs 1 and 2a). Regional bedrock highs rising up to 175 m above the surrounding topography are aligned SW–NE and relatively low in altitude, and are dissected by three NW–SE through-valleys probably incised by subglacial meltwaters and later modified by proglacial outwash. Low-amplitude moraine ridges occur throughout the zone, but form two major moraines. The largest (IS1: Fig. 2b) extends east–west, includes kame terraces and small eskers or crevasse fill ridges, and the multiple ridge crests record ice retreat northwards. Further north, the Tarleton moraine complex (IS2: Fig 2b) forms a large set of arcuate ridges aligned north–south then curving NE–SW towards the coast. Sets of trough and fan sandur are most common within and down glacier of these major moraines (Fig. 1). Zone 2 describes an undulating bench of moraines and kames that formed between the retreating ice margins (LD1 and LD2) and the West Pennine Moors (Fig. 1). The adjacent upland West Pennine Moors (Zone 3) have been dissected by deeply incised and misfit channels. These channels are aligned NW–SE, form part of a larger network of channels, and most likely record meltwater overflows from glacial lakes dammed in the lower Ribble Valley (Earp *et al.*, 1961; Aitkenhead *et al.*, 1992). Zone 3 is dominated by ice-moulded bedrock with occasional drumlins and moraines, with most glacigenic sediment concentrated in the valleys.

The Ribble Valley (Zone 4) dissects central Lancashire and is flanked by a subdued low-amplitude glacial bench (Chiverrell et al., 2009a,b, 2010; Foster *et al.*, 2009), which is marked with sandur, kames and cross-valley orientated moraine ridges. The largest moraines form arcuate sets (RV1 and 2) at the mouth of the Ribble Valley (Fig. 2b). This glacial bench and RV1 terminate at the apex of an extensive (~70-km^2) low-angle spread of glacial diamicton with occasional sand and gravel (Fig. 1). Drumlins in zone 4 (Fig. 1), the Ribble-head drumlin field, form a valley-orientated pattern that bifurcates SW towards the Ribble Valley (Fs 7) and SE towards the Rivers Aire and Wharf (Fs 8: Fig. 2a) (Mitchell, 1991; Mitchell and Hughes, 2012a). In the north of zone 4 there are drumlins and the crests of drumlinized sections of ribbed terrain that suggest ice flow SE up the Wenning Valley around the Bowland Fells (Fs 10: Fig. 2a).

Zone 5 is dominated a swathe of low, sub-parallel ridges that arc west and north-west (LD3: Fig 2b), and comprises the 'Kirkham End Moraine' (Gresswell, 1967). Two major entrenched proglacial channel systems dissect the moraine (Fig. 1). Further north arcuate moraines occur but are more complex with numerous sub-parallel ridges (LD4: Fig 2b),

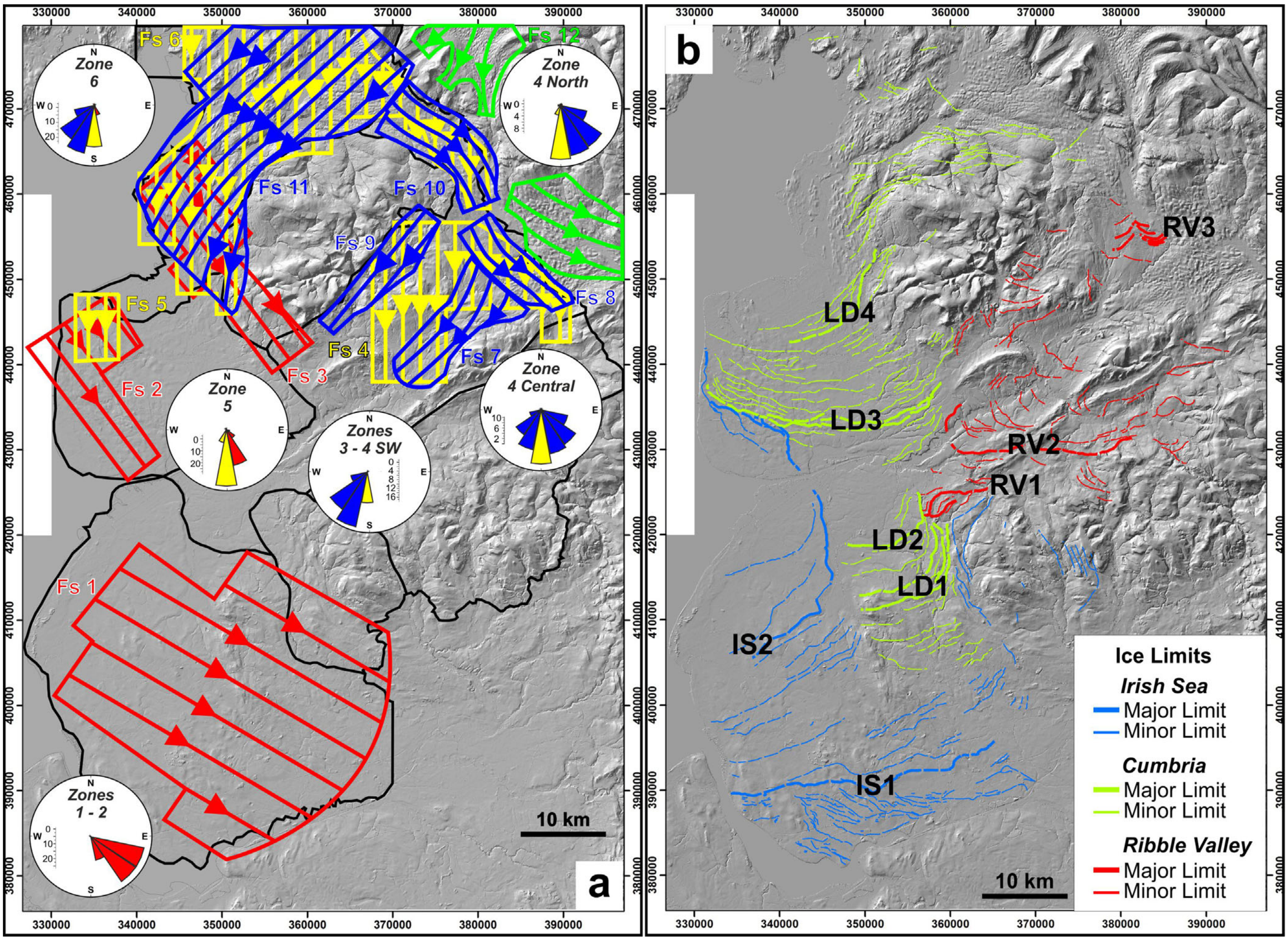

Figure 2. (a) Compilation of ice flow sets derived from glacigenic bedform orientation. Each zone shows a rose diagram of the drumlin crestline orientations (the colours correspond to those used for each flow set). (b) Major (labelled and bold) and minor ice margin positions interpreted from the geomorphic map, and colour coded for the ice sources for each margin [Irish Sea (IS1–2), Lake District (LD1–4), Ribble Valley (RV1–3)].

intervening troughs, sandur, and enclosed and water-filled basins (kettle holes) that are increasingly buried by extensive Holocene deposits. In the east a NW–SE orientated glacigenic bench (30–90 m OD) formed between the ice margin and the Bowland Fells. The Bowland Fells (Zone 6) comprise ice-scoured bedrock lacking *in situ* glacigenic sediment, but occasional high-altitude drumlinoid forms show a north–south ice flow direction (Figs 1 and 2a). Up ice from marginal limit LD4 (Fig. 2b), Zone 7 extends furthest north and is dominated by subglacial landforms with numerous drumlins and widespread ribbed moraine. In the east, ribbed terrain shows west–east crest-line orientations, whereas the Lancaster–Kendall lowlands to the west are dominated by an extensive swarm of drumlins with cross-cutting flow directions (Figs 1 and 2a).

Subglacial bedforms and ice flow

Ice flow in the region is divided in two three phases; flow phase 1 is composed of flow-sets 1–3 (Fs 1–3) that extend (probably from offshore) into the south of the region (Fs 1), north of the Ribble (Fs 2) and south across the Bowland Fells (Fs 3) where they are most common (Fig. 2a). Flow-sets 1–3 comprise drumlins with a NW–SE trend and they display mean elongation ratios of 2: 1 (can range from 8: 5 to 5: 1) (Fig. 1). Flow phase 1 is interpreted as reflecting IS ice advancing onshore and onwards to maximum limits in the English Midlands (Chiverrell and Thomas, 2010). Flow phase 2 is associated with more restricted ice extent and recorded by Fs 4–6 (Fig. 2a). This phase is composed of drumlins with north–south crest-line orientations and a mean elongation ratio of 3: 1 (range from 11: 5 to 9: 3). In the north Fs 5 and 6 overprint Fs 2 and Fs 3 (flow phase 1), with drumlin orientations reflecting ice flow from the eastern Lake District. High-altitude drumlins on the Bowland Fells and similarly elongated and north–south orientated drumlins in the upper Ribble catchment (Fs 4) suggest flow phase 2 included ice extending southward at high elevations. Where the flow-sets cross-cut each other, flow phase 2 appears to post-date flow phase 1.

Associated with more reduced ice extent, there is a third flow phase comprising Fs 7–13 (Fig. 2a) and this includes the Ribble-head drumlin field (Mitchell, 1991; Mitchell and Hughes, 2012a). These flow-sets are associated with ice flows that are more valley-confined and thus suggest greater influence of bedrock topography than during previous flow phases. This bedrock constraint is reflected in the more local alignment of drumlins, although elongation ratios are typically 5: 2 in all flow-sets (ranging from 8: 5 –23: 5). The Lancaster–Kendall drumlin field (Fs 11) has a NE–SW orientation, cross-cutting Fs 3 and Fs 6 (flow phases 1 and 2, respectively), reflecting that during retreat stages ice sourced in the eastern Lake District flowed out into Morecambe Bay. In the upland valleys, drumlin orientations suggest valley-parallel ice flow up the Wenning valley (Fs 10). Ice generated in the Pennine Ice Field (Mitchell, 1991) extends south before splaying south-west into the Hodder (Fs 9) and Ribble (Fs7) valleys, and south (Fs 8) to south-east (Fs13: Mitchell and Hughes, 2012) towards the eastward-draining valleys of the Pennines. This variation in drumlin orientation is mirrored by ice-flow indications in the ribbed terrain that display crest-lines perpendicular to the overprinting drumlins, lending further support to the splitting of ice-flow around higher elevation terrain. This topographically confined flow appears to have been sourced from the Lake District and North Yorkshire (Fs 12) and given superimposition on earlier, cross-cutting flow-sets, this is interpreted as the final ice-flow phase recorded by the bedform record.

