Proceedings of the Geologists' Association 135 (2024) 217–236

Contents lists available at ScienceDirect

Proceedings of the Geologists' Association

journal homepage: www.elsevier.com/locate/pgeola

The late Quaternary glacial depositional environment at Filey Bay, eastern England: Accretionary mechanisms for thick sequences of tills and stratified diamictons

David J.A. Evans [a,*], David H. Roberts [a], Emrys Phillips [b]

[a] Department of Geography, Durham University, South Road, Durham DH1 3LE, UK
[b] British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, UK

ARTICLE INFO

Article history:
Received 14 November 2023
Received in revised form 8 January 2024
Accepted 24 January 2024
Available online 4 April 2024

Keywords:
Subglacial traction till
Stratified diamictons
Glacilacustrine
North Sea Lobe
Moraine

ABSTRACT

Construction of the Holderness/Flamborough Head moraine belt on the East Yorkshire coast, England, records the oscillatory onshore flow of the North Sea Lobe of the British-Irish Ice Sheet from ~25.8 to ~19.7 ka BP, during which time a thick sequence of multiple diamictons and associated stratified sediments were emplaced. The sedimentology of a >40 m thick stratigraphy through the moraine belt at Filey Bay, in combination with local borehole records, is used here to reconstruct the depositional processes associated with glacier ice moving *ca.*, 12 km onshore and damming the mouth of the Vale of Pickering, which resulted in the accumulation of an unusually thick and complex sequence of deposits traditionally classified as the "Filey till". The base of the sedimentary sequence comprises stratified diamictons, which are interpreted as glacilacustrine deposits emplaced predominantly by sediment gravity flows in an ice-contact 'mud apron' on the distal slope of a subaqueous push ridge constructed in the earliest proglacial lake in Filey Bay; a vertical increase in coarse-grained lithofacies records increasing glacier proximity. Glacier overriding of the mud apron is recorded by a stacked sequence of tills that interdigitate with lake sediments inland. A zone of till-lake sediment interdigitation migrated first westward during North Sea Lobe advance and then eastward during its retreat, into and out of Glacial Lake Pickering, respectively. Multiple tills and intra-till stratified beds and lenses at the top of the sequence at Filey represent alternating deforming bed-sliding bed facies (subglacial traction tills and subglacial canal fills) associated with the construction of inset push moraines, constructed by sub-marginal incremental thickening or punctuated aggradation. This depositional scenario addresses the problems arising from genetic classifications of substantial accumulations of glacigenic diamictons as 'till' when modern analogues indicate only modest thicknesses of subglacial traction till beneath glaciers. Onshore thickening of glacigenic deposits through subaqueous push moraine construction and mud apron progradation is compatible with glacier surging behaviour, but not necessarily solely diagnostic of a surging North Sea Lobe during the last glaciation.

1. Introduction

The landform–sediment assemblages of Holderness, eastern England (Fig. 1) continue to be critical to palaeoglaciological reconstructions of the last British–Irish Ice Sheet (BIIS; Clark et al., 2022), as highlighted by studies on glacial stratigraphy (Bisat, 1939, 1940; Catt and Penny, 1966; Rose, 1985; Catt, 2007; Evans and Thomson, 2010), glacial sedimentology (Lamplugh, 1911; Evans et al., 1995; Boston et al., 2010; Busfield et al., 2015) and the dating of key deposits (Penny et al., 1969; Evans et al., 2017; Bateman et al., 2018). Central to the development of late Quaternary ice sheet reconstructions in the region, both onshore and offshore (Bateman et al., 2015; Dove et al., 2017; Roberts et al., 2013, 2018, 2019; Evans et al., 2021), is the genetic interpretation of the extensive till sheets and associated deposits that make up the morainic topography demarcating the extent of onshore flow by the former North Sea Lobe of the BIIS (Farrington and Mitchell, 1951; Eyles et al., 1994; Evans and Thomson, 2010). Early descriptions of the cliff stratigraphy in the Filey area by Bisat (1939, 1940) highlighted multiple tills (termed "clays") and intervening stratified deposits, much of which were classified as laminated. Importantly, Bisat (1940) depicts a stratigraphy at Hunmanby Gap, in the centre of Filey Bay, in which three lower tills and their intervening laminated deposits are arranged in an anticlinal structure, presumably a large open fold. This was overlain by a "silt basin", represented by horizontally bedded silts and varved clays interrupted by various horizons of fine gravel, with bedding draping the flanks of the fold in the underlying deposits.

* Corresponding author.
E-mail address: d.j.a.evans@durham.ac.uk (D.J.A. Evans).

https://doi.org/10.1016/j.pgeola.2024.01.003

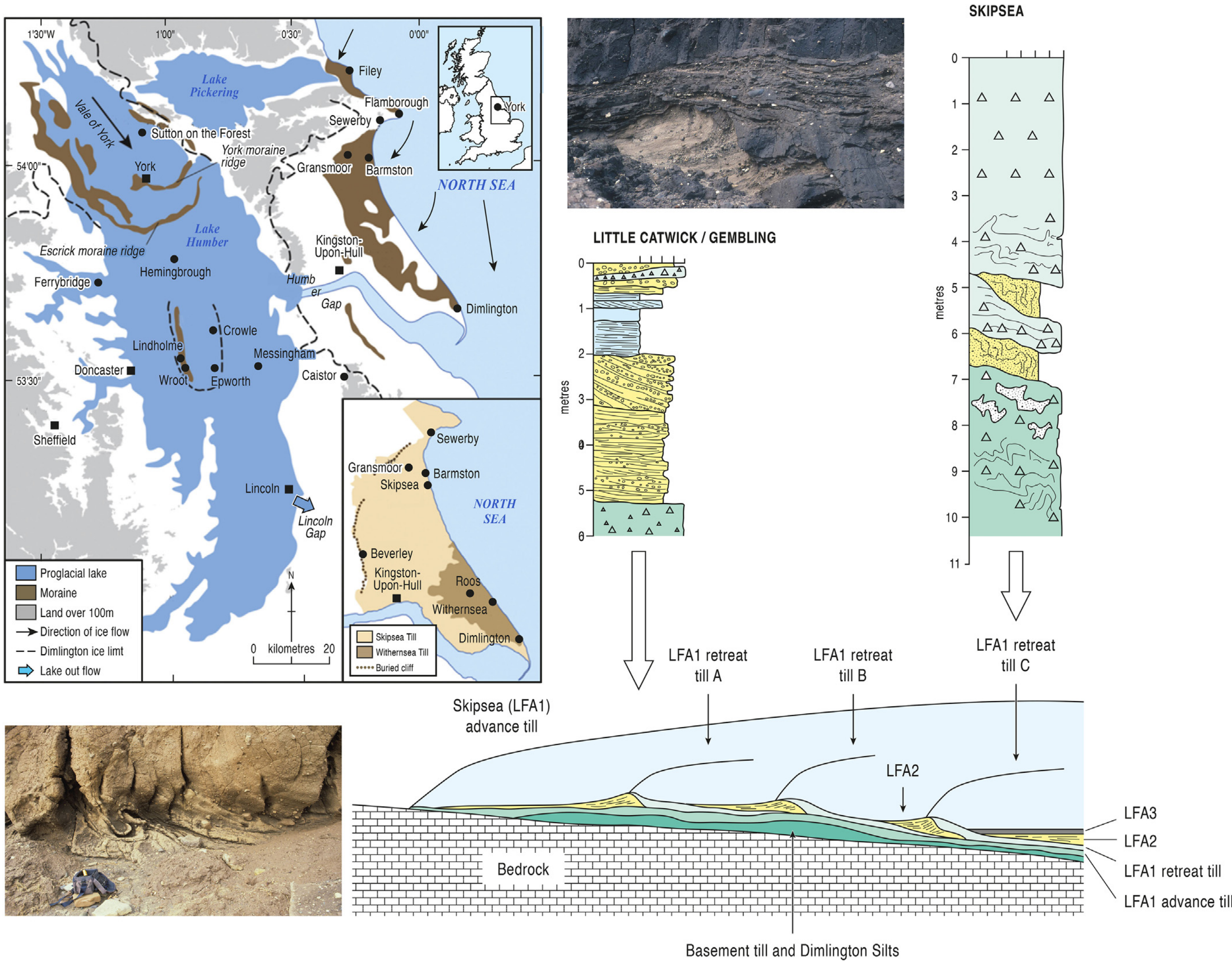


Fig. 1. Location maps and pertinent glacial geomorphological and stratigraphical information. The Dimlington Stadial ice limit is demarcated by the extent of the Skipsea and Withernsea tills and major morainic topography (after Bateman et al., 2015). The idealised stratigraphical cross profile is based on the deposits of the Holderness lowlands (after Evans and Thomson, 2010) and depicts the typical depositional scenario for the region in which localised subaqueous grounding line fan deposits (LFA 2), laterally grading into subglacial canal fills, lie between Skipsea advance and retreat tills (LFA 1). This regional stratigraphy is exemplified by the Little Catwick/Gembling and Skipsea locations. Upper photograph exemplifies the glacitectonised upper boundary between LFA 2 and overlying canal fill deposits and LFA 1 retreat till (exposure is *ca.*, 2 m high). Lower left photograph exemplifies the crudely stratified and deformed nature of LFA 1 advance till, illustrated by the lower "Filey Till" at Filey Bay.

A thick sequence of multiple tills ("Purple Clays") capped the stratigraphy, although this too contained a large lens of "thick well-bedded gravels" in the north side of Filey Bay. Bisat (1940) entertained the notion that such complexity in the glacigenic deposits of the area recorded "minor oscillations" of the ice sheet margin.

Later depositional models explaining the genesis of the morainic topography and associated glacigenic deposits proposed the widespread occurrence of subglacial deformation and onshore accretion of fine-grained subglacial materials by the North Sea Lobe. Important sedimentological characteristics of the glacial deposits in the region are the multiple (stacked) matrix-supported diamictons and intervening stratified lenses, representative of a spatial and temporal subglacial till mosaic of deformation and sliding bed facies (Eyles et al., 1982; Boulton and Dobbie, 1993, 1998; Evans et al., 1995). Additionally, it has been proposed that proglacial and sub-marginal glacitectonic disturbance and cannibalization of glacilacustrine deposits, laid down in front of the advancing and oscillating ice sheet margin, provided significant volumes of material for glacitectonite and diamicton production and consequent moraine construction. This is reflected in the stratified sand and gravel cores of extensive areas of the Holderness moraine ridges where subaqueous/grounding line fans have been partially overridden by an oscillating ice margin (Boston et al., 2010; Evans and Thomson, 2010) (Fig. 1).