We interpret the sequencing of flow-sets (Fig. 2b) to reflect changes in ice source with thinning and back-wasting of the ice sheet. Initially an IS component dominated, probably during the ice advance to maximum limits, but as the IS ice masses declined regional ice-flows switched to Lake District sources and were no longer confined by IS ice. Ice flow directions became more confined by topography with further back-wasting and thinning of the ice masses. In general none of the drumlins displays elongation ratios sufficiently attenuated to be diagnostic of ice streaming (Stokes and Clark, 1999) in lowland Lancashire. However, other diagnostic criteria are met, principally ice mass dimensions (width >30 km, maximum length >200 km) and convergent flow patterns draining the eastern Lake District and ISB (Stokes and Clark, 2001). It seems that while the ice masses here were unlikely to be streaming at the time of bedform generation, they may have fed a larger ice mass that may have been streaming down-glacier.

Ice marginal limits and retreat

At a broad scale the identified limits (Fig. 2b) are similar to those described by Clark *et al.* (2012), but contain greater detail and the moraines clearly document the unzipping of different ice-sources. In the south, these moraines are spaced ~1–4 km (Zone 1: Figs 1 and 2b) apart and probably record minor ice marginal still-stands, followed by a major standstill that formed a belt of moraines and kames (IS1) during a general north-west retreat. Broadly synchronous moraines along the flanks of the West Pennine Moors reflect down-wasting and decoupling of IS ice from the bedrock uplands. This interpretation is consistent with the belt of ice-marginal kames and moraines that dominate zone 2 (Figs 1 and 2b). The second major ice limit (IS2, Fig. 2b) was generated as IS ice retreated north-west, with IS moraines up-glacier of IS2 either more subdued or offshore. The remainder of the region records the northward retreat of LD ice margins and retreat of the RV Glacier. South of the Ribble, moraines are relatively minor and fragmentary, with the exception of a more continuous set of moraines (LD1 and LD2) against the bedrock rise (Figs 1 and 2f). Between LD1 and LD2 moraine spacing reduces to <1 km, suggesting a slowdown in retreat, perhaps associated with unzipping from the bedrock uplands. North of the RV the more substantial moraine complexes (LD3 to LD4) record major ice-margin still-stands or repeated oscillations (ridge spacing of ~0.5–2 km) (Figs 1 and 2b). Connected to the south-east end of the LD3 limit are a set of major moraines with crest-lines orthogonal to the axis of the RV (the Chorley moraine, cf. Price *et al.*, 1963) and record a synchronous still-stand (RV1 to RV2) of the retreating RV Glacier. The extensive fan fronting RV1 points to extensive sedimentation into a lake basin created between a retreating RV Glacier (RV1 and RV2) and the damming IS ice at or around IS2. The accommodation space indicated by creating this ice-dammed lake basin requires retreat of LD ice to LD3, while IS ice remained around IS2 (Fig. 2b). Up ice of LD3/4 and RV2, ice-marginal indicators are less frequent and more subdued, suggesting either rapid retreat of ice margins northward or a reduction in sediment availability (Fig. 2b).

Sedimentology

Exposure of the Quaternary succession in Lancashire is limited to sand and gravel operations that reveal detail on the stratigraphy and sedimentology of the ice-marginal kame belt in Zone 2, the ridges of the Kirkham Moraine (Zone 5) and the glacigenic bench in the Ribble Valley (Zone 4). Elsewhere (zones 1, 5 and 6) stratigraphical information has been derived from boreholes, but data are lacking from upland areas (zones 3 and 7) (Fig. 1).

Manchester embayment (Zone 1)

Extending south-east of zone 1, a borehole series (line 1) has been constructed along a 10-km west–east stretch of the M62 motorway (Fig. 3), and shows a thick sediment sequence that buries a bedrock terrain marked by lows that are part of bedrock-incised valleys that cross the region (Howell, 1973; Johnson, 1985). This series (more than eight) of NW–SE aligned troughs are incised into bedrock, >40 km in length and 2–3 km wide, and they include the Dee and Mersey estuaries (Howell, 1973; Johnson, 1985). The over-deepening has incised up to 30–60 m below sea level in places and they have been described as tunnel valleys (Johnson, 1985). On Fig. 3 these valleys are filled with a basal sandy stony diamicton >5 m in thickness that appears to interdigitate with, and in places is buried by, 7–8-m-thick proglacial outwash sand and gravels, and laminated glacilacustrine silts and clays (Thomas, 1984a; Thomas *et al.*, 2004). Flanking Glaze Brook a further sandy stony diamicton caps the glacial sequence. This sequence represents the deglaciation and pull-back of ice, with glacigenic sediments filling an erosive landscape with a succession of glacial diamicton and proglacial sediments dominated by laminated muds of probable glacilacustrine origin. The lake waters were probably dammed between ice to the north and west by an ice margin that extended to the rising bedrock of the mid-Cheshire sandstone ridge (blocking drainage towards the Mersey and Dee estuaries).

Ice-marginal kame belt (Zone 2)

Exposures in zone two are limited to Lydiate Lane Quarry (NGR SD 556 241) located in gently sloping terrain upslope from the RV1/2 outwash fan (Fig. 1). The quarry is cut into a bench composed of sand and gravel, truncated in the east by an NW–SE aligned and misfit glacial outwash channel. Working faces showed a generalized vertical succession of outwash sands and gravels overlying a basal diamicton (Fig. 4). The sand and gravels reflect their derivation from eroded Permo-Triassic sandstones with a sand matrix bright orange in colour and including numerous erratic clasts from the Lake District (e.g. Shap granite). In character the deposits resemble the distal sandur model of Thomas *et al.* (1985), with two first-order fining-up cycles (Fig. 4). Within the second order, cycles reflect falling flow regime in a distal sandur produced either by aggradation of bar-forms or by channel migration (Miall, 1977; Thomas *et al.*, 1985). In summary, the sequence shows progression from an ice-contact setting to an ice-distal outwash sandur, which

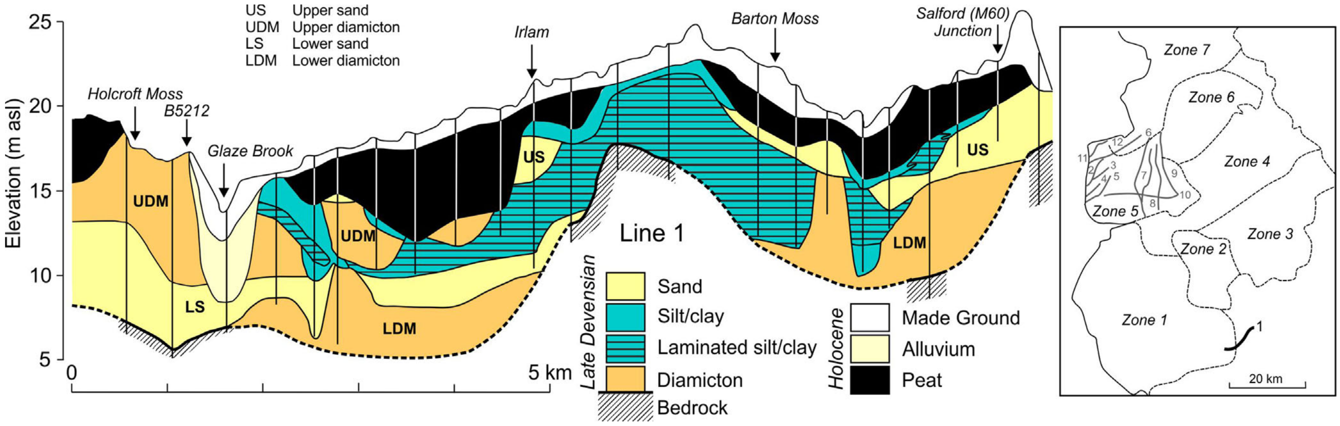

Figure 3. Borehole cross-section (line 1) in south-east zone 1, with the location shown on the inset map.

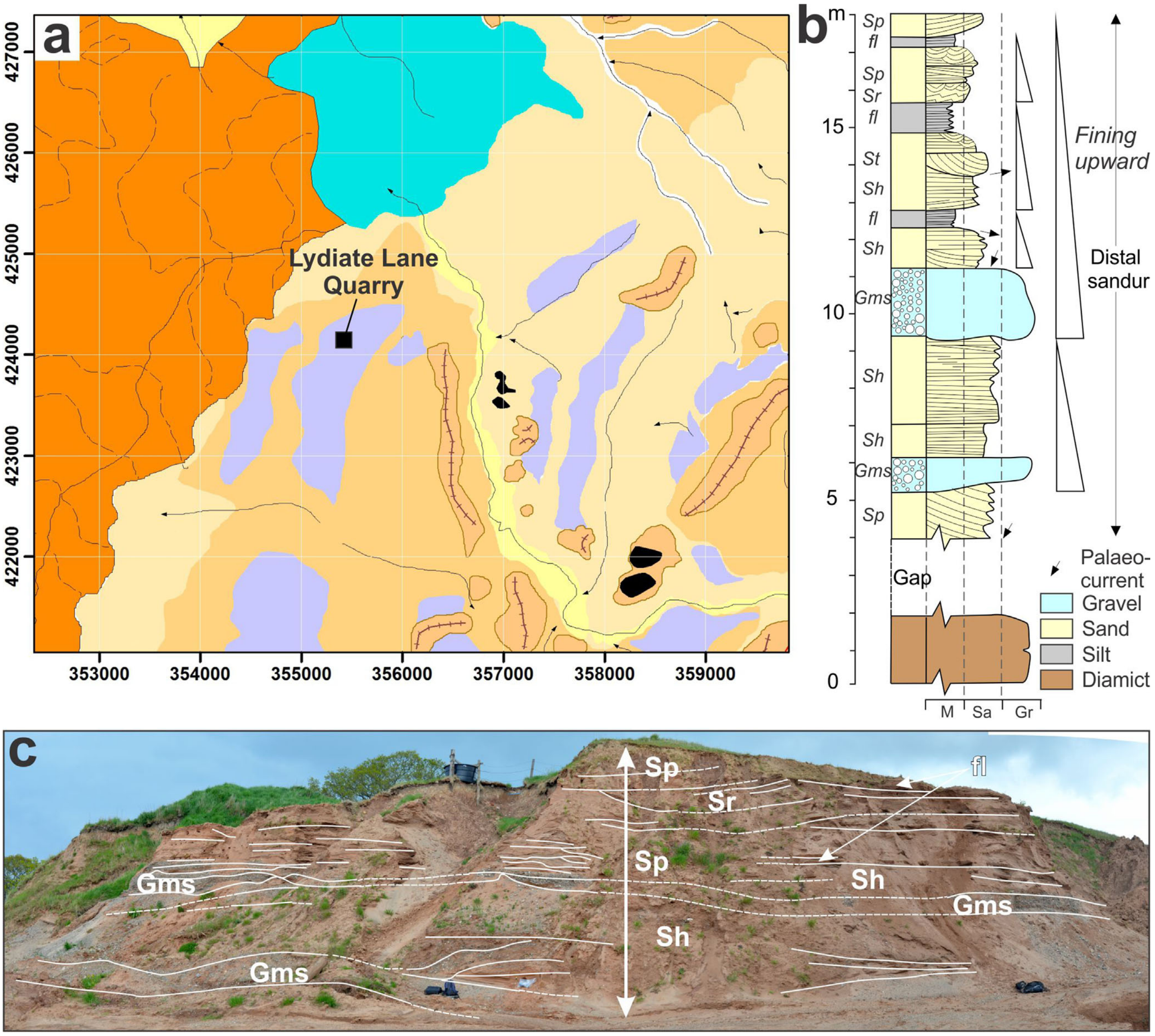

Figure 4. (a) Geomorphic map of the area around Lydiate Lane Quarry (symbols as in Fig. 1). (b) Summary stratigraphy of the sequence at Lydiate Lane Quarry. (c) Photograph of the sequence identifying key lithofacies. The main unit boundaries are shown by the white lines. Log location is indicated by the white arrow.

from the geomorphology was being funnelled along the eastern margin of LD2 limit ice (Figs 1 and 2b).

Lower Ribble Valley (Zone 4)

Exposures in the entrenched part of the lower RV are almost entirely lacking, but limited borehole coverage and records of historical exposures suggest it is underlain by extensive laminated glacilacustrine muds indicative of ice-free conditions and the establishment of ice-dammed lakes (Earp *et al.*, 1961; Aitkenhead *et al.*, 1992; Foster *et al.*, 2009). A former quarry at Hurst Green (NGR SD394 378) 11.5 km inside ice limit RV2 (Figs 1 and 2) revealed a six-phase stratigraphical sequence (Fig. 5) that showed steeply dipping sand and gravel (units 2–4) foresets reflecting an ice-proximal glacilacustrine deltaic environment. These foresets are buried by either massive, gravelly debris flow diamicton containing subrounded clasts (unit 5) or horizontally laminated sandy silty lacustrine bottom-set muds (unit 6) with occasional dropstones (<5 cm) (Fig. 5). These bottom-sets reflect superimposition of a further lake floor sequence not fully visible in the degraded exposures and suggest that water levels were dynamic and highly variable, a characteristic typical of ice-dammed lakes (Thomas, 1984a). The overall sequence is suggestive of an ice-contact delta or subaqueous fan, which is morphologically supported by the flat surface that the quarry is cut into, with a westward water flow from an ice margin located to the east.

Retreat from the Kirkham moraine (zone 5)

Lithostratigraphical sections

Bradley's Quarry (NGR SD 507 339) provides the only significant exposures in the Kirkham Moraine (LD3), and is cut into a flat surface bounded by moraine ridges (limit LD3)

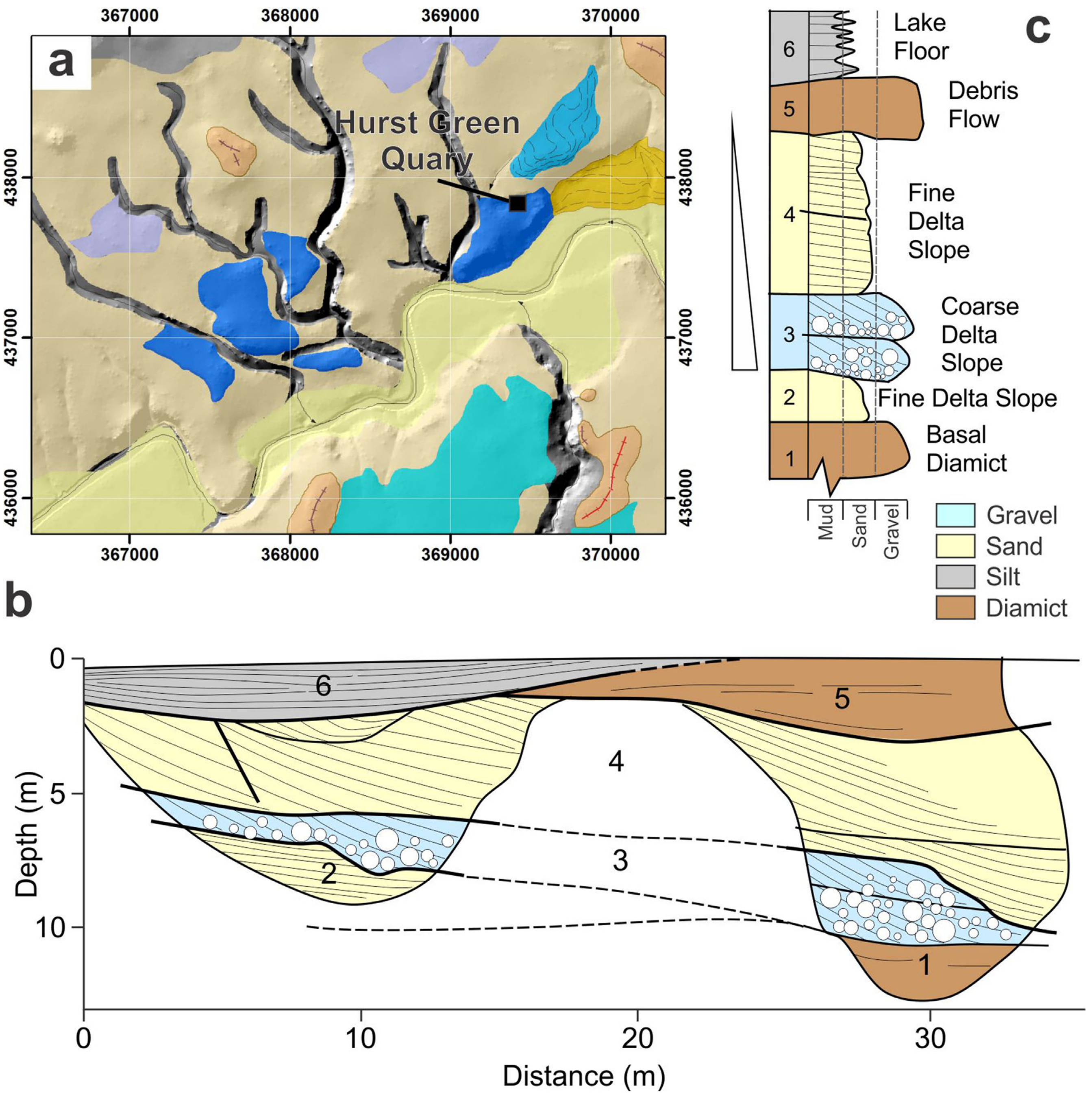

Figure 5. (a) Geomorphic map of the area around Hurst Green Quarry (symbols as in Fig. 1), (b) lateral stratigraphical section and (c) generalized vertical succession of the sediment exposures. Unit numbering corresponds to those used in the log.

(Fig. 1). A composite succession derived from adjacent exposures (Fig. 6B) shows an upward progression through the stratigraphy (Fig. 6C – east), composed of six stacked major sedimentary phases (Fig. 6C). Phases 1 and 2 comprise a fining sequence from parallel and ripple laminated fine sand to parallel laminated silt, probably reflecting an ice-proximal to distal series of turbidites lain down across a lake bed (Thomas, 1984a; Thomas *et al.*, 2004). These are capped by stiff, dark brown laminated muds and massive clays that indicate deposition within standing water from suspension rain-out onto the basin floor. Phase 3 (Fig. 6C) consists of a series of gravels and sands occurring in discrete 0.5–1.5-m-thick, laterally overlapping packages rarely more than 5–10 m in cross-section. The packages (Facies A–D) display no apparent cyclical order and only limited lateral continuity (Fig. 6C, D). *Facies A* is dominant and consists of parallel-laminated and

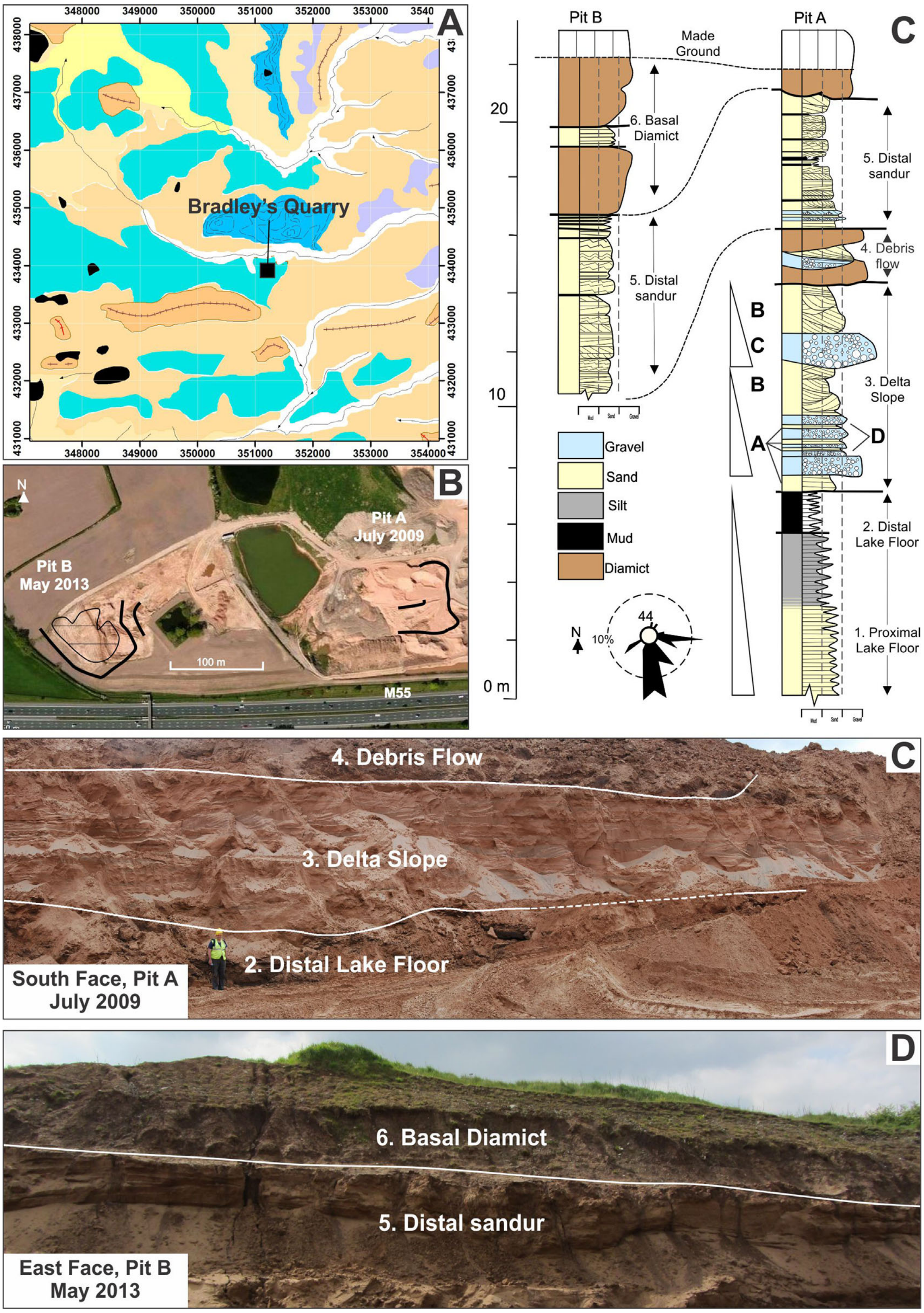

Figure 6. (A) Geomorphic map of the area around Bradley's Quarry (symbols as in Fig. 1), (B) aerial photograph image (Google Earth) of the quarry, overlain by the pits investigated in 2009 and 2013, as well as their main section faces (black lines), and (C) summary stratigraphic logs of the exposed sequences. Annotated photograph of the stratigraphy in (C) Pit A and (D) Pit B. The main unit boundaries are shown by the white lines and unit numbers correspond to those used in the log.