This depositional setting is common around the margins of the former late Quaternary BIIS where ice lobes moved onshore, often oscillating and forming dammed proglacial lakes against the rising topography inland. This was accompanied by the production of thick drift sequences comprising folded and thrust stacked glacitectonites. Stratigraphically, such deposits have traditionally been classified as "tills" because they represent the geologic-climatic unit that documents glaciation. However, more intensive sedimentological investigations on such sequences have yielded significantly more information on glacial depositional processes, facilitating a greater understanding of the genesis of these deposits and their significance for palaeo-ice sheet dynamics (*e.g.*,Ó Cofaigh and Evans, 2001; Evans and Ó Cofaigh, 2003; Thomas et al., 2004; Thomas and Chiverrell, 2007; Evans and Thomson, 2010; Roberts et al., 2013). An important research question that arises is how can such substantial thicknesses of "till" (*i.e.*, tens of metres) be generated when modern analogues indicate that only modest (<1.5 m) thicknesses of subglacial traction till are formed beneath glaciers (Boulton and Hindmarsh, 1987; Evans et al., 2016, 2018; Evans, 2018). Existing models of regional till architecture (*e.g.*,Boulton, 1996a, 1996b; Eyles et al., 2011) explain till thickening as an ice-marginal process where subglacial materials are advected towards a marginal depositional zone, away from an up ice erosional zone. This results in the formation of a sub-marginal thickening wedge (advance and retreat tills; Fig. 1), with ice-marginal stability resulting in the stacking of such wedges and the production of abnormally thick till sequences/composite push moraines comprising individual till units of only modest (<1.5 m) thickness (*e.g.*, Evans et al., 2016, 2018). This is supported by both modern process observations (Evans and Hiemstra, 2005; Johnson et al., 2010) and numerical modelling (Leysinger-Vieli and Gudmundsson, 2010). Such tills are the products of squeezing and flowage (extrusion) and/or sub-marginal freeze on driven by seasonal cycles (Krüger, 1993, 1994, 1996; Matthews et al., 1995; Evans and Hiemstra, 2005). Alternatively, a more instantaneous construction process could be the bulldozing, folding and stacking of proglacial materials by surging, particularly in subaqueous settings (Drozdowski, 1987; Sharp, 1988; Ingólfsson et al., 2016; Kristensen et al., 2009). Such a concept was applied to the East Yorkshire setting by Lamplugh (1911).

At Filey Bay on the East Yorkshire coast, cliffs comprising over 40 m of horizontally layered, multiple diamictons and associated stratified sediments (Fig. 2) represent the localised thickening of deposits within the Holderness/Flamborough Head coastal moraine belt (Bisat, 1940; Farrington and Mitchell, 1951), constructed at the onshore flowing margin of the North Sea Lobe of the BIIS (Eyles et al., 1994; Evans and Thomson, 2010; Evans et al., 2021). Although the interaction of subglacial to sub-marginal processes with Glacial Lake Humber to form a moraine belt and its associated Skipsea and Withernsea tills is well documented (Fig. 1) (Eyles et al., 1994; Evans et al., 1995; Evans and Thomson, 2010), the origin of the unusually thick "Filey Till" on the north side of Filey Bay has received less attention. Despite the earlier descriptions by Bisat (1940) of complex glacigenic deposits in this area, Edwards (1981) identified only two tills, correlating them with the Skipsea and Withernsea tills, even though the latter does not occur north of Hornsea (Fig. 1) (Catt, 1991; Eyles et al., 1994). The complexity of the stratigraphy here was further conveyed by Evans et al. (1995), who identified two lithofacies associations (LFA), comprising diamictons LFA 1a (massive) and 1b (pseudo-laminated) and intervening stratified sands and gravels LFA 2. Beneath the deposits, the bedrock that controls the promontory of Filey Brigg comprises relatively flat lying Jurassic limestones, the upper few metres of which are highly fractured and contorted and appear to have been periglacially and/or glacitectonically disturbed by complex, southwest verging overfolds and sheath folds. Data published by Evans et al. (1995) are used here to augment a more detailed sedimentological investigation. The genetic interpretation proposed for the Filey Bay stratigraphic sequence by Evans et al. (1995) entailed a subglacial deforming-sliding bed mosaic environment beneath the former North Sea Lobe, a scenario that is now re-visited based upon further field investigations designed to address the problem of the formation of abnormally thick till sequences in the ancient sedimentary record.

Fig. 2. Example of the exposures of glacigenic deposits in Filey Bay, represented by the Filey Brigg cliff. Corallian Limestone bedrock forms the marine platform and outcrops in the basal few metres. Note the horizontal strata that represent stratified sediments between diamictons.

In summary, the primary aim of this study is to explain the former depositional processes and environments associated with the accumulation of abnormally thick and partially stratified glacigenic deposits, traditionally classified as the terminal moraine and till demarcating the onshore extent of the North Sea Lobe of the last BIIS. This involves a critical evaluation of site-specific and regional sedimentology in the context of the stratigraphic architecture that has been predicted by ice sheet scale models of migrating till depositional zones (Boulton, 1996a, 1996b). Previous refinements of such models have been necessary in settings similar to Filey Bay, where ice sheet lobes have moved onshore and dammed local drainage and hence their former margins are recorded by abnormally thick packages of sub-marginal tills and associated subaqueous fans arranged in inset, partially overprinted landform—sediment assemblages (*e.g.*,Evans and Ó Cofaigh, 2003; Thomas et al., 2004). A secondary aim is to evaluate the notion that the complexity of the glacigenic deposits in the Filey Bay area records ice sheet marginal oscillations that may be reconciled with the wider regional stratigraphy.

2. Methods

The exposures in Filey Bay are located in the coastal cliffs in the north corner of the bay and extending onto the peninsula known as Filey Brigg (centred on 54° 13′ 05″ N, 00° 16′ 31″ W). They were recorded in scaled section sketches which included information on primary sedimentary structures, bed contacts, sediment body geometry, sorting and texture and macroscopic deformation structures. These characteristics were then used to classify lithofacies types and to allocate facies codes following the procedures of Evans and Benn (2021). The previously published vertical profile log for north Filey Bay (Filey Brigg; Evans et al., 1995) was also used, augmented by new observations and data collected during this study. Conversion of the lithofacies to architectural elements followed and further developed the scheme of Boyce and Eyles (2000), as this is designed to capture the common characteristics of complex glacigenic sequences comprising deformed material (glacitectonites), multiple diamictons and their associated stratified interbeds. The architectural element classifications in the Boyce and Eyles (2000) scheme are DE (diamicton element), I-c (coarse interbed) and I-f (fine interbed) and DZ (deformed zone).

Clast macrofabrics were measured on samples of 50 clasts from the diamictons using the dip and azimuth (orientation) of the A-axes of clasts, predominantly in the range of 30–125 mm (A-axis length), based on the principle that clast A-axes will tend to rotate to parallelism with the direction of shear in a Coulomb plastic medium like till (*cf*., March, 1932; Ildefonse and Mancktelow, 1993; Hooyer and Iverson, 2000; Benn and Lukas, 2021). A-axis orientations and dips were then plotted on Schmidt equal-area lower hemisphere stereographic projections using the spherical Gaussian weighted method in Rockworks™. Contouring of these stereoplots represents standard deviations from the mean. Statistical analysis of the macrofabrics was undertaken using eigenvalues (S1, S2 and S3), based on the degree of clustering around three orthogonal vectors (V1, V2 and V3), presented in fabric shape ternary diagrams (Benn, 1994; Benn and Lukas, 2021). This identifies end-members as being predominantly isotropic fabrics (S1 ~ S2 ~ S3), girdle fabrics (S1 ~ S2»S3) or cluster fabrics (S1»S2 ~ S3), allowing visual categorisation of samples according to their isotropy and elongation. The fabric shapes are then compared to those of deposits of known origin, specifically lodged clasts, glacitectonites, subglacial A and B horizon tills and sediment gravity flows as well as laboratory generated shear strain signatures (Benn and Evans, 1996; Evans and Hiemstra, 2005; Iverson et al., 2008; Evans et al., 2018; Benn and Lukas, 2021) in order to guide genetic interpretations of the enclosing materials.

Samples for microstructural analysis were collected as monoliths (10 × 10 cm) that were detached from the stratified diamicton in the lower part of the section face. The location, orientation, depth and way-up of the sample were marked on the sample during collection so that kinematic indicators (Passchier and Trouw, 1996; van der Wateren et al., 2000; Phillips et al., 2007), such as the sense of asymmetry of folds and fabrics, as well as the sense of displacement on faults, could be established and used to provide information on the former stress regime. It is important that the orientation of the samples relative to the presumed direction of ice-push is established, as only a thin section cut parallel to this principal stress direction will exhibit the most complete record of deformation and its intensity. Sample preparation involved the initial replacement of porewater by acetone, which was then progressively replaced by a resin and allowed to cure. The thin sections were examined using a standard Zeiss petrological microscope. High-resolution digital scans of the thin sections have been used to analyse the clast microfabrics (coarse silt to small pebble) developed within the diamictons, following protocols outlined in Phillips et al. (2011). The grain long axis orientation data collected are plotted on a series of rose diagrams using the commercial software package StereoStat by Rockworks™ (see Phillips et al., 2011 for details).

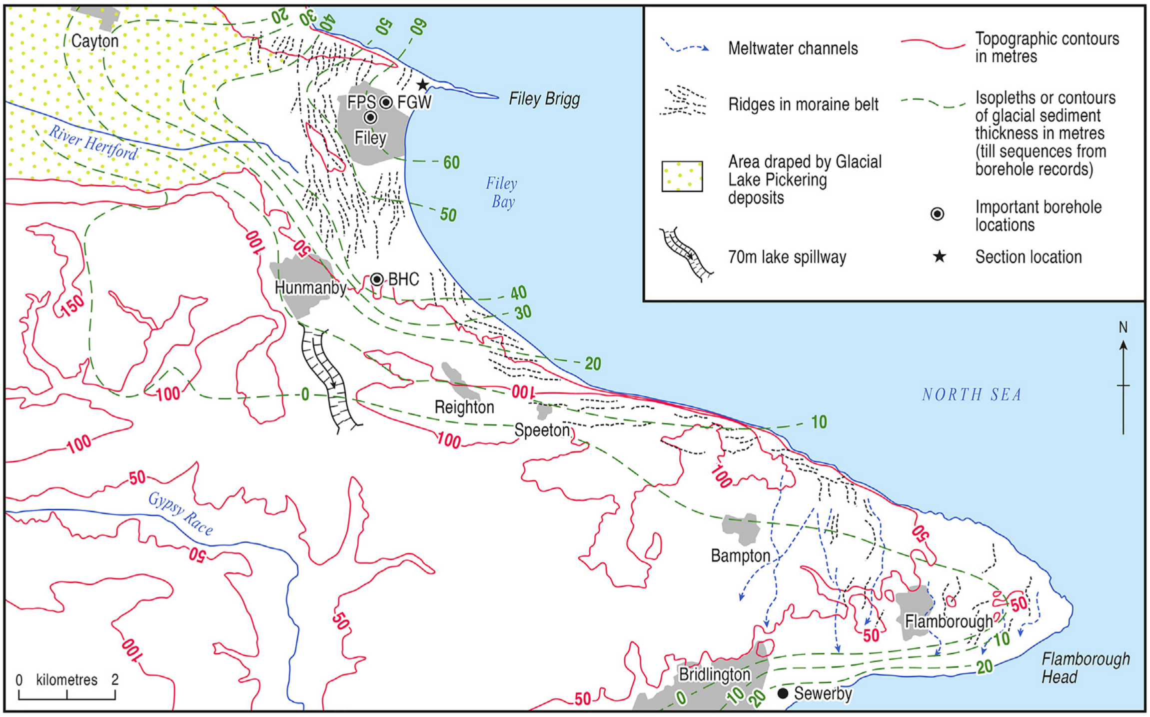
In order to place the outcrop sedimentology into a broader geographical context, the borehole records held by the British Geological Survey were consulted and used to compile contours of drift thickness and to assess the nature and extent of complex glacigenic depositional sequences in the Filey Bay area. The high-resolution topography of the Flamborough Moraine in this area was also characterised using the available Environment Agency LiDAR imagery (https://houseprices.io/lab/lidar/map).