rippled sand in upward-fining sets from granule gravel through coarse, medium to fine sand containing isolated oversize clasts and clast clusters, and was most probably deposited as cyclical delta front turbidite flows (Nemec *et al.*, 1999; Lønne and Nemec, 2004). *Facies B* consists of large cross-cutting dune-sets that comprise planar cross-beds and small trough structures, <1 m in thickness and filled with small-scale (<1–2 cm) graded cycles from coarse to fine sand (Fig. 6C). The dunes, typical of the upper parts of delta foresets, are formed by dune migration down the foreset slope. *Facies C* consists of troughs up to 1 m thick and 12 m wide, either filled with multiple, trough cross-stratified sets of upward-fining cycles from granule gravel to coarse sand, or fine to medium, massive or faintly laminated sand. These channels pass down-current into *Facies B*, perhaps serving to transfer sediment over the delta breakpoint between topset and foreset. In more ice-proximal settings, well-sorted, clast-supported cobble to occasional boulder gravel (*Facies D*) formed sheets <1 m thick that thin rapidly down current and wedge out (Fig. 6C), probably representing avalanching of coarser bedload down the delta slope (Thomas, 1984a; Nemec *et al.*, 1999; Lønne and Nemec, 2004; Thomas and Chiverrell, 2006).

Phase 4 (Fig. 6C) comprises a down-flow thickening wedge of stony diamicton, lying disconformably on delta slope sands and gravels (Phase 3). The diamicton was poorly exposed, but given it is partially stratified and includes thin, discontinuous sheets of interstratified sand and gravel, it is probably either a flow-till or debris flow deposit (Lønne and Nemec, 2004). Phase 5 is represented by sands and gravels that generally fine-upwards (Fig. 6C), but differ in character to those of Phase 3 as they display stacked and repeating fining-up cycles. These cycles vary in order from (i) planar cross-bedded sets of graded small pebble to granule gravel, passing into planar cross-bedded coarse to medium sands, parallel-laminated medium and fine sands and rippled sands, to (ii) truncated cycles of parallel-laminated sands, giving way to Type A and B ripples and then thin sheets of massive, laminated and draped muds. These end-member lithofacies cycles reflect either the falling flow of floods or lateral bar form migration within an ice-marginal sandur (Thomas *et al.*, 1985). Disconformably capping the entire sequence, Phase 6 (Fig. 6C) comprises predominantly massive diamicton, but containing thin beds <0.7 m thick, or lenses of stratified sand and gravel. The boundary is marked by small-scale bed disruption in the underlying sands and by diamicton-filled channel incision at the base. The diamicton is probably a flow-till composed of supraglacial debris from an adjacent glacier margin, or a subglacial till emplaced during minor re-advance (Thomas and Chiverrell, 2006).

In summary, the sections show that the moraine was initially composed of glacilacustrine deposits that show decreasing proximity to the ice margin. This sequence gives way to progradation of a delta front with interbedded debris flow diamicton (Nemec *et al.*, 1999; Lønne and Nemec, 2004), before ultimate deposition of distal outwash sandur (Thomas *et al.*, 1985; Sambrook Smith *et al.*, 2005, 2006). However, the capping subglacial diamictons and ridge-form dominated geomorphology indicate that readvance or minor ice-marginal oscillations have ridden over what is predominantly a glacilacustrine and glacifluvial succession.

Borehole sections

Lithostratigraphical cross-sections (lines 2–10) have been interpreted from borehole records crossing the Kirkham moraine (LD3) and more subdued moraines further north (LD4) (Fig. 7). Lines 2–5 are aligned west–east (lines 2–5) crossing the curved axis of the moraine (LD3) in the coastal zone (Fig. 7), and further east lines 6–9 cross major ice limits LD3 and LD4 in a south–north direction (Fig. 7). Line 10 follows the axis of the LD3 moraine west–east giving information on the lateral variability in the stratigraphy (Fig. 7).

Lines 2–5 traverse ice limits IS2 and LD3, which form a likely suture that developed between IS and LD ice as they unzipped during deglaciation (Figs 2b and 7). In the north (Line 2) there is a complex stratigraphy between IS2 and LD3 with laminated silt–clay lake muds interbedded with diamicton and outwash sands (Fig. 7). As ice retreated from LD3, a <15-m-thick sandur sequence developed. Line 3 ends east of the suture zone and records a complex of moraines that comprise the LD3 limit and are composed of laminated lake muds interbedded with diamicton (Fig. 7). The succession of moraine ridges and the stacking of glacilacustrine and probably subglacial diamicton reflect creation and obliteration of lake and outwash sandur depocentres by repeated ice-marginal oscillation (Evans and Twigg, 2002; Thomas and Chiverrell, 2007). Line 4 shows a similar sequence but with outwash deposits accumulating inside IS2 limits (Fig. 7). From north to south (lines 2–4) kettle-holes are an increasing component of the land-system and reflect the melt-out of stagnant or dead ice buried predominantly within the outwash sediments, producing the complicated undulating or pitted terrain (Fig. 7). Line 5 includes an extensive pitted outwash sandur developed between the ice margin and IS2 moraines, with kettle basins reflecting melt-out of buried dead ice. At depth (line 4) fronting LD3 limit there is a <30-m-thick sand and gravel outwash fan (Fan A) (Fig. 7) (Fard, 2003). This is part of a repeating pattern of ice-front fan and delta forms filling the accommodation space created between IS-, LD- and RV-sourced ice (Figs.- 1 and 2b).

Lines 6–9, progressing from west to east, transect the major moraine limits LD3 and LD4 south–north (Figs 2b and 7) and highlight the pronounced lateral and vertical variability in the lithostratigraphy. Ice limit LD3 describes a complex of moraine ridges, termed the Kirkham End Moraine (Gresswell, 1967). The stratigraphy varies from sediments dominantly composed of diamicton (line 6) to complex ice front fans composed of diamicton, outwash sand and gravel, and glacilacustrine muds (line 7) similar to Bradley's Quarry exposures crossed on this transect (Fig. 7). Further east diamicton dominates (line 8), with another outwash fan reflected by outwash sands and lake muds (line 9: Fig. 7). The undulating geomorphology and diamicton at the surface point to over-ride of these glacifluvial and glacilacustrine units by ice during either a readvance or minor marginal oscillation. This lateral variation in lithofacies along the LD3 limit is confirmed by line 10, which is parallel to the moraine axis. It highlights zones of proglacial outwash fan and glacilacustrine sediments in the east around (i) Bradley's Quarry, (ii) Kirkham and (iii) in the west towards the coast (Fig. 7). Passing northwards between LD3 and LD4 limits there is a complicated stratigraphy, with ice front fans and what the morphostratigraphy suggests are trough sandur in the generally lower-lying terrain. There are also other smaller moraines that document minor ice still-stand or marginal oscillation during the LD3 to LD4 retreat. LD4 shows increasing bedrock control over the geomorphology and a thinning of the lithostratigraphical sequence from west to east. The general pattern is of a series of moraines comprising the LD4 complex and dominantly composed of diamicton, but with thick sequences of outwash sand and gravels in places (e.g. line 7) and glacilacustrine sand, silt and clay (lines 6 and 8). This vertical and lateral variability point to the dynamic nature of

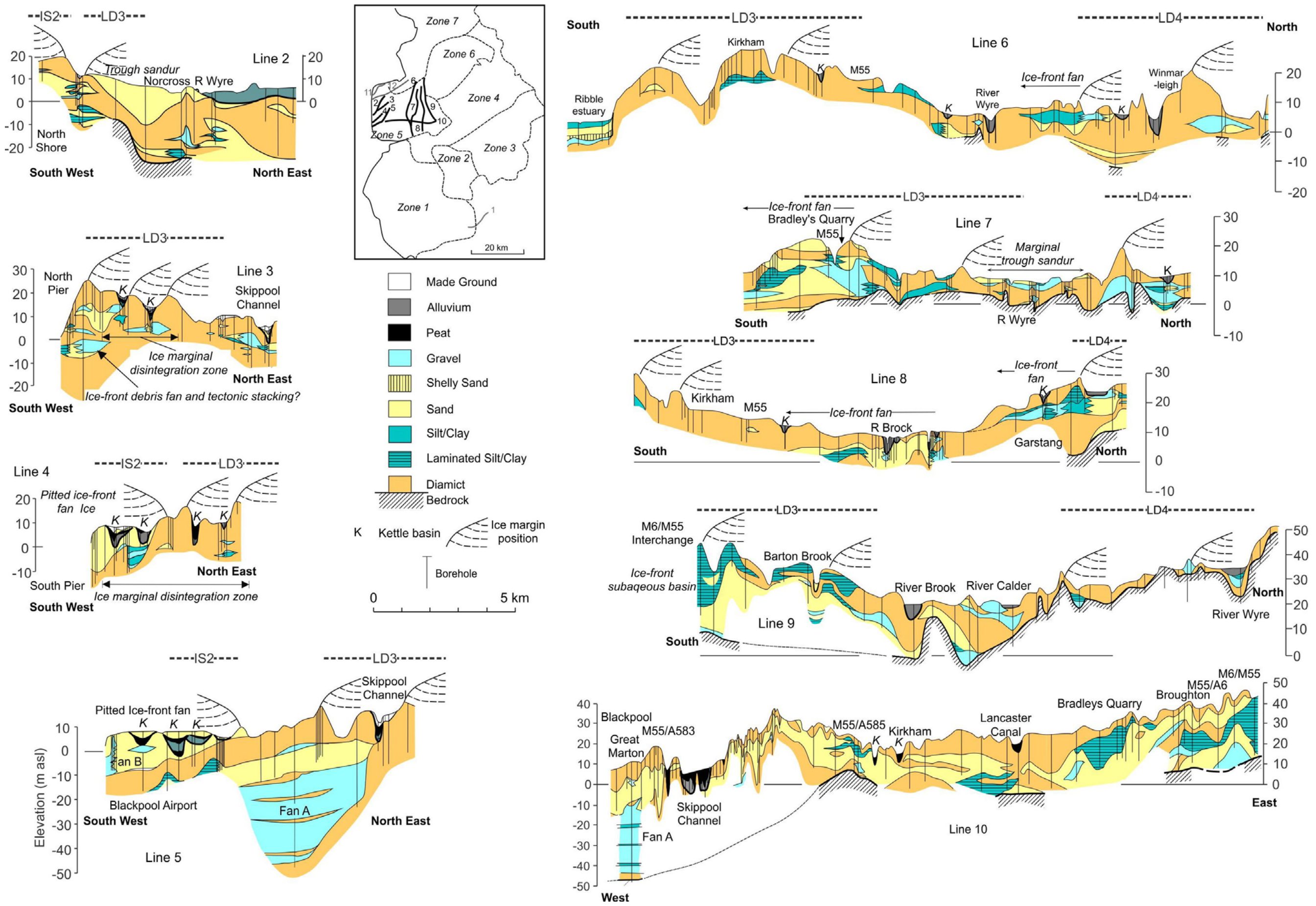

Figure 7. Borehole cross-sections within zone 5 (lines 2–10). The line locations are shown in the inset map. The main ice margin positions labelled IS(1–2) or LD(1–4) correspond to those in Fig. 2(b).

proglacial environments during marginal retreat, with development of sandur and ice contact lakes often in turn overridden during minor ice margin readvance or oscillation (Evans and Twigg, 2002; Thomas and Chiverrell, 2007).

North Lancashire drumlin field (Zones 6 and 7)

Parallel to the north coast of the Fylde, two SW–NE-orientated parallel cross-sections (lines 11 and 12; Fig. 8) characterize the stratigraphy across the zone 5/6 boundary. The rockhead lies at −20 to −25 m OD on line 11 and is overlain by a thick sequence of diamicton, sand and gravel and laminated muds, buried by >20 m of estuarine sands, organic silts and clays and peats of Holocene age. The glacigenic sediments are complex, with stacking of diamicton units, which in the west include interbedded laminated glacilacustrine muds and sand, and in the east glacifluvial sands. Line 12 shows an irregular rockhead that dips steeply to the west beneath the channel of the River Wyre, reaching depths of −20 to −40 m, and is overlain by ca. 20 m of thick diamicton that locally interdigitates with gravels, sands and laminated muds in the west. These interbedded sediments probably form part of a former lake basin and sandur that filled a suture that developed between the retreating IS4 and LD4 margins. At Preesall (Fig. 8; line 12) the diamicton thickens and rises to the surface forming a series of 10–15-m high drumlins (Wilson *et al.*, 1990; Aitkenhead *et al.*, 1992).

Regional deglacial chronology

An outline geochronology for advance and retreat of the ice in the region during the late Devensian is secured by a combination of ^{14}C, OSL and TCN dating at six locations identified on Fig. 1 (SE, Shap erratics; LWB, Low Wray Bay; FA, Four Ashes; D, Dowkabottom; NE, Norber erratics; WC, Warton Crag). Discussion of the OSL and TCN ages is 'ka', with uncalibrated ^{14}C measurements quoted as 'k ^{14}C a BP' and calibrated ages as 'k cal a BP'. The advance to maximum limits in the English Midlands is secured by the dating of ice-free conditions including the organic deposits at Four Ashes (Staffordshire) ^{14}C dated to 30.5 ± 0.44 and 30.7 ± 0.77k ^{14}C a BP (Morgan, 1973) and at Dowkabottom silt-rich deposits in karstic depressions in the Carboniferous limestone have been OSL dated to 27.8 ± 2.6 ka (Telfer *et al.*, 2009) (both locations shown on Fig. 1). The retreat of ice north of the LD4 ice limit is constrained by OSL dating that targeted silt-rich loessal deposits in a karstic depression at Warton Crag (103 m OD) (Carboniferous limestone) (Fig. 1), denoting ice-free conditions at 19.3 ± 2.6 ka (Telfer *et al.*, 2009). Retreat of ice margins from the mapped region are constrained by TCN dating erratic boulders a short distance to the north and east, and ^{14}C dating the transition to organic muds in Windermere in the south Lake District. This TCN dating has targeted a suite of granite boulders extending south from the Shap granite in eastern Cumbria (Fig. 1) (Wilson *et al.*, 2013) and the Norber (Silurian greywacke) erratic boulders in the upper Ribble Valley (Fig. 1) (Vincent *et al.*, 2010). Wilson *et al.* (2013) report ^{10}Be ages for four boulders near Shap between 16.4 ± 0.9 and 20.9 ± 1.1 ka. Four samples from the Norber erratics (Vincent *et al.*, 2010; Wilson *et al.*, 2012) have yielded ^{36}Cl ages of between 23.2 ± 1.7 and 17.7 ± 1.6 ka using the production rate of Phillips *et al.* (2001) and 18.9 ± 1.4 and 14.3 ± 1.3 ka using

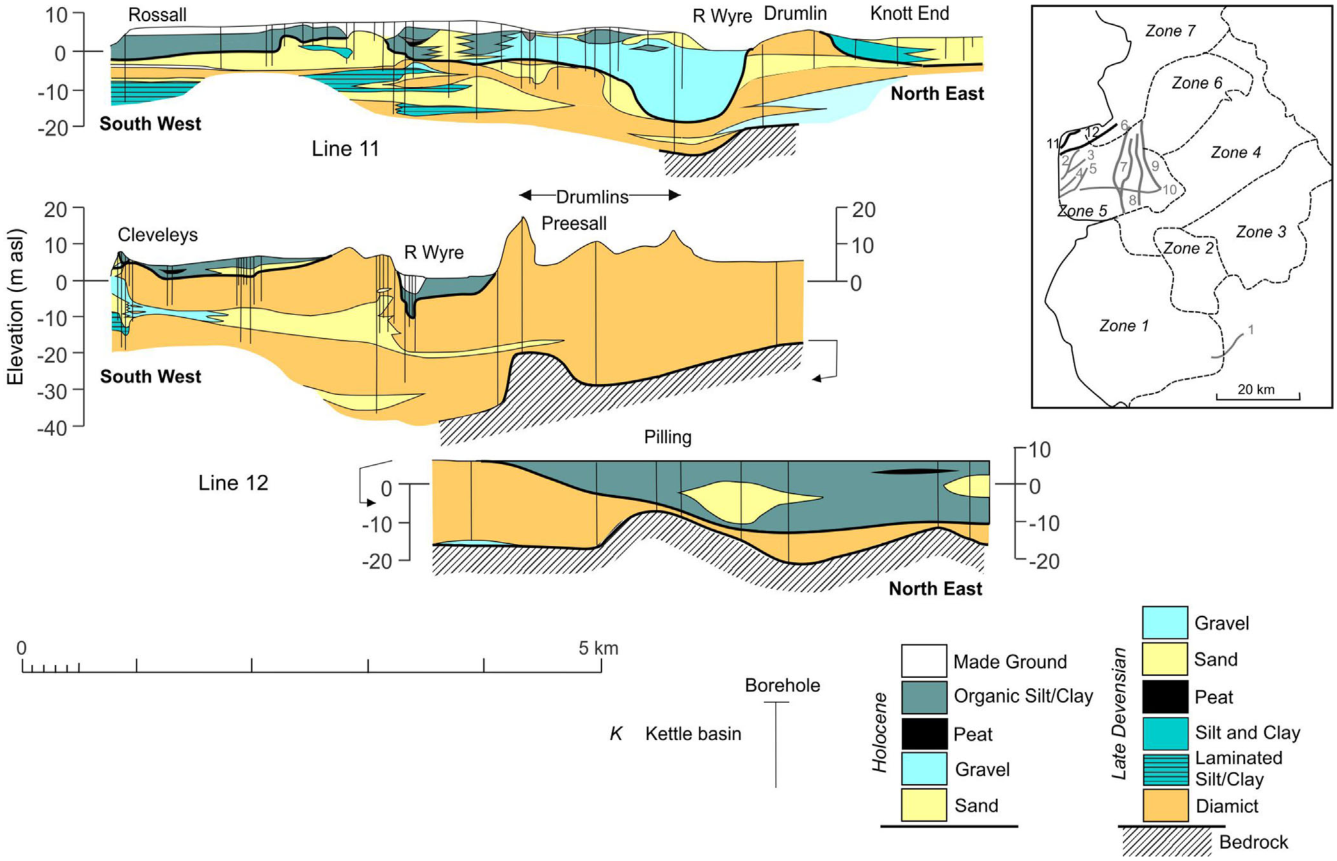

Figure 8. Borehole cross-sections within the north of zone 5 and zone 6 (lines 11 and 12). The line locations are shown in the inset map.

the production rate of Stone *et al.* (1996). The transition from varved clays to organic interstadial muds in Windermere has been radiocarbon dated to 14.6 ± 0.28 and 14.6 ± 0.36k ^{14}C a BP (Fig. 1) (Harkness, 1981).

Bayesian modelling of this geochronology used a relative order model from oldest to youngest (Fig. 9) (cf. Chiverrell *et al.*, 2013), with (i) the ice advance to maximum limits (Four Ashes – Dowkabottom), (ii) a phase describing the deglaciation of lowland Lancashire (Warton Crag), (iii) marginal retreat beginning to vacate ice source areas in the Lake District and upper Ribble Valley (Shap and Norber) and (iv) further retreat into the central Lake District (Windermere). The erratic boulders at Norber include three that pass a χ^2 test (95% level) and the probabilities combine to an age of 20–15.8 ka. The Shap erratics are more problematic with two that pass a χ^2 test (95% level) and produce a combined age of 19–16.5 ka, but with both younger and older outlier boulders. The Bayesian model is conformable with agreement indices >60% (A = 128%: Fig. 9). The modelled ages or posterior density estimates (identified in italics) constrain the deglaciation of lowland Lancashire, including the retreats from LD2 to north of LD4 and RV1 to RV3, to the period *21–17.5 ka* (2 sigma range). Modelled as a group with the Windermere ^{14}C measurements, the age probability distributions for Warton Crag, Shap and Norber overlap and constrain the complete deglaciation of zones 4 and 6 to after *18.6–17.3 ka.*

Discussion

Rates and styles of deglaciation in Lancashire

During the advances to LGM limits the identity of the smaller glaciers in the eastern ISB that expanded from the three principal source areas (i.e. southern Scotland, the Lake District and the northern Pennines) were probably lost as these ice masses expanded into the English Midlands (Chiverrell and Thomas, 2010; Clark *et al.*, 2012). Ice flow at this time probably generated the subglacial bedforms that form flow-sets FS 1–3 (Fig. 2b). Although ice streaming behaviour has been attributed to the ISIS draining south-west into the Celtic Sea, we find no definitive evidence (cf. Stokes and Clark, 1999) for it in the geomorphology of Lancashire (Fig. 1). Instead, the sediment and landform signature in Lancashire is mostly the product of rapid, late MIS 2, deglaciation of the region. This ice-marginal retreat and thinning resulted in the collapse of a single large ice mass that was fed from multiple sources into individual, semi-independent glaciers that gradually decoupled and became independent in the east Irish Sea, Lake District and Ribble Valley. Our Bayesian modelling has produced age ranges very similar to those obtained in equivalent modelling of the retreat of the ISIS further west, with ice-marginal retreat from Anglesey to the Isle of Man dated to 21.9–20.7 and 17.8–16.9 ka (Chiverrell *et al.*, 2013). The modelled geochronology suggests deglaciation was accomplished over 3.7–2.1k years at marginal retreat rates that average 25–50 m a^{-1}.