3. Geomorphology and sedimentology of the Filey Bay glacigenic deposits

3.1. Glacial geomorphology and borehole stratigraphies

The hummocky terrain that constitutes Farrington and Mitchell's (1951) "Flamborough Head moraine" and Valentin's (1957) "Speeton moraine" (also named "Filey moraine" and "Cayton-Speeton" moraine; Eddey et al., 2022) is a 2–5 km wide coastal belt, stretching from Sewerby in the south to Cayton in the north, that records the onshore advance of the North Sea Lobe during the Dimlington Stadial of the last glaciation (Fig. 1 & Fig. 3a). It blocks the easterly flow of the inland drainage, most significantly that of the Vale of Pickering, where Glacial Lake Pickering was created at the time of moraine construction and existed from around 24–18 ka (Evans et al., 2021). Reconstructions of the depth and extent of the lake vary. A 70 m OD level, draining through a 70 m spillway in the outer edge of the moraine belt near Hunmanby, King's (1965) Hunmanby Dale channel, has been proposed for the last glaciation by Kendall (1902) and Evans et al. (2017). In contrast, a pre-last glaciation age has been proposed for this high lake level by Eddey et al. (2022), even though Hunmanby Dale is not even partially plugged by sediments, as would be expected if it had been incised prior to the last glaciation. A 29–35 m channel between Flotmanby and Filey has been related to drainage from a lower 30 m lake level during ice recession from inner Filey Bay (Evans et al., 2017). High-resolution LiDAR images reveal that the hummocky terrain of the moraine belt in places displays a series of inset linear ridges that are sub-parallel to the topographic contours and the coast (Fig. 3b). These are particularly well-developed on the terrain immediately west of the Filey town but are recognisable along the whole of the moraine belt (Fig. 3a).

Data retrieved from the British Geological Survey borehole archive facilitated the mapping of superficial (drift) thickness, particularly sediment sequences predominantly composed of diamictons (presumably till), which was then converted into isopleths. This reveals that superficial sediment (drift) thicknesses of up to 60 m occur around the Filey town and more than 40 m in the area inland of Filey Bay, extending up to 4 km westwards towards the Vale of Pickering (Fig. 3a). Three important boreholes are reproduced here (Fig. 4a) as representative of thick and complex sequences of diamicton (till) and associated stratified deposits. At Filey, 64 m and 55 m long boreholes obtained, respectively, in 1927 from the a



b

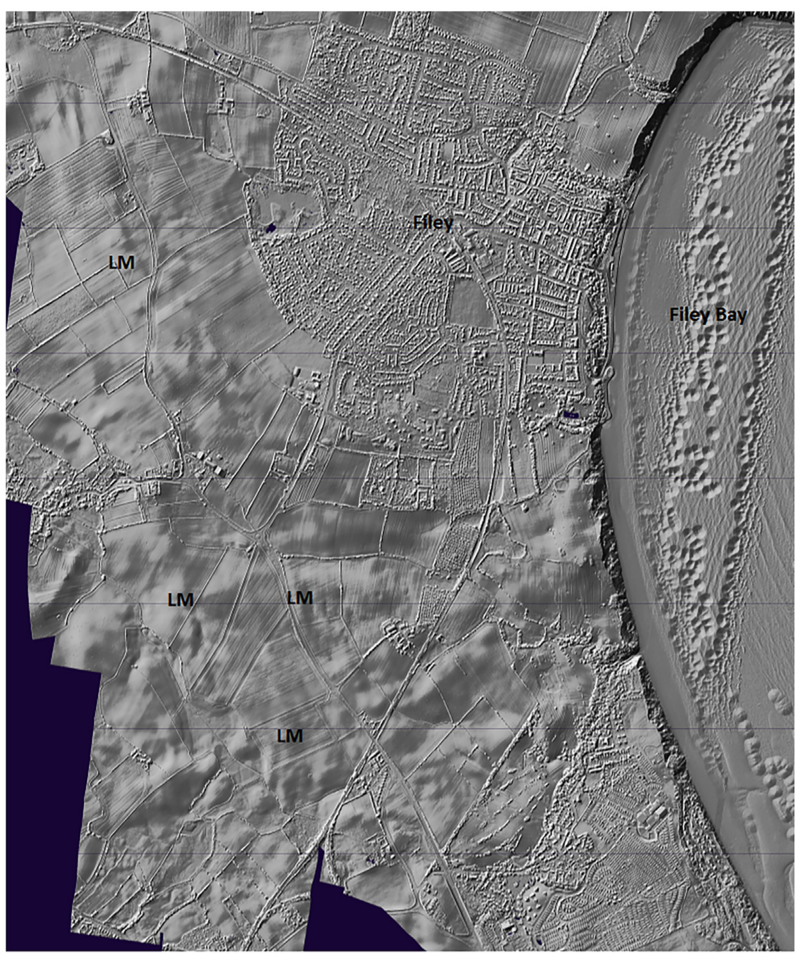


Fig. 3. Location map (a) of the Filey Bay area, showing topography, glacial sediment thickness and glacial landforms, and LiDAR image (b) of an area of the Flamborough Head moraine around the Filey town site, showing the patchy linearity of the hummocky morainic terrain. Linear moraine ridges stretch almost continuously from north to south on the left side of the image (examples marked LM). LiDAR extract from the Environment Agency. Image is 3 km across.

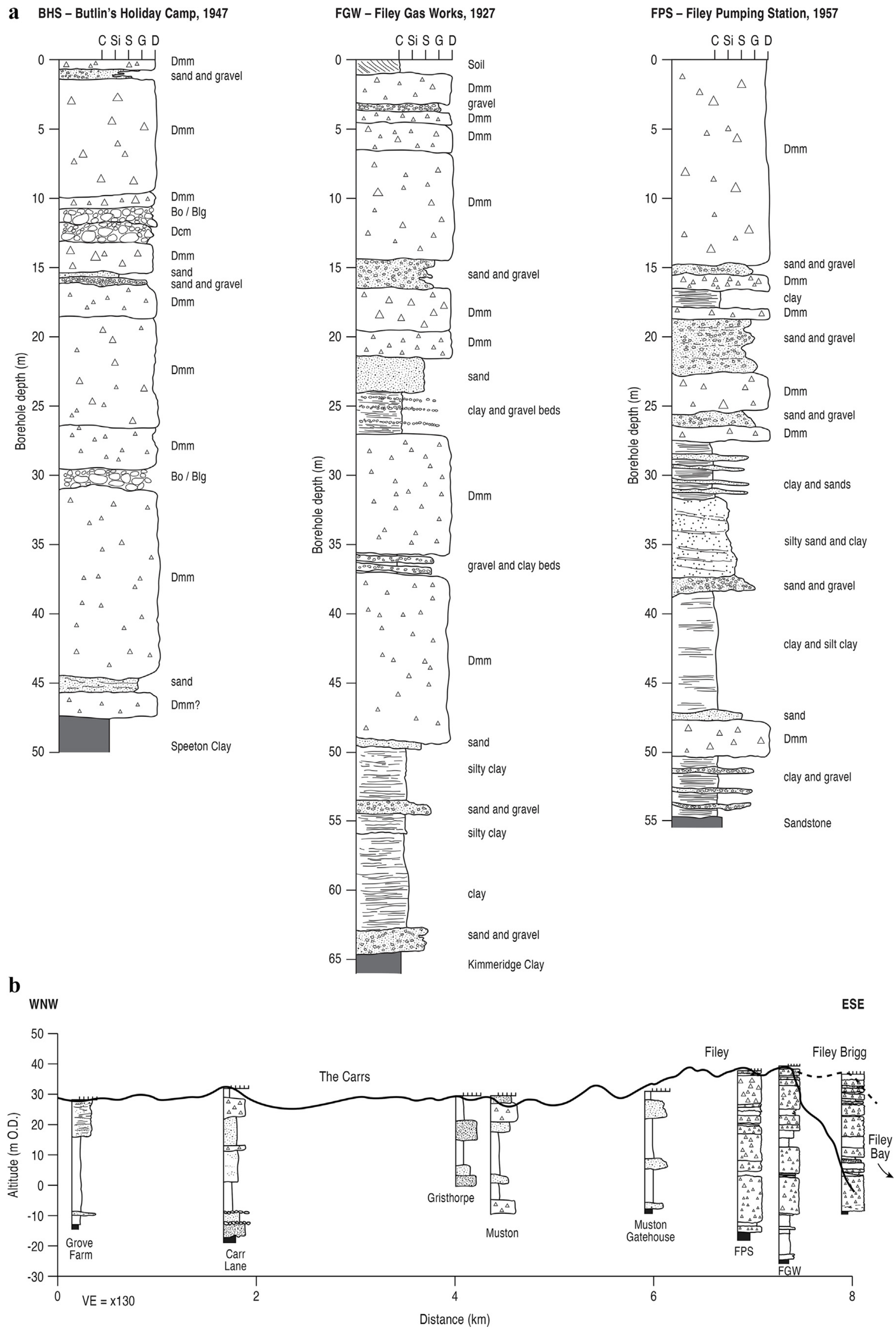


Fig. 4. Borehole records of the Filey Bay area, with lithofacies classifications interpreted from initial loggers records: a) details of three major boreholes (located in Fig. 3a) from the Filey town site; b) topographic cross profile from Filey Bay to the east end of the Vale of Pickering with details of major boreholes, including those of the Filey town site. Diamictons are identified by triangle symbols. Rockhead is identified by the basal black colour coding on all logs except Gristhorpe and Muston. BGS borehole numbers = 460,519 (Grove Farm); 460,484 (Carr Lane); 460,458 (Gristhorpe); 460,460 (Muston); 460,464 (Muston Gatehouse); 464,063 (FPS); 464,062 (FGW).