Two major retreat phases are evident in the geomorphology (Fig. 2c–e) with, during Phase 1, the initial retreat of the ice margin into south Lancashire producing lakes in the Manchester embayment dammed by IS ice. Further marginal retreat created accommodation space across and including the lower Ribble valley, in which further ice-dammed lakes developed. The IS2 ice limit, including the Tarleton moraine, blocked the Ribble Valley as it extended south to bedrock highs. The Bamber Bridge fan issues from coalescing LD and RV ice masses and the stratigraphy of ice limit LD3 shows further lake sediments fronting the retreating margin of LD ice. Extensive glacilacustrine deposits throughout the lower

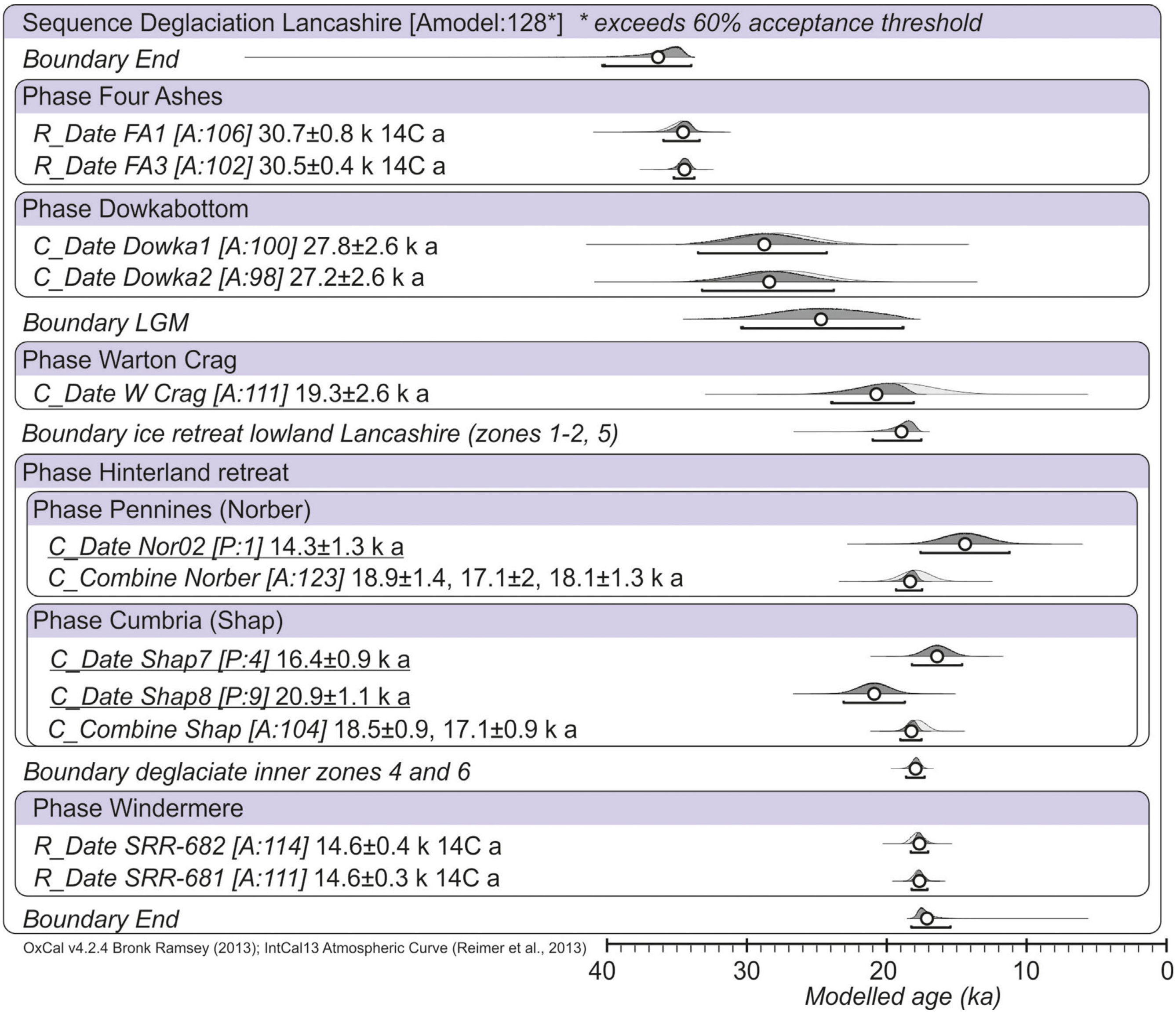

Figure 9. Bayesian model of the dating control and showing the OxCal keywords that defines the relative order used in the model (Ramsey, 2009). The Sequence model (Ramsey, 2009) has the dated events in the order defined (oldest to youngest) interpreted solely from the pattern of ice-marginal retreat (Fig. 2b). The Sequence model is divided into Phases which contain dating information grounded for specific sites or sub-regions. Phases are separated by Boundaries which generate the modelled age estimates used to constrain deglaciation of the region. Each age distribution (light grey) represents the original relative probability age measurement and is overlain by the modelled posterior density estimate (dark grey and italicized text). Outliers to the model that have been excluded or down-weighted in the modelling are underlined.

Ribble, Hodder and Calder, and well represented in the LD3 Moraine (Kirkham), testify to damming of meltwater by a glacier in the eastern ISB. This suggests that LD and RV ice deglaciated more rapidly than IS ice, perhaps reflecting a continued supply of ice to that in the ISB from south-west Scotland, while that sourced from Cumbria and the Northern Pennines was exhausted earlier, supporting indications elsewhere in the Pennine–Cumbria region (Wilson *et al.*, 2013; Wilson and Lord, 2014; Livingstone *et al.*, 2015). Phase 2 includes the building of the Kirkham moraine complex (IS2–LD3), where the geomorphology, sediment-landform assemblages and stratigraphy identify a signature of ice stagnation and disintegration in the west (e.g. chaotic patterns of moraine ridges and kettle holes) and more active oscillatory ice-margin behaviour against the eastern rock margin. The marked curvature of the Kirkham moraine belt, incorporating limits IS2 and LD3, suggests that it represents a response to the progressive 'unzipping' of an inter-glacier suture opening between the LD and adjacent IS glaciers. Thus, the retreat from limit IS2–LD3 was accompanied by contradictory evidence for ice stagnation and disintegration in the south, with the generation of flow-set Fs-11 (Fig. 2e) in the north Lancashire drumlin field slightly later in the sequence of events. Following the ice mass realignment interpreted here, the region deglaciated completely and the lack of marginal moraines suggests this probably occurred rapidly during which some subglacial forms were partially buried by outwash deposits fronting the retreating ice margin.

Relationships to adjacent sectors of the ice sheet

Ice-marginal retreat in the eastern ISB was accomplished over 3.7–2.1 ka at rates of roughly 25–50 m a^{-1}, and was significantly slower than rates reconstructed for the former ISIS in the Celtic and western ISB (550–100 m a^{-1}) (Chiverrell *et al.*, 2013). However, the western and eastern ice masses in the wider ISB were constrained by different bedrock topographies and complex ice-marginal interaction with one another, as well as by independent changes in individual flow rates, basal temperatures, sediment load and marginal environments. In the east slower rates probably reflect the decline of an ice mass with a largely terrestrial margin. Instability afforded by a subaqueous margin (Dove *et al.*, 2015) is supported to a certain extent by the more rapid margin retreat from LD1 to LD3, compared with more stable IS2 limit (Fig. 2). The presence of an ice-dammed lake here, when coupled with an already rapidly thinning ice mass probably driven by exhaustion of local ice sources, renders the ice mass much less stable. It seems more than coincidental that we have rapid retreat of LD and Ribble ice (reflected by fewer moraines) where we also have evidence for a lake, whereas slower marginal retreat appears to have dominated outside of the lake footprint to the west (from IS1 to IS2) and north (from LD3 northwards) where there is clear imprint of more frequent moraines. Potentially rapid decline of this lacustrine sector may have included flotation and break-up of the tongue until it reached a more stable terrestrial pinning point to the north (LD3).

Van Landeghem *et al.* (2009) presented geomorphological data from further west in the ISB, which show that westerly fast and streaming ice flows were generated during the drawback of ice margins into the western ISB. Bayesian modelling of the western ISIS indicates this probably occurred after 22.5–21.2 ka (Chiverrell *et al.*, 2013), pre-dating the deglaciation of Lancashire at 18.6–17.3 ka. Glacial bedforms in the western ISB between Anglesey and the Isle of Man (e.g. elongated drumlins and flutes) provide a signature of ice streaming (Van Landeghem *et al.*, 2009), which contrasts sharply with the non-streaming behaviour to the east in Lancashire. We regard these differences in ice behaviour as reflecting the influence of a glacimarine margin in the western ISB, in contrast to the terrestrially retreating margin in the east. As western ISIS withdrew northwards, the modelled geochronology (Fig. 9; Chiverrell *et al.*, 2013) points towards a temporal correspondence between marginal retreat from the Kirkham Moraine and the Bride Moraine across the north of the Isle of Man (Thomas, 1984b), suggesting the eastern and western branches of ISIS were synchronous at this time. Although the western ISIS was significantly larger (width and length) than that in the east, the rapid discharge of ice into the ISB in the west (evidenced iceberg keel scours preserved on the sea floor reflecting a calving ice margin cf. Van Landeghem *et al.*, 2009) meant that the western margin caught up with the slower terrestrially retreating margin in the east.

The differences in behaviour of regional ice masses on retreat perhaps reflect the comparative scales of the ice sources and the nature of the ice margin. Ice in the western ISB terminated in marine waters, was much less confined by topography than ice to the east, and retreated as more or less two ice margins that split around the Isle of Man. Whereas in the east the margins were mostly terrestrial, there was greater confinement by topography and the marginal geometry was more complicated with the ice mass fed by smaller, more local sources in the Lake District and Pennines. Ice retreat in the ISB shows variations in the degree of synchronization, with at maximum the west significantly further advanced extending far into the Celtic Sea (Scourse and Furze, 2001; Hiemstra *et al.*, 2006; Scourse *et al.*, 2006; McCarroll *et al.*, 2010; Chiverrell *et al.*, 2013; Furze *et al.*, 2014; Praeg *et al.*, 2015). The western and eastern ice margins in the ISB synchronized in retreat north of Anglesey, but there is evidence of further asynchrony developing during latter stages. For example, the accommodation space created by the evacuation of a more dominant eastern IS glacier from an LS3 limit and linking Kirkham with the Bride Moraine (Thomas, 1984b) potentially allows for more rapid south-westerly flows of LD ice, producing the overprinting of flow-set Fs11 in the north Lancashire drumlin field.

Wider implications for ice behaviour and dynamics

The former ice dynamics in the Lancashire region and wider ISB are a behavioural model for what could happen to contemporary ice masses as they thin and draw back. There are clear lateral differences in ice-marginal retreat rates between these adjacent marine- and terrestrially terminating ice margins. The rates of retreat in Lancashire are significantly slower than rates reconstructed for the former ISIS in the Celtic Sea and western ISB (550–100 m a^{-1}) (Chiverrell *et al.*, 2013), and for the McMurdo Sound (WAIS) ice stream over 7.6 ka timescales (120 m a^{-1}) (Conway *et al.*, 1999), and rates of retreat recorded for WAIS (e.g. 450 m a^{-1} for Ice Stream B/Whillans Ice Stream during 1968–1998; Conway *et al.*, 1999; Thomas *et al.*, 2011; Jakobsson *et al.*, 2012). In addition, the reversion to more local driving of glacier behaviour that dominates lowland Lancashire is represented elsewhere in the former BIIS (e.g. the Solway lowlands; Livingstone *et al.*, 2012), in modelling experiments using the palaeo-BIIS (Boulton and Hagdorn, 2006), and has parallels in contemporary glaciers in Iceland (e.g. Breiðamerkurjökull; Evans and Twigg, 2002) and in West Antarctica (Rignot *et al.*, 2014). With the reversion to ice dynamics being driven by local sources, lateral variation from marine to terrestrial margins and undulating sub-ice topographies may mean that lakes are likely to become a significant component of the land-system. Clearly this was the case in Lancashire, but is also becoming prevalent in Iceland with contemporary rapid ice-marginal retreat (e.g. Bennett and Evans, 2012). This has significant implications for retreat dynamics and rates, with lakes and over-deepened basins in general synonymous with instability and more rapid decline during retreat episodes (Bennett and Evans, 2012; Dove *et al.*, 2015). There is also considerable lateral variability in the dynamics of ice at major still-stand or re-advance positions, with central sectors (Kirkham moraine) showing stagnation and collapse resulting in a dead-ice topography of basins and mounds, in contrast to more dynamic behaviour against lateral margins shown by repeated well-defined moraine ridges documenting the retreat. Furthermore, longitudinal separations of stagnant ice behaviour, with dead ice topography (LD3: Fig. 2b) at the reconstructed former ice margins, contrast with more active deforming bed conditions up-glacier that produced drumlins (FS11: Fig. 2a). Similar passive distal margins with more active up-ice zones has been observed at rapidly retreating contemporary glacier margins in south-east Iceland (e.g. Falljökull; Phillips *et al.*, 2014), while in Lancashire the ice masses were larger and the evidenced stagnant and active ice behaviour need not be contemporaneous.

Conclusions

Integrating fine-resolution mapping of the glacial landform record with exposure and borehole data, we document the decline of ice masses in eastern Lancashire and the adjacent ISB. The ice-marginal retreat, although at present poorly constrained chronologically, was relatively rapid (50–25 m a^{-1}), but slower than retreat rates reconstructed for the former ISIS in the Celtic Sea and western ISB (Chiverrell *et al.*, 2013). These rates are equivalent to those reconstructed for other parts of the ice sheet (Clark *et al.*, 2012). Our work shows a complex and varied behaviour of glaciers and ice streams during deglaciation, including differences within the same glacier (e.g. west and east

ISB). Although similar differences are being captured by glacier numerical models (e.g. fig. 5 in Hubbard *et al.*, 2009), their incorporation in such models requires more detailed investigation of glacier geometries and bed conditions during retreat stages. This can only be achieved by detailed investigation of former ice sheet beds because contemporary analogues provide observations over relatively short timescales (i.e. tens of years), while ice-sheet-scale processes occur over much longer timescales (i.e. thousands of years). Likewise, when investigating former ice sheets it is not sufficient to explore glacial landform patterns alone. Instead robust analysis requires a combination of landform pattern, sediment records and chronology to decipher retreat patterns and ice dynamics. The disparity in retreat patterns in the eastern ISB in part reflects the lack of a calving margin and the terrestrial nature of the ice masses in the eastern ISB and lowland Lancashire. However, there are also local differences in the retreat patterns and rates, with ice vacating the lower and middle Ribble Valley creating accommodation space for an ice-dammed lake. The more rapid retreat in the RV and LD glaciers, relative to IS ice, probably reflects the smaller ice source areas feeding these glaciers and development of calving margins associated with ice-dammed lakes. We conclude that the drawdown and retreat of this sector of the last BIIS displays a switch to local conditioning and control over ice dynamics (Clark *et al.*, 2012) and this may become an increasing component in the projected decline of contemporary ice sheets and glaciers.

Supplementary information

Figure S1. High-resolution geomorphological map of Lancashire overlain on a hillshaded elevation model. The map extent is shown by the black box within the inset map (top left). The mapped area has been divided into seven zones that are demarcated by the labelled black polygons. This is an expanded large-scale version of Fig. 1.

Acknowledgments. R.C.C. and G.S.P.T. thank English Heritage for their financial support through Aggregate Levy Sustainibility Fund Grant 3928 and for academic and logistical support. In particular, we would like to thank Dr Jennie Stopford (English Heritage), Peter Iles [Specialist Advisor (Archaeology) Lancashire County Council] and Phil Catherall (Environment Agency) for their advice and assistance. Lancashire County Council and the Environment Agency are thanked for providing digital data, particularly the LiDAR data. This work was in part supported by the Natural Environment Research Council consortium grant BRITICE-CHRONO NE/J009768/1. We also thank landowners for allowing access to land and for their general good-will. The paper is published with the permission of English Heritage but opinions expressed are entirely those of the authors.

Abbreviations. BIIS, British–Irish Ice Sheet; ISB, Irish Sea Basin; LD, Lake District; LGM, Last Glacial Maximum; OSL, optically stimulated luminescence; RV, Ribble Valley; TCN, terrestrial cosmogenic nuclide.

References

Aitkenhead N, Bridge D, Riley NJ *et al.* 1992. *Geology of the Country around Garstang*. HM Stationery Office: London.

Bennett GL, Evans DJA. 2012. Glacier retreat and landform production on an overdeepened glacier foreland: the debris-charged glacial landsystem at Kvíárjökull, Iceland. *Earth Surface Processes and Landforms* **37**: 1584–1602.

Boulton G, Hagdorn M. 2006. Glaciology of the British Isles Ice Sheet during the last glacial cycle: form, flow, streams and lobes. *Quaternary Science Reviews* **25**: 3359–3390.

Bradwell T, Stoker MS, Golledge NR *et al.* 2008. The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews* **88**: 207–226.

Carr SJ, Hiemstra JF. 2013. Sedimentary evidence against a local ice-cap on the Shetland Isles at the Last Glacial Maximum. *Proceedings of the Geologists' Association* **124**: 484–502.

Carr SJ, Holmes R, van der Meer JJM *et al.* 2006. The Last Glacial Maximum in the North Sea Basin: micromorphological evidence of extensive glaciation. *Journal of Quaternary Science* **21**: 131–153.

Chiverrell RC, Foster GC, Marshall P *et al.* 2009a. Coupling relationships: hillslope-fluvial linkages in the Hodder catchment, NW England. *Geomorphology* **109**: 222–235.

Chiverrell RC, Foster GC, Thomas GSP *et al.* 2010. Sediment transmission and storage: the implications for reconstructing landform development. *Earth Surface Processes and Landforms* **35**: 4–15.

Chiverrell RC, Foster GC, Thomas GSP *et al.* 2009b. Robust chronologies for landform development. *Earth Surface Processes and Landforms* **34**: 319–328.

Chiverrell RC, Thomas GSP. 2010. Extent and timing of the Last Glacial Maximum (LGM) in Britain and Ireland: a review. *Journal of Quaternary Science* **25**: 535–549.

Chiverrell RC, Thrasher IM, Thomas GSP *et al.* 2013. Bayesian modelling the retreat of the Irish Sea Ice Stream. *Journal of Quaternary Science* **28**: 200–209.

Clark CD, Hughes ALC, Greenwood SL *et al.* 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews* **44**: 112–146.

Conway H, Hall BL, Denton GH *et al.* 1999. Past and future grounding-line retreat of the West Antarctic Ice Sheet. *Science* **286**: 280–283.

Dove D, Arosio R, Finlayson A *et al.* 2015. Submarine glacial landforms record Late Pleistocene ice-sheet dynamics, Inner Hebrides, Scotland. *Quaternary Science Reviews* **123**: 76–90.

Dunlop P, Shannon R, McCabe M *et al.* 2010. Marine geophysical evidence for ice sheet extension and recession on the Malin Shelf: new evidence for the western limits of the British Irish Ice Sheet. *Marine Geology* **276**: 86–99.

Earp JR, Poole EG, Whiteman AJ. 1961. *Geology of the Country around Clitheroe and Nelson*. HM Stationery Office: London.

Evans DJA. 2003. *Glacial Landsystems*. Arnold: London.

Evans DJA, Cofaigh CÓ. 2003. Depositional evidence for marginal oscillations of the Irish Sea ice stream in southeast Ireland during the last glaciation. *Boreas* **32**: 76–101.

Evans DJA, Twigg DR. 2002. The active temperate glacial landsystem: a model based on BreiÐamerkurjökull and Fjallsjökull, Iceland. *Quaternary Science Reviews* **21**: 2143–2177.

Everest JD, Bradwell T, Stoker M *et al.* 2013. New age constraints for the maximum extent of the last British-Irish Ice Sheet (NW sector). *Journal of Quaternary Science* **28**: 2–7.

Eyles N, McCabe AM. 1989. The Late Devensian (<22,000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin. *Quaternary Science Reviews* **8**: 307–351.

Fard AM. 2003. Large dead-ice depressions in flat-topped eskers: evidence of a Preboreal jökulhlaup in the Stockholm area, Sweden. *Global and Planetary Change* **35**: 273–295.

Foster GC, Chiverrell RC, Thomas GSP *et al.* 2009. Fluvial development and the sediment regime of the lower Calder, Ribble catchment, northwest England. *Catena* **77**: 81–95.

Furze MFA, Scourse JD, Pieńkowski AJ *et al.* 2014. Deglacial to postglacial palaeoenvironments of the Celtic Sea: lacustrine conditions versus a continuous marine sequence. *Boreas* **43**: 149–174.

Golledge NR, Finlayson A, Bradwell T *et al.* 2008. The last glaciation of Shetland, North Atlantic. *Geografiska Annaler: Series A* **90**: 37–53.

Gresswell RK. 1967. The geomorphology of Fylde. In *Liverpool Essays in Geography: a Jubilee Collection*, Stell RW, Lawton R (eds). Longmans: London; 25–42.

Harkness DD. 1981. Scottish Universities Research and Reactor Center radiocarbon measurements-Iv. *Radiocarbon* **23**: 252–304.

Hiemstra JF, Evans DJA, Scourse JD *et al.* 2006. New evidence for a grounded Irish Sea glaciation of the Isles of Scilly, UK. *Quaternary Science Reviews* **25**: 299–309.

Howell FT. 1973. The sub-drift surface of the Mersey and Weaver catchment and adjacent areas. *Geological Journal* **8**: 285–296.

Hubbard A, Bradwell T, Golledge N *et al*. 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British-Irish ice sheet. *Quaternary Science Reviews* **28**: 758–776.

Huddart D. 1971. Textural distinction of Main Glaciation and Scottish Readvance tills in the Cumberland lowland. *Geological Magazine* **108**: 317–324.