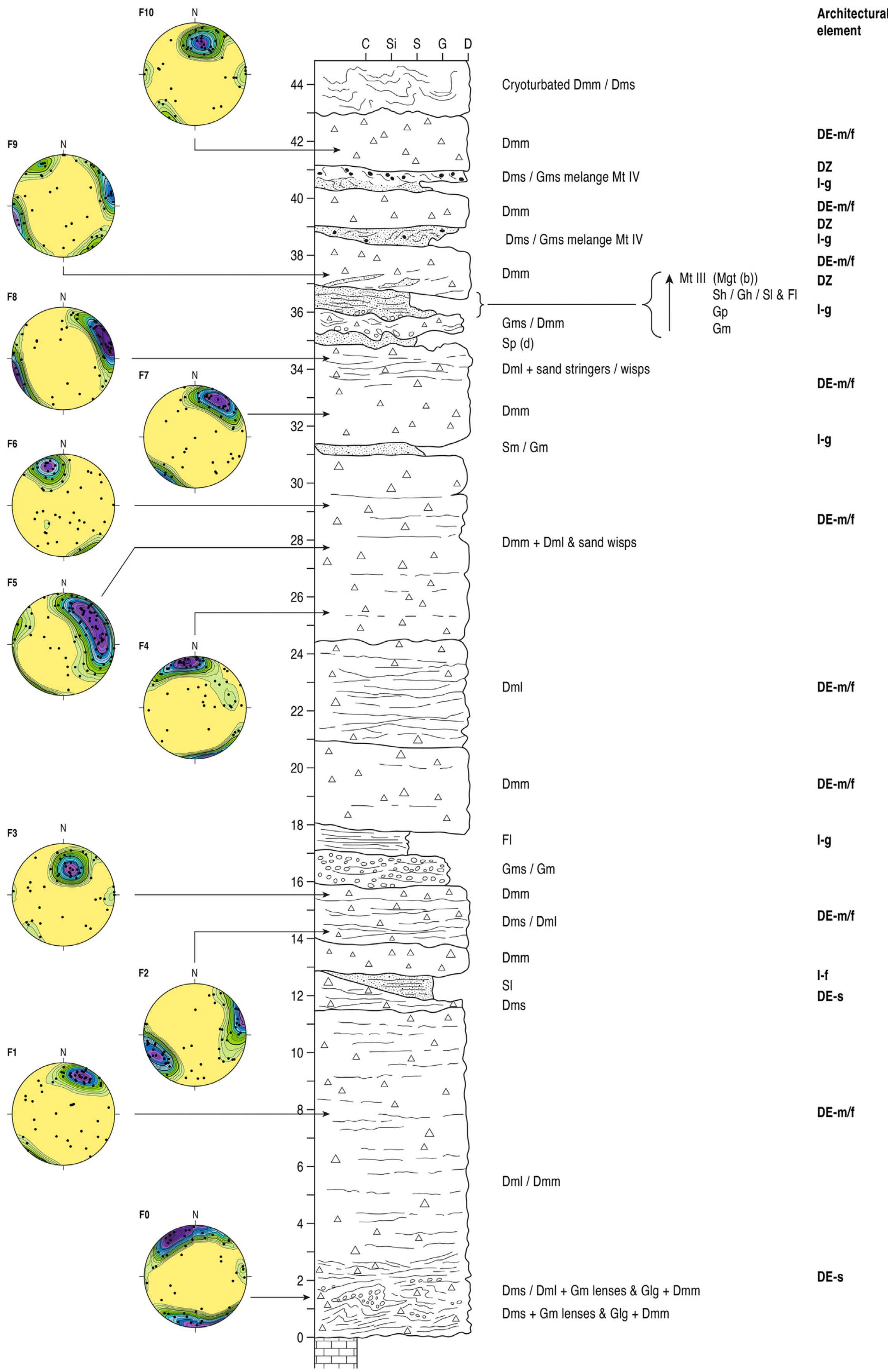


Fig. 5. Vertical profile log for north Filey Bay/Filey Brigg with associated clast macrofabric data. (After Evans et al., 1995).

former gas works (FGW; BGS no.464062) and in 1957 from the water pumping station (FPS; BGS no.464063), penetrated multiple massive, matrix-supported diamictons (Dmm; reported at the time as "boulder clays" or "clays with stones"), each one ranging from 0.8 to 15 m thick. These were mostly separated by stratified deposits, but at the top of the FGW borehole there were two uninterrupted sequences comprising two and three diamictons. The thickness of the stratified deposits ranges from 0.5 to 20 m, but the thickest units occurred towards the base of the boreholes; at FGW this comprised 15 m of apparently laminated or rhythmically bedded sands, silts and clays with minor sand and gravel beds, and at FPS it comprised 27.5 m of similar deposits sub-divided into two units by 2.5 m of diamicton (Fig. 4a).

A further 47 m long borehole collected in 1947 from the former Butlins Holiday Camp (BHC; BGS no.463993) near Hunmanby contained multiple diamictons (Dmm/"boulder clays") which dominated the sequence, with individual units ranging from 0.5 to 13.5 m thick. Intervening stratified deposits were less prominent in this borehole, comprising ≤1.2 m thick beds of openwork boulders or lags (Bo/Blg), clast-supported, massive diamicton (Dcs) or ≤1 m thick beds of sand and gravel.

In order to place the borehole records of the Filey area into context with the stratigraphy of the drift covered terrain at the eastern end of the Vale of Pickering, a topographic transect from Filey Brigg to Grove Farm is presented in Figure 4b that depicts the stratigraphy of the boreholes located along the line of the transect. This shows that the multiple diamictons and intervening stratified deposits of the Flamborough Head moraine in Filey Bay are gradually replaced in the lower topography of the eastern Vale of York by waterlain deposits. These mainly comprise fine-grained clays, silts and sands, with intervening gravel units which in places appear to be lags in otherwise fine-grained sequences. Such fine-grained sequences are also prominent at the base of the Filey Gas Works and Pumping Station borehole logs, constituting an increasingly thicker sequence in a westerly direction (Fig. 4a). Further west, diamictons appear only towards the base and top of the sequence in the Muston borehole and at the top and middle of the succession at Carr Lane, both settings being coincident with mounds on an otherwise flat to slightly undulatory former lake plain.

3.2. Filey Brigg section

3.2.1. Macroscale description

The stratigraphic sequence and associated clast macrofabric data, as originally logged by Evans et al. (1995) and here augmented by additional field data, are presented in the vertical profile log in Figure 5. The diamictons vary according to their macroscale appearance (Fig. 6), being either massive and matrix-supported with locally developed fissility (Dmm/Dmf; LFA 1a of Evans et al., 1995) or laminated to stratified (Dml/Dms; LFA 1b of Evans et al., 1995). Although some diamicton units appear to be entirely one or the other (Dmm/Dmf or Dml/Dms), there is internal variability and, hence, the LFA classifications of Evans et al. (1995) are removed here. Instead, it appears that, with the exception of the basal 11.5 m thick example, the diamicton units are 1.4–6.5 m thick and grade vertically from massive to laminated/stratified and then into subordinate but mostly laterally extensive stratified units (LFA 2 of Evans et al., 1995) of 0.4–2.0 m thick (Fig. 7 & Fig. 8) in a prominently horizontally stacked sequence (Fig. 2); some stratified units form convexo-planar lenses. In only one case, at 24.5 m, is there an absence of an intervening stratified unit. The stratified units comprise facies characterised by a range of grain sizes (Fig. 7), including massive and matrix-supported gravels (Gm, Gms; with minor Dms), cross-bedded sands and gravels (Sp, Gp) as well as horizontally bedded or laminated gravels, sands and fines (Gh, Sh, Sl, Fl). These mostly normal graded, fining-upward sequences are also deformed, best illustrated by the stratified units in the upper 10 m of the stratigraphy; where deformed they are classified as either Type III or Type IV mélange (*sensu* Cowan, 1985; Evans, 2018). The lamination within the diamictons is manifested in places as sand stringers and wisps, which appear to be highly attenuated intrabeds (*e.g.*, at 34 m) and/or intraclasts detached from underlying, deformed stratified units (*e.g.*, at 37 m; Fig. 6f); hence this is not depositional lamination *per se* but rather pseudo-lamination or banding (sensu Evans, 2018).

Stratification (S0) within the diamictons at Filey Bay is best developed within the basal 3 m (Fig. 9 & Fig. 10), where laterally extensive bedding and lenses occur and locally display prominent fold structures within the base of the thickest diamicton unit (11.5 m thick). The bedding here displays clear grain size partitioning, including abrupt switches at boundaries between matrix-supported diamictons and poorly-sorted, massive coarse gravels as well as gravel lags (Fig. 6b). The stratification (S0) dips at typically shallow angles (5°–25°) towards the north/northwest (Fig. 9c). Slight variation in the colour, grain size (occurrence of pebbles/cobbles) and relative intensity of the internal stratification facilitates the division of the basal diamictons into a number of laterally continuous to lenticular units separated by undulating to irregular erosive surfaces (Fig. 9a, b & Fig. 10). These erosion surfaces are locally marked by a thin, discontinuous layer of gravel/gravel lag or gravelly diamicton (Fig. 6b). Inclined surfaces within the stratified diamictons near the base of the section are thought to represent a primary (sedimentary) cross-stratification (Fig. 9a & Fig. 10a). Lamination is locally very strongly developed and contains lonestones beneath which laminae are displaced downwards, thereby indicating a dropstone origin (Fig. 6d, e).

The deformation of the layering within the stratified diamictons near the base of the section is characterised by a number of recumbent isoclinal folds (F1; Fig. 9d, e & Fig. 10) which locally result in the overturning of the stratification. The horizontal to very gently dipping axial surfaces of these folds appear coplanar to the stratification within the diamicton, with these "intrafolial" folds being confined to a single unit of stratified diamicton (Fig. 10). This suggests that folding was probably syn-sedimentary, occurring during or immediately after the deposition of the diamicton and prior to the accumulation of the overlying sedimentary sequence; this assumption is supported by the folds being truncated by the erosive base of an overlying massive diamicton (Fig. 10). Structural data obtained for these non-cylindrical, mesoscale folds indicate that they plunge at very shallow angles (2°–3°) towards the west and north-northeast (Fig. 9c), consistent with an overall sense of displacement towards the northwest. The curvilinear nature of the fold axial traces indicates that soft-sediment deformation was highly ductile in nature, possibly reflecting the water-rich nature of the sediments during folding. This is also indicated by the presence of an area of highly disharmonic folding, leading to a complex outcrop pattern of deformed matrix-supported gravel, gravelly diamicton and massive diamicton (Fig. 9d, e). The curved to arcuate axes of these open to tight, recumbent to gently inclined folds appear to record a sense of overturning into the cliff face and towards the west/northwest, compatible with the overall sense of shear recorded by the structurally underlying isoclinal folds. A clast macrofabric (F0) from the basal stratified diamicton (Fig. 5) displays a girdle distribution with a mean lineation azimuth of 353° and S1 eigenvalue of 0.53, compatible with the northwesterly sense of displacement in the structural data and stratification (S0) dip direction.

Clast macrofabrics from the diamictons lying above the basal stratified and folded 3 m of material at Filey Bay (F1–10, Fig. 5) reveal reasonably consistently orientated clast A-axes alignments dipping predominantly: 1) northwards/north-northeastwards (F1, 3 & 10); 2) northeastwards/east-northeastwards (F5, 7, 8 & 9); and 3) north-northwesterly (F4 & 6). Fabric F2 displays a bi-modal ENE-WSW alignment. Clast macrofabric shapes (Fig. 11) resemble those of Icelandic subglacial traction tills, with no indications of the particularly strong clustering typical of tills that comprise high proportions of lodged clasts. The weakest fabrics, F6 and F9, are related to highly variable clast dips and high girdling, respectively, with F9 being

Fig. 6. Sedimentary details of the diamictons at Filey Brigg: a) crude stratification with lenses of poorly-sorted gravel; b) stratified diamicton with thin, discontinuous layers of gravel and gravel lags; c) massive to fissile Dmm; d) and e) crudely stratified to laminated diamicton, containing lonestones and downward displaced laminae (dropstones) indicated by finger; f) glacitectonically deformed contact between sand and gravel lens and overlying Dmm, whereby sand stringers and wisps have been dragged upwards into the diamicton.

derived from within a basal zone of a Dmm with densely spaced and attenuated sand lenses rooted in an underlying, deformed stratified lens.

3.2.2. Microscale description (basal stratified unit 0–3 m)

Four samples of the stratified and folded diamicton (TS/Dms1–4; Fig. 12) and three samples of the adjacent, subordinate massive diamicton (TS/Dmm1–3; Fig. 12b) were collected from the base of the section between 1.5 and 2 m (Fig. 9) in order to examine the composition, texture and microscale deformation structures present within these contorted and largely stratified deposits.

The stratified diamicton is composed of thin alternating, irregular, lenticular to wispy layers of silty diamicton, silt and sand (Fig. 12). The boundaries between the layers are typically sharp and range from gently undulating to highly irregular in form. The sand layers are typically matrix-poor and largely composed of angular to subangular, low to moderate sphericity grains of monocrystalline quartz with minor feldspar and polycrystalline quartz (Table 1). The diamicton layers are lithologically similar to the massive diamicton described above, comprising angular to subangular, medium sand to small pebble sized clasts composed of sedimentary (mudstone, siltstone, limestone) and igneous (basalt) rock fragments (Table 1) within a finer silty matrix. The presence of angular mud/silt intraclasts indicates that deposition of the stratified diamicton was accompanied by minor reworking of pre-existing sediments. Although stratified, no obvious grading, cross-lamination or other sedimentary structures have been recognised. Thin irregular veinlets of sand and sandy silt cross-cut the diamicton (Fig. 12i and iii) suggesting that these sandy sediments have undergone

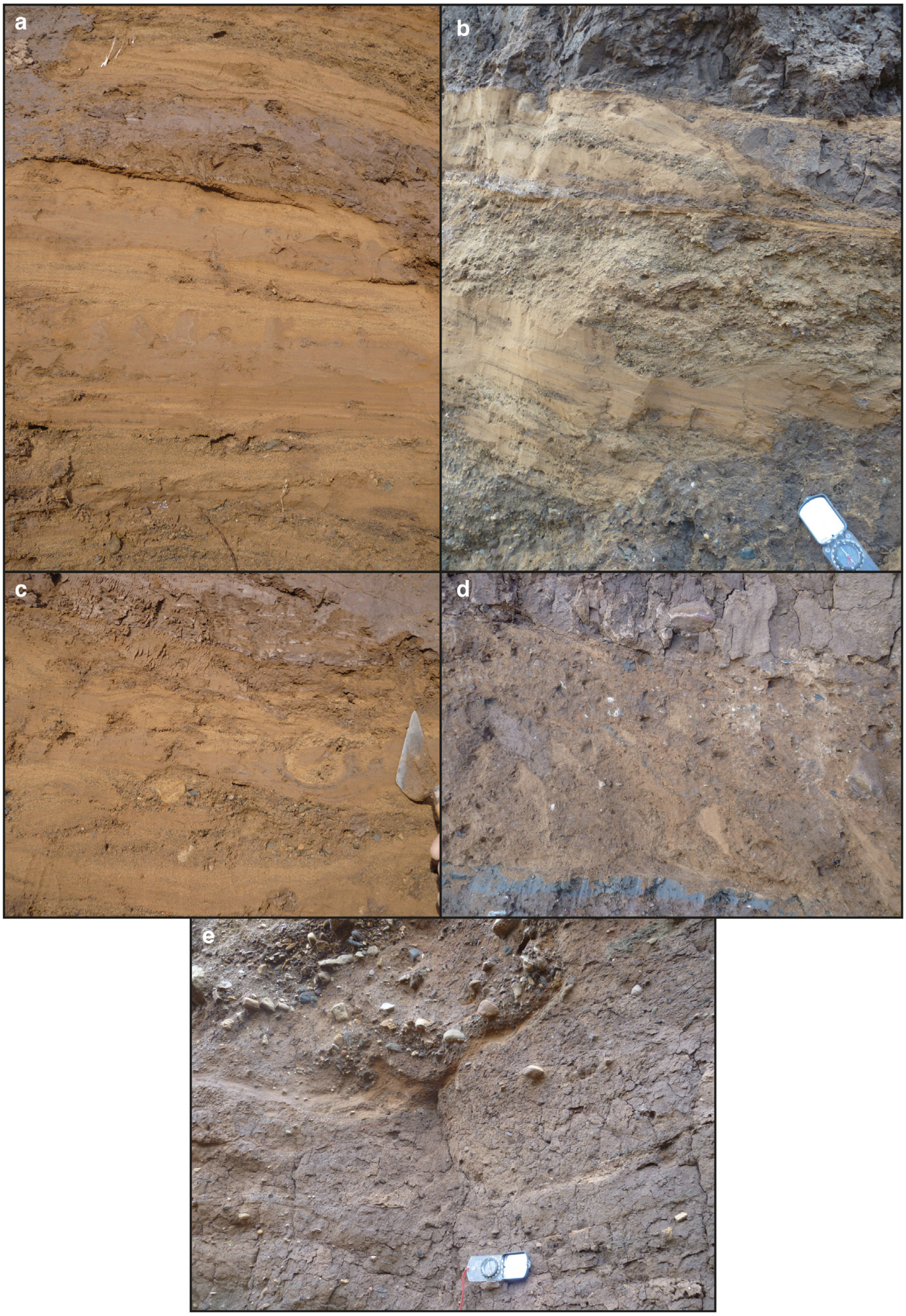


Fig. 7. Sedimentary details of the stratified lenses between diamictons at Filey Brigg: a) horizontally bedded sands and fine gravels, with pebble gravel lags and lenses, fining upwards to laminated sands, silts and clays, with minor components of horizontally bedded sands and rare gravel lenses. Note also the load structures developed in the upper beds of clay-rich laminae; b) stratified sand and gravel sequence within a convexo-planar, inter-diamicton lens. Above the scoured base, horizontally bedded, medium to coarse gravels grade upwards into cross-bedded to horizontally bedded coarse sands with gravel lenses, which are scoured and filled by cross-bedded sandy gravel, coarsening upwards into massive to crudely cross-bedded coarse pebble to cobble gravels. This is truncated by a complex mélange zone containing boudins, tectonic lamination and wisps of diamicton surrounded by shear attenuated bodies of cross-stratified sands and gravels, which in places also display boudins. Note also the occurrence of sand wisps in the base of the overlying diamicton; c) crudely horizontally bedded to laminated sequence of coarse to fine sands, silts and clays interrupted by poorly-sorted gravel scour fills and lenses. Note also ball and pillow type soft sediment deformation structures; d) Type III–IV melange between two diamictons, comprising matrix-supported gravel with minor sand and clay boudins and displaying crude open folds; e) deeply-incised scour in diamicton and filled with sand, matrix-supported gravel, gravelly diamicton and poorly-sorted openwork gravel. Note also gravel lags and synclinal bedding structures representative of scour infill.

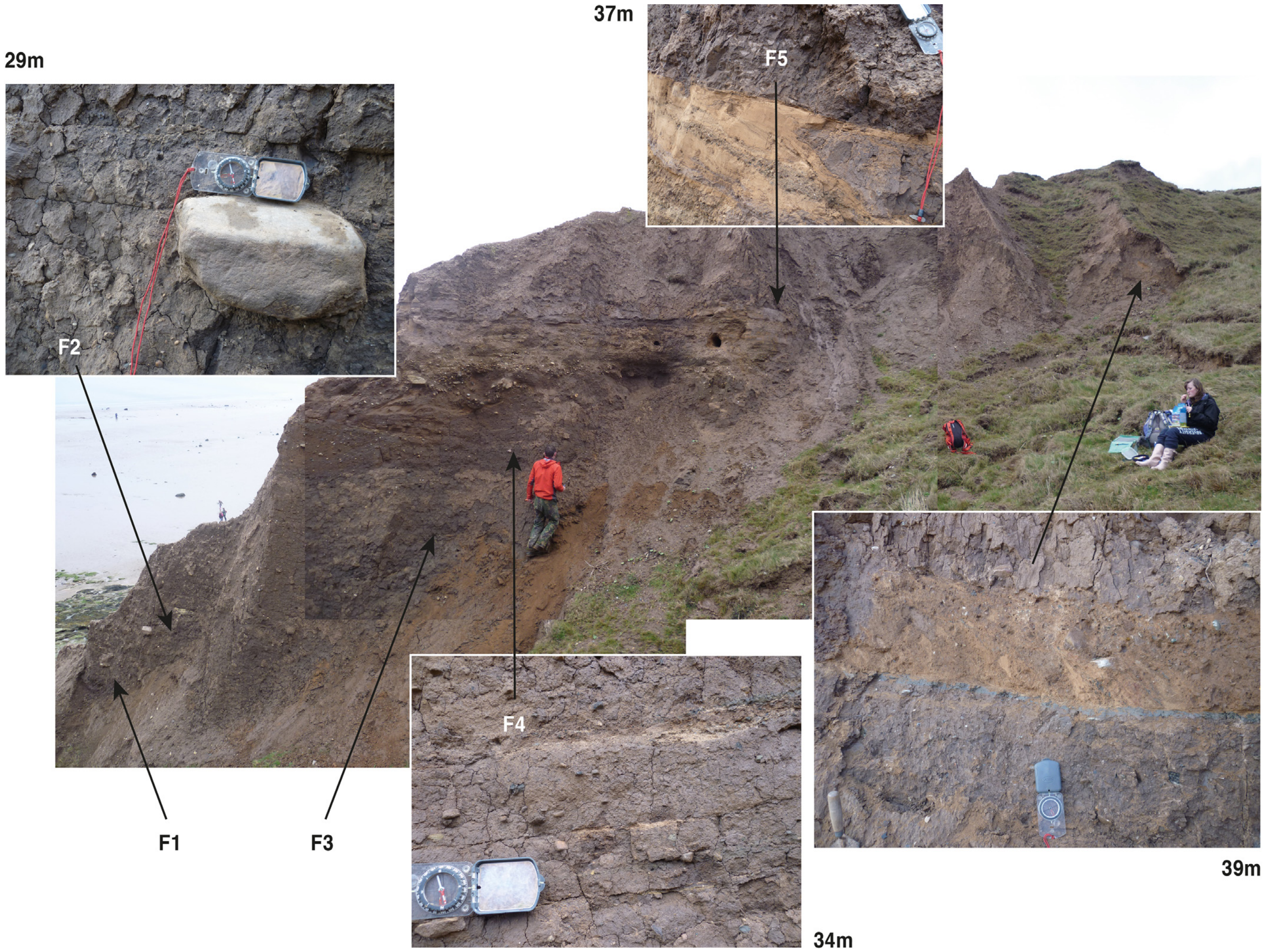


Fig. 8. Stratigraphic and sedimentological details of the upper 25 m of the Filey Brigg section, showing details of diamictons and intervening stratified lenses and intrabeds/wisps, as well as clast macrofabric locations F1–5.

localised liquefaction, remobilisation and injection. At low magnification, the stratification in samples TA/Dms1, 3 and 4 is locally offset by a number of moderate to gently dipping extensional faults (Fig. 12i, iii & iv). The amount of displacement accommodated by these small-scale normal faults is typically in the order of a few millimetres. At higher magnifications the individual fault planes appear diffuse with no clear associated dislocation surface or obvious deformation (plasmic fabric, cataclasis).

The massive diamicton is poorly sorted and comprises coarse sand to small pebble-sized clasts within a fine silty red-brown matrix (Fig. 12b). The absence of a plasmic fabric within the matrix may reflect either a lack of clay minerals and/or the presence of finely disseminated carbonate. No obvious sedimentary structures (*e.g.*, graded bedding) or deformation structures (*e.g.*, folds, faults, plasmic fabrics, rotational structures) can be seen. The larger clasts are typically angular to subangular in shape and composed of sedimentary (siltstone, mudstone, sandstone, limestone) and igneous (basalt, microgabbro, granite) rock fragments (Table 1), with the more elongate clasts locally showing a preferred shape alignment defining a variably developed clast microfabric (compare Fig. 12bi and ii). Occasional subrounded clasts were also noted, including broken fragments of larger pebbles, indicating that the sediment is polycyclic in nature. The fragments of the clastic sedimentary rocks show varying degrees of alteration/replacement by carbonate. Low to moderately spherical and typically angular to subangular silt to fine sand grains within the matrix of the massive diamicton are mainly composed of monocrystalline quartz with minor amounts of polycrystalline quartz, feldspar, calcite/dolomite (Table 1).

The range of sedimentary rock fragments within both the stratified and massive diamictons (Table 1) is consistent with the bedrock geology of the Filey area, which is dominated by the Late Jurassic mudstones, siltstones and sandstones, suggesting that the debris being incorporated into the diamictons was locally sourced. However, the basaltic to doleritic igneous rock fragments possibly represent more far-travelled detritus from the Paleogene and Permo-Carboniferous dykes and sills which crop out along the coast of Tyneside and Northumberland farther to the north. The rare appearance of shell fragments (foraminifera, gastropods and possible *Gryphaea*) reflects an offshore source for at least part of the diamicton matrices and is consistent with macroscale observations of shell fragments in the Holderness glacigenic deposits (Catt and Penny, 1966; Eyles et al., 1994; Evans and Thomson, 2010).

Clast microfabrics within both the massive and stratified diamictons are relatively poorly developed (Fig. 12) reflecting either the relatively low intensity of soft-sediment deformation and/or their overall fine grain size making it difficult to define the long axes of the finer silt particles. Thin sections of the massive diamicton (TA/Dmm1–3; Fig. 12b) show a progressive increase in the relative intensity of the clast microfabrics, reflected in the development of a more pronounced

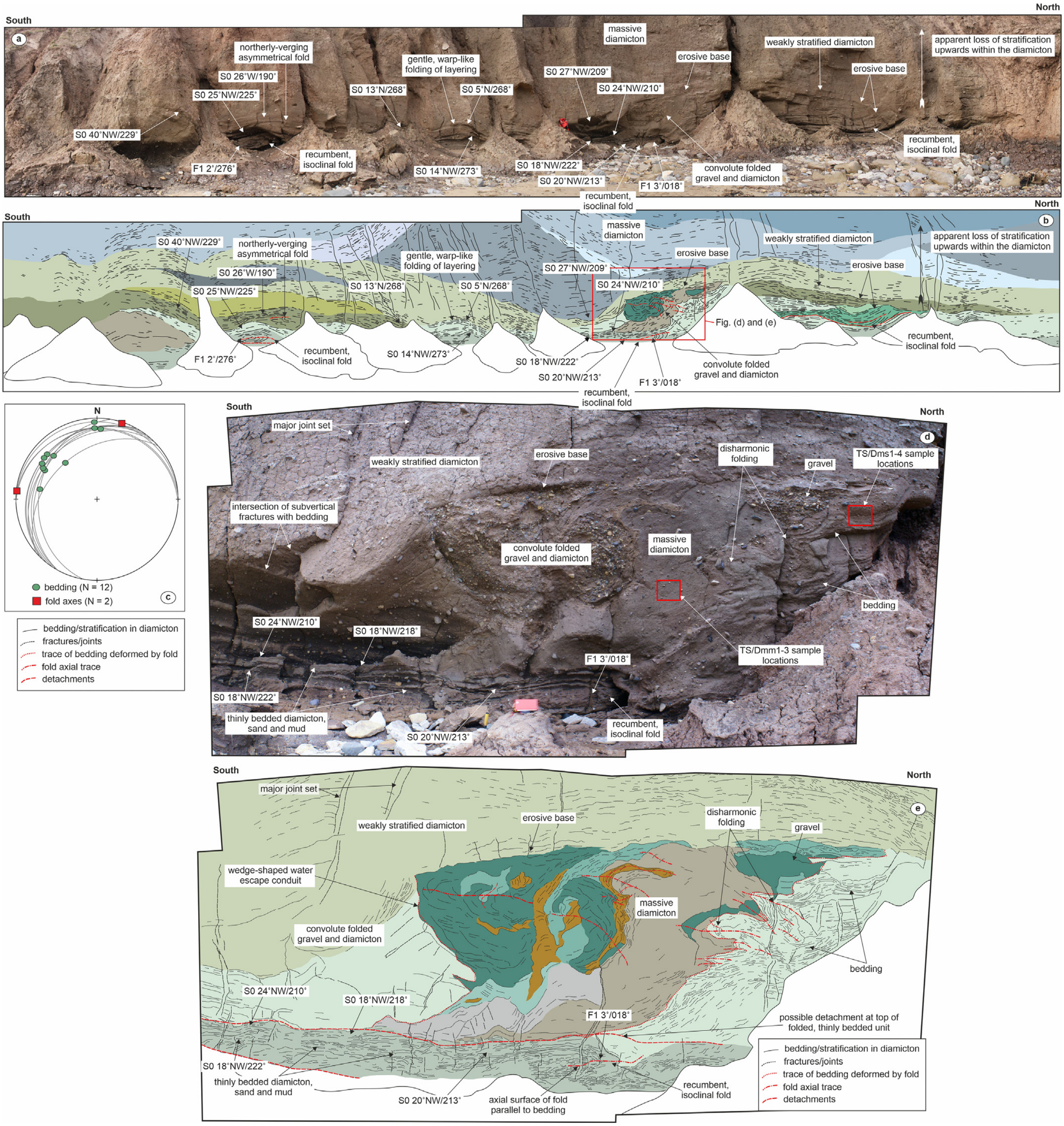


Fig. 9. (a) and (b) Photomontage and detailed interpretation of the lower, stratified part of the sequence exposed at Filey Brigg; (c) Lower hemisphere stereographic projection showing the plunge of folds and dip and strike of bedding (planes and dip/dip direction) within the stratified diamictons at the base of the sequence at Filey Brigg; (d) and (e) Photomontage and detailed interpretation of the complex soft-sediment deformation (disharmonic folding) observed within lower, stratified part of the sequence exposed at Filey Brigg (see text for details). Colour codings are used to visually differentiate areas of specific sedimentary and structural appearance within the basal, largely stratified diamicton (DE-s architectural element).

preferred orientation on the associated rose diagrams. Three microfabrics have been identified defined by relatively short microfabric domains (pale blue colour on Fig. 12b): (i) the dominant fabric is a gently to moderately inclined clast microfabric dipping at between 25° and 45°, with an average dip of *c.*, 30°; (ii) a less well-developed sub-horizontal foliation; and (iii) a weakly developed steeply dipping to sub-vertical clast microfabric. In TS/Dmm3, the microfabric domains defining the main foliation are arcuate, sigmoidal to irregular in form and locally define an asymmetrical S-shaped geometry with the sub-horizontal fabric (Fig. 12biii). Comparable microfabrics have been recognised within the stratified diamicton, where the gently dipping (*c.*, 30°) foliation occurs coplanar to the gently to moderately dipping normal microfaults observed within samples TS/Dms1 and TS/Dms3 (Fig. 12i and ii). This relationship is consistent with both sets of structures having developed in response to R-type Reidel (extensional) shear.

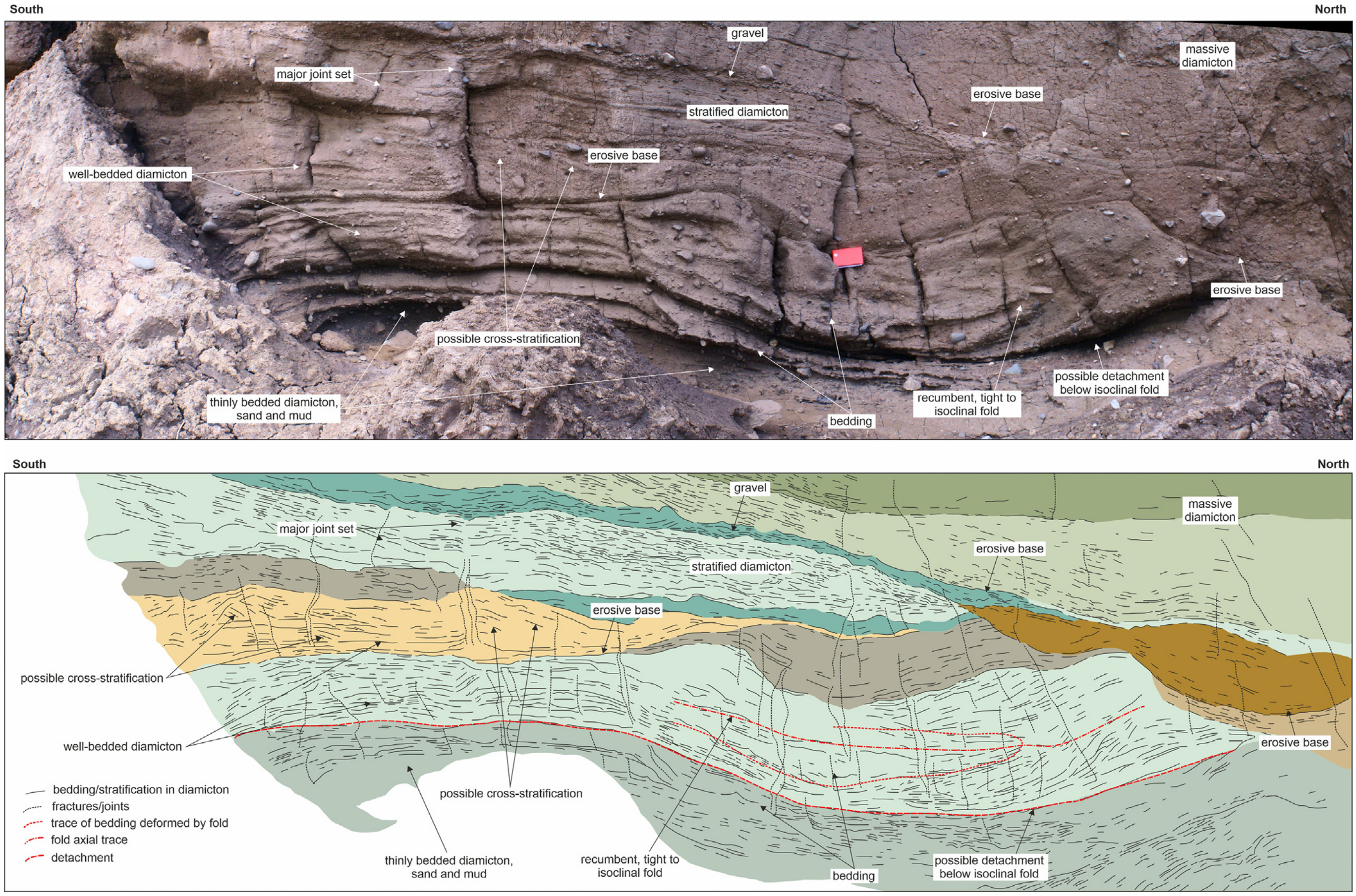


Fig. 10. Photomontage and detailed interpretation of the stratified diamictons and cross-cutting (erosional) relationships displayed between the diamictons forming the lower, stratified part of the sequence exposed at Filey Brigg. Also shown is a recumbent, tight to isoclinal fold within one of the stratified diamictons (see text for details).

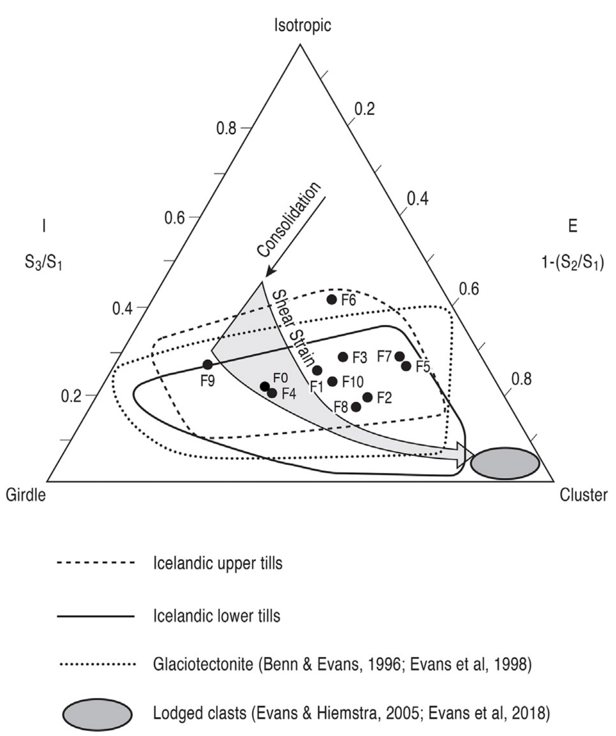


Fig. 11. Clast fabric shape ternary plot containing samples (black dots) from Filey Brigg and envelopes for deposits of known origin. Consolidation and shear strain indicators are from Iverson et al. (2008).

3.3. Interpretation

Interpretations are now organised according to scale, with the Filey Brigg section being analysed prior to the observations on regional borehole records and the wider geomorphology. Given the similarity in stratigraphic architecture to the deposits described and analysed using an architectural elements approach by Boyce and Eyles (2000), an adaptation of their classification is adopted herein.

The matrix-supported diamictons and poorly-sorted, massive coarse gravels and gravel lags that occur in the most prominently stratified diamicton in the basal 3 m at Filey Brigg clearly document subaqueous sedimentation. This resulted in the accumulation of a vertical sequence of laterally continuous beds or lenses, often displaying strong lamination and dropstones and separated by erosional boundaries, upon which gravel lags or gravelly diamictons record winnowing and/or scouring at the base of subaqueous sediment gravity flows. Similarly, the inclined surfaces within the stratified diamictons represent clinoforms that accumulated by the stacking of mass flows. The syn-sedimentary nature of the localised folding within the stratified diamictons indicates that repeated aggradation of sediment gravity flows took place within a rapidly accumulating sequence of subaqueous and/or highly water saturated deposits; the highly ductile nature of this soft-sediment deformation, especially the highly disharmonic folding, is consistent with a high-water content in the sediments during their disturbance.

The similar nature of the clast microfabrics within both the dominant stratified and subordinate massive diamictons exposed in the basal 3 m at Filey Brigg is summarised in Figure 12. This highlights: (i) a gently to moderately inclined microfabric with an average dip of *c.*, 30°, which forms the dominant foliation within these deposits; (ii) a

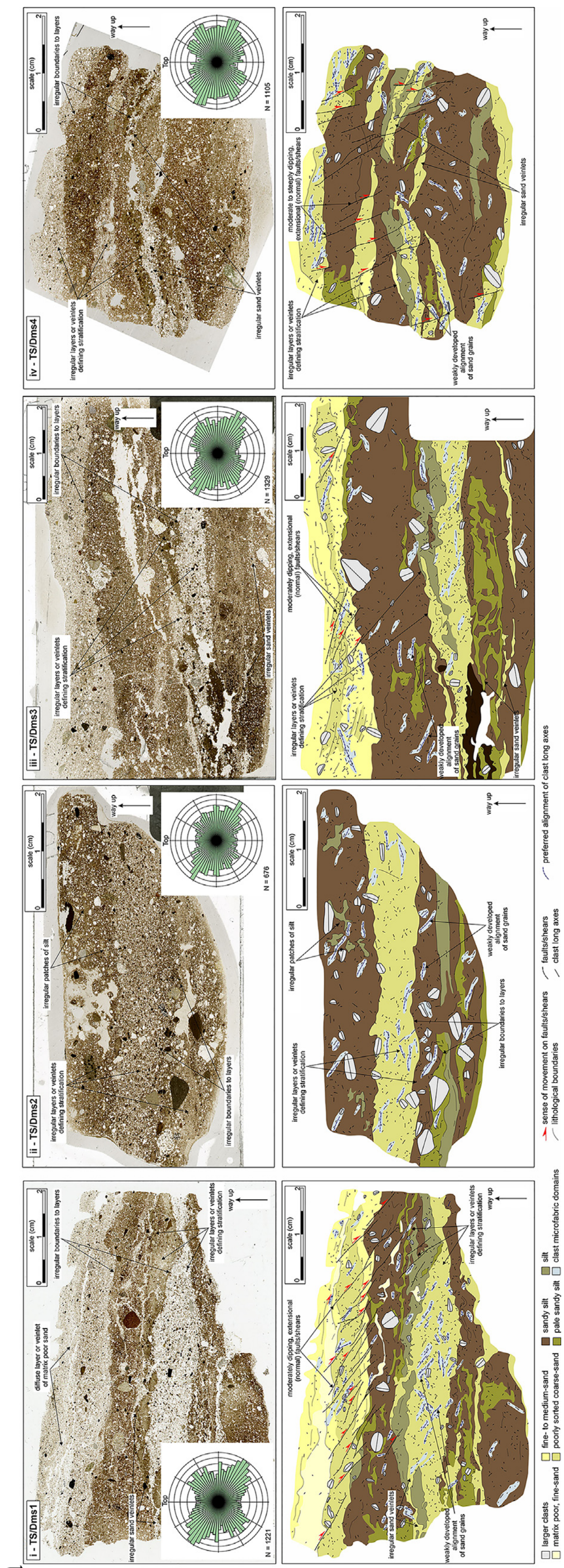


Fig. 12. a: High-resolution scans and detailed microsedimentological and microstructural interpretations of the thin sections of the stratified diamictons: (i) sample TS/Dms1; (ii) sample TS/Dms2; (iii) sample TS/Dms3; and (iv) TS/Dms4. The rose diagrams (N = number of clasts) show the variation in microfabric development within samples defined by the preferred orientation of the long axes of coarse silt to sand grade clasts (see text for details). b: High-resolution scans and detailed microsedimentological and microstructural interpretations of the thin sections of massive diamictons: (i) sample TS/Dmm1; (ii) sample TS/Dmm2; and (iii) sample TS/Dmm3. The rose diagrams (N = number of clasts) show the variation in microfabric development within samples defined by the preferred orientation of the long axes of coarse silt to sand grade clasts (see text for details).

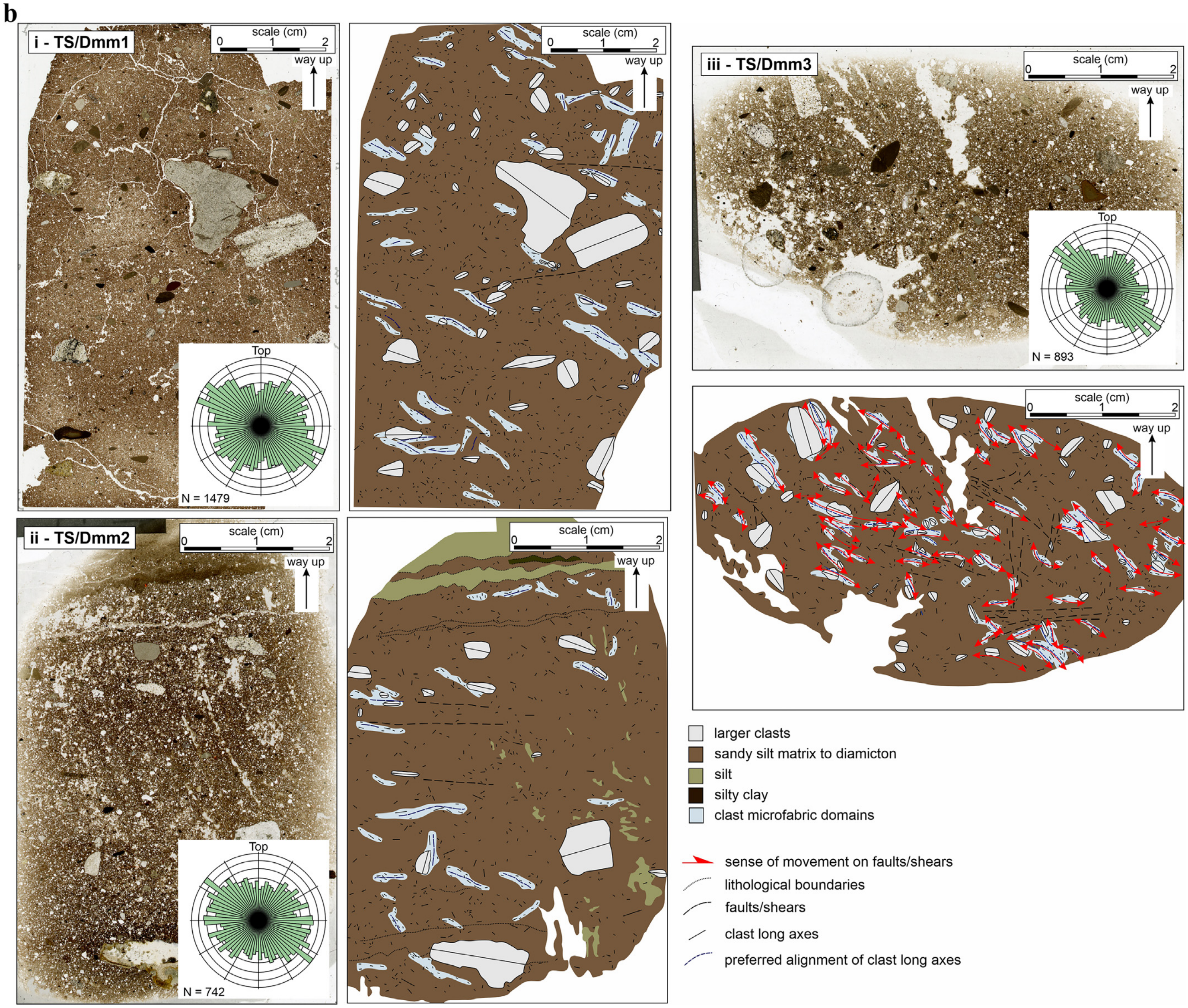


Fig. 12 (*continued*).

second less well-developed sub-horizontal foliation; and (iii) a weakly developed steeply dipping to sub-vertical fabric. The consistency of the clast microfabric dips indicates that the diamictons were either deformed during the same deformation event, or that the orientation of the stress regime remained relatively constant during several separate phases of deformation. In addition, all three foliations are heterogeneously developed, indicating that this syn-sedimentary soft-sediment deformation was not pervasive and is likely to have been partitioned into discrete horizons within the diamictons. The relationships displayed between the three clast microfabrics within the massive diamictons are consistent with them defining gently dipping R (foliation 1), subhorizontal Y (foliation 2) and steeply dipping R′ (foliation 3) type Reidel shears.

In the stratified diamicton, the dominant microfabric occurs coplanar with the gently to moderately dipping normal microfaults, consistent with both sets of microstructures having developed in response to extension associated with the development of R-type Reidel shears. This extensional deformation may have either occurred in response to flexural slip on the limbs of the mesoscale recumbent isoclinal folds (observed in outcrop; Fig. 9 &10) or as a result of soft-sediment deformation during the deposition of the diamictons as a series of mass flows. Processes invoked by both hypotheses would have led to the attenuation (thinning) and eventual boudinage of the sandy layers within the stratified diamictons, possibly resulting in the locally wispy, lenticular appearance of this stratification. However, in detailed studies of subaerial ice-contact mass flows, Phillips (2006) and Reinardy and Lukas (2009) concluded that fine sands and muds interbedded with clast- and matrix-supported diamictons can be explained as a poorly sorted clay to fine sand-rich slurry expelled from the tops of advancing mass flows. These water-rich, typically clay to silt-dominated slurries were progressively overridden and deformed (sheared) by the advancing mass flow with localised liquefaction and injection of the sand into the base of the overriding flow (see Phillips et al., 2022). A similar model can be applied to the stratified diamictons exposed at the base of the Filey Brigg section, where such finely layered deposits were likely laid down in front of an advancing mass flow, or at the distal/leading edge of an ice-contact apron or fan which become progressively overridden and deformed. Recumbent mesoscale folding and microscale deformation of the stratified diamictons may have either occurred as these deposits were being overridden by the contemporaneous mass flows, or during their emplacement (flow) down the leading edge of an ice-contact, subaqueous debris flow-fed fan/apron.

Table 1
Clast composition based upon detailed analysis of the thin sections of the massive and stratified diamictons exposed at Filey.

Sample number	Rock fragments	Silt and sand	
		Major	Minor to accessory
TS/Dmm1	Mudstone, siltstone, finely crystalline limestone, hematised mudstone, quartz arenite, micritic limestone, basalt, altered basalt, silicified fault rock, calcareous siltstone, hematised basalt	Monocrystalline quartz, polycrystalline quartz, feldspar	Mono- and polycrystalline carbonate minerals, opaque minerals, muscovite/white mica, garnet, shell fragments, biotite, amphibole, foraminifera, tourmaline, chlorite possible gryphaea fragment
TS/Dmm2	Siltstone, chert, mudstone, quartzose siltstone, hematised rock, finely crystalline limestone, micritic limestone, basalt, altered basal, sandstone, chloritised rock, dolerite	Monocrystalline quartz, polycrystalline quartz, feldspar	Shell fragments, opaque minerals, monocrystalline carbonate minerals, chlorite, amphibole, muscovite/white mica
TS/Dmm3	Quartzose siltstone, fine-grained sandstone, mudstone, altered basalt, hematised basalt, finely crystalline limestone, granitic rock, fine siltstone, quartzose fine-grained sandstone	Monocrystalline quartz, polycrystalline quartz, feldspar	Opaque minerals, pyroxene, chert/cryptocrystalline quartz, mono- and polycrystalline carbonate minerals, muscovite/white mica, gastropod fragment, garnet
TS/Dms1	Mudstone, siltstone, finely crystalline limestone, basalt, calcareous siltstone, quartzose siltstone	Monocrystalline quartz, polycrystalline quartz, feldspar	Opaque minerals, mono- and polycrystalline carbonate minerals, muscovite/white mica, chlorite, pyroxene, amphibole, biotite, epidote, glauconite, zoisite/clinozoisite, shell fragments
TS/Dms2	Mudstone, siltstone, altered basalt, fine-grained sandstone	Monocrystalline quartz, polycrystalline quartz, feldspar	Opaque minerals, mono- and polycrystalline carbonate minerals, muscovite, garnet, glauconite
TS/Dms3	Mudstone, siltstone, altered basalt, fine-grained sandstone, pilotaxitic basalt	Monocrystalline quartz, polycrystalline quartz, feldspar	Opaque minerals, mono- and polycrystalline carbonate minerals, pyroxene, epidote, cryptocrystalline quartz/chert, shell fragments
TS/Dms4	Mudstone, siltstone, altered basalt, fine-grained sandstone, chert, finely crystalline limestone, indurated quartz arenite/quartzite, quartz arenite, basalt	Monocrystalline quartz, polycrystalline quartz, feldspar	Opaque minerals, mono- and polycrystalline carbonate minerals, shell fragments, muscovite, chlorite, amphibole, epidote, chlorite

The depositional geometry of the fan/apron is represented by the architecture of the stratification (S0) as well as the internal structural data, which indicate sedimentation and soft-sediment flowage and folding on a slope of 5°–25° towards the north/northwest. This suggests that subaqueous fan/apron progradation was from an offshore lobate ice margin towards the mouth of the Vale of Pickering, where a proglacial lake was dammed by the advancing ice lobe. The clast macrofabric (F0) from the basal stratified diamicton reflects gravity flowage and clast dip alignments towards the NNW on the palaeo-depositional slope (*cf.*, Mills, 1991).

The appearance of a 40 m thick sequence of sub-horizontal units of diamicton (each 1.4–6.5 m thick), lying above the basal 3 m of stratified and folded diamictons at Filey Brigg, records the deposition/accretion of a vertical stack, which was repeatedly interrupted by the sedimentation of stratified deposits in beds or lenses up to 2.0 m thick. A relatively consistent repetition from massive, locally fissile diamicton with strongly aligned macrofabrics passing upwards into laminated/stratified diamicton overlain by stratified deposits indicates that the depositional environment repeatedly changed from one of diamicton accretion by relatively high stress imparted from the north, north-northeast or northeast to one of subaqueous sedimentation with highly variable fluvial discharge regimes ranging from gravelly mass flows to silt/clay drapes. The emplacement of these subaqueous deposits involved planation or erosional scour into the diamictons to form interbeds and convexo-planar lenses. Normal grading in the lenses records the gradual fall in discharge after the initial scour infill. This was followed by the deformation of the tops of the interbeds and lenses to varying depths due to ice-bed recoupling, completely removing these deposits (*e.g.*, at 24.5 m and likely also at 21 m; Fig. 5) or converting them to a Type III or Type IV mélange. Flame-like stringers and wisps of sand at the top of the mélange show clear evidence of having been dragged upwards into the overlying diamicton, eventually forming detached and attenuated intraclasts (Fig. 6f). This style of contact between interbed/lens top and diamicton base is typical of glacitectonite production and cannibalisation to form glacitectonic slices/lamination within the basal layers of subglacial traction tills (Boulton et al., 2001; Brandes and Le Heron, 2010; see Evans, 2018 for review). This is consistent with a subglacial deforming-sliding bed mosaic scenario in which subglacial traction till emplacement is punctuated by the sequential development of canal fill deposits, as previously envisaged in this region by Eyles et al. (1982) and Evans et al. (1995). The consistently orientated and moderately strong clast macrofabrics of the diamictons indicate emplacement by glacier ice moving onshore from the north and northeast, consistent with previous reconstructions of the North Sea Lobe of the BIIS constructing the Flamborough Head moraine belt.

The above macro- and microscale interpretations of a complex gradational sequence of deposits prompt the identification of architectural elements similar to those promoted by Boyce and Eyles (2000) for similar stacked sequences of tills and stratified interbeds. Given the variable characteristics of the diamictons at Filey Brigg we adopt the diamict element (DE) of Boyce and Eyles (2000) but employ a subdivision of massive to fissile/laminated (DE-m/f) and stratified (DE-s). These relate, respectively, to genetic classifications of subglacial traction till and subaqueous sediment gravity flow deposits. Where deformed, the materials are classified as a deformed zone (DZ), which applies to the mélanges (glacitectonites) developed at the tops of the canal fill deposits. The interbeds (canal fills) at Filey Brigg do not comply sedimentologically with those of Boyce and Eyles (2000) in that most cannot be classified as coarse or fine but rather a combination of the two, predominantly displaying normal grading; hence the classification "graded interbed" (I-g) is proposed as an addition to those of I-c (coarse) and I-f (fine) in the Boyce and Eyles (2000) scheme. Using these architectural elements, the complete vertical sequence comprises a change in depositional environment from an ice-contact, debris flow-fed apron (DE-s), prograding in front of the North Sea Lobe and fed by subglacial traction till released at the glacier snout into an ice-dammed lake (*i.e.*, Lake Pickering), to a subglacial setting, characterised by the emplacement of deforming-sliding bed mosaic deposits/subglacial traction till (DE-m/f & I-g). The initial gradual nature of the change in these depositional environments is recorded by the occurrence of stratified diamictons (DE-s) between the earliest tills and canal fills between 13 and 18 m in the section, indicating a close proximity between subglacial