Huddart D. 1991. The glacial history and glacial deposits of the north and west Cumbrian lowlands. In *Glacial Deposits of Great Britain and Ireland*, Ehlers J, Gibbard PL, Rose J (eds). Balkema: Rotterdam 151–167.

Huddart D. 1994. The Late Quaternary glacigenic sequence: landforms and environments in coastal Cumbria. In *The Quaternary of Cumbria – Field Guide*, Boardman J, Walden J (eds). Quaternary Research Association: London 59–77.

Hughes ALC, Clark CD, Jordan CJ. 2014. Flow-pattern evolution of the last British Ice Sheet. *Quaternary Science Reviews* **89**: 148–168.

Jakobsson M, Anderson JB, Nitsche FO *et al*. 2012. Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica. *Quaternary Science Reviews* **38**: 1–10.

Jansson KN, Glasser NF. 2005. Palaeoglaciology of the Welsh sector of the British-Irish Ice Sheet. *Journal of the Geological Society* **162**: 25–37.

Johnson RH. 1985. The imprint of glaciation on the west Pennines Uplands. In *The Geomorphology of North-West England*, Johnson RH (ed.). Manchester University Press: Manchester; 237–262.

Knight J. 2004. Sedimentary evidence for the formation mechanism of the Armoy moraine and Late Devensian glacial events in the north of Ireland. *Geological Journal* **39**: 403–417.

Knight J, McCabe AM. 1997. Drumlin evolution and ice sheet oscillations along the NE Atlantic margin, Donegal Bay, western Ireland. *Sedimentary Geology* **111**: 57–72.

Livingstone SJ, Evans DJA, Ó Cofaigh C. 2010a. Re-advance of Scottish ice into the Solway Lowlands (Cumbria, UK) during the Main Late Devensian deglaciation. *Quaternary Science Reviews* **29**: 2544–2570.

Livingstone SJ, Evans DJA, Ó Cofaigh C *et al*. 2012. Glaciodynamics of the central sector of the last British–Irish Ice Sheet in Northern England. *Earth-Science Reviews* **111**: 25–55.

Livingstone SJ, Ó Cofaigh C, Evans DJA *et al*. 2010b. Sedimentary evidence for a major glacial oscillation and proglacial lake formation in the Solway Lowlands (Cumbria, UK) during Late Devensian deglaciation. *Boreas* **39**: 505–527.

Livingstone SJ, Roberts DH, Davies BJ *et al*. 2015. Late Devensian deglaciation of the Tyne Gap Palaeo-Ice Stream, northern England. *Journal of Quaternary Science* **30**: 790–804.

Longworth D. 1985. The Quaternary history of the Lancashire Plain. In *The Geomorphology of Northwest England*, Johnson RH (ed,). Manchester University Press: Manchester 178–200.

Lønne I, Nemec W. 2004. High-arctic fan delta recording deglaciation and environment disequilibrium. *Sedimentology* **51**: 553–589.

McCabe AM, Clark PU, Clark J. 2005. AMS ^{14}C dating of deglacial events in the Irish Sea Basin and other sectors of the British-Irish ice sheet. *Quaternary Science Reviews* **24**: 1673–1690.

McCabe AM, Dardis GF, Hanvey PM. 1984. Sedimentology of a Late Pleistocene submarine-moraine complex, County Down, Northern Ireland. *Journal of Sedimentary Research* **54**: 716–730.

McCabe AM, Dardis GF, Hanvey PM. 1987. Sedimentation at the margins of a Late Pleistocene ice-lobe terminating in shallow marine environments, Dundalk Bay, eastern Ireland. *Sedimentology* **34**: 473–493.

McCabe AM, Dunlop P. 2006. *The Last Glacial Termination in Northern Ireland*. Geological Survey of Northern Ireland: Belfast.

McCarroll D, Stone JO, Ballantyne CK *et al*. 2010. Exposure-age constraints on the extent, timing and rate of retreat of the last Irish Sea ice stream. *Quaternary Science Reviews* **29**: 1844–1852.

Merritt JW, Auton CA. 2000. *An Outline of the Lithostratigraphy and Depositional History of Quaternary Deposits in the Sellafield District, West Cumbria, Proceedings of the Yorkshire Geological and Polytechnic Society*. Geological Society of London; 129–154.

Miall AD. 1977. A review of the braided-river depositional environment. *Earth Science Reviews* **13**: 1–62.

Mitchell WA. 1991. *Western Pennines: a Field Guide*. Quaternary Research Association: London.

Mitchell WA, Hughes ALC. 2012. The Late Devensian glaciation in the Yorkshire Dales. In *Cave Archaeology and Karst Geomorphology of North West England*, O'Regan HJ, Faulkner T, Smith IR (eds). Quaternary Research Association: London 34–45.

Morgan AV. 1973. The Pleistocene geology of the area north and west of Wolverhampton, Staffordshire, England. *Philosophical Transactions of the Royal Society of London* **265**: 233–297.

Nemec W, Lønne I, Blikra LH. 1999. The Kregnes moraine in Gauldalen, west-central Norway: anatomy of a Younger Dryas proglacial delta in a palaeofjord basin. *Boreas* **28**: 454–476.

Ó Cofaigh C, Evans DJA. 2007. Radiocarbon constraints on the age of the maximum advance of the British–Irish Ice Sheet in the Celtic Sea. *Quaternary Science Reviews* **26**: 1197–1203.

Parkes AA, Waller RI, Knight PG *et al*. 2009. A morphological, sedimentological and geophysical investigation of the Woore Moraine, Shropshire, England. *Proceedings of the Geologists' Association* **120**: 233–244.

Phillips E, Finlayson A, Bradwell T *et al*. 2014. Structural evolution triggers a dynamic reduction in active glacier length during rapid retreat: evidence from Falljokull, SE Iceland. *Journal of Geophysical Research-Earth* **119**: 2194–2208.

Phillips FM, Stone WD, Fabryka-Martin JT. 2001. An improved approach to calculating low-energy cosmic-ray neutron fluxes near the land/atmosphere interface. *Chemical Geology 175*: 689–701.

Praeg D, McCarron S, Dove D *et al*. 2015. Ice sheet extension to the Celtic Sea shelf edge at the Last Glacial Maximum. *Quaternary Science Reviews* **111**: 107–112.

Price D, Wright WB, Jones RCB. 1963. *Geology of the Country Around Preston*. HMSO: London.

Ramsey CB. 2009. Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon* **51**: 1023–1045.

Rignot E, Mouginot J, Morlighem M *et al*. 2014. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters* **41**: 3502–3509.

Sambrook Smith GH, Ashworth PJ, Best JL *et al*. 2005. The morphology and facies of sandy braided rivers: some considerations of scale invariance. *Special Publications of the International Association of Sedimentologists* **35**: 145–158.

Sambrook Smith GH, Ashworth PJ, Best JL *et al*. 2006. The sedimentology and alluvial architecture of the sandy braided South Saskatchewan River, Canada. *Sedimentology* **53**: 413–434.

Scourse JD, Evans DJA, Hiemstra JF *et al*. 2006. Pleistocene stratigraphy, geomorphology and geochronology In *The Isles of Scilly: Field Guide*, Scourse JD (ed.). Quaternary Research Association: London; 13–22.

Scourse JD, Furze MFA. 2001. A critical review of the glaciomarine model for Irish sea deglaciation: evidence from southern Britain, the Celtic Shelf and adjacent continental slope. *Journal of Quaternary Science* **16**: 419–434.

Stokes CR, Clark CD. 1999. Geomorphological criteria for identifying Pleistocene ice streams. *Annals of Glaciology* **28**: 67–74.

Stokes C, Clark CD. 2001. Palaeo-ice streams. *Quaternary Science Reviews* **20**: 1437–1457.

Stone JO, Allan GL, Fifield LK *et al*. 1996. Cosmogenic chlorine-36 from calcium spallation. *Geochimica et Cosmochimica Acta* **60**: 679–692.

Telfer MW, Wilson P, Lord TC *et al*. 2009. New constraints on the age of the last ice sheet glaciation in NW England using optically stimulated luminescence dating. *Journal of Quaternary Science* **24**: 906–915.

Thomas GSP. 1984a. A Late Devensian glaciolacustrine Fan-Delta at Rhosesmor, Clwyd, North Wales. *Geological Journal* **19**: 125–141.

Thomas GSP. 1984b. The origin of the glacio-dynamic structure of the Bride Moraine, Isle of Man. *Boreas* **13**: 355–364.

Thomas GSP. 1989. The Late Devensian glaciation along the western margin of the Cheshire-Shropshire lowland. *Journal of Quaternary Science* **4**: 167–181.

Thomas G, Chiverrell R, Huddart D. 2004. Ice-marginal depositional responses to readvance episodes in the Late Devensian deglaciation of the Isle of Man. *Quaternary Science Reviews* **23**: 85–106.

Thomas GSP, Chiverrell RC. 2006. A model of subaqueous sedimentation at the margin of the late Midlandian Irish Ice Sheet, Connemara, Ireland, and its implications for regionally high isostatic sea-levels. *Quaternary Science Reviews* **25**: 2868–2893.

Thomas GSP, Chiverrell RC. 2007. Structural and depositional evidence for repeated ice-marginal oscillation along the eastern margin of the Late Devensian Irish Sea Ice Stream. *Quaternary Science Reviews* **26**: 2375–2405.

Thomas GSP, Connaughton M, Dackombe RV. 1985. Facies variation in a Late Pleistocene supraglacial outwash sandur from the Isle of Man. *Geological Journal* **20**: 193–213.

Thomas R, Frederick E, Li J *et al*. 2011. Accelerating ice loss from the fastest Greenland and Antarctic glaciers. *Geophysical Research Letters* **38**.

Van Landeghem KJJ, Wheeler AJ, Mitchell NC. 2009. Seafloor evidence for palaeo-ice streaming and calving of the grounded Irish Sea Ice Stream: implications for the interpretation of its final deglaciation phase. *Boreas* **38**: 119–131.

Vincent PJ, Wilson P, Lord TC *et al*. 2010. Cosmogenic isotope (36Cl) surface exposure dating of the Norber erratics, Yorkshire Dales: further constraints on the timing of the LGM deglaciation in Britain. *Proceedings of the Geologists' Association* **121**: 24–31.

Wilson AA, Evans WB, Warrington G. 1990. *Geology of the Country Around Blackpool. HM* Stationery Office: London.

Wilson P, Barrows TT, Lord TC *et al*. 2012. Cosmogenic isotope analysis and surface exposure dating in the Yorkshire Dales In *Cave Archaeology and Karst Geomorphology of North West England*, O'Regan HJ, Faulkner T, Smith IR (eds). Quaternary Research Association: London 117–135.

Wilson P, Lord T. 2014. Towards a robust deglacial chronology for the northwest England sector of the last British-Irish Ice Sheet. *North West Geography* **14**: 1–11.

Wilson P, Lord T, Rodés Á. 2013. Deglaciation of the eastern Cumbria glaciokarst, northwest England, as determined by cosmogenic nuclide (^{10}Be) surface exposure dating, and the pattern and significance of subsequent environmental changes. *Cave and Karst Science* **40**: 22–27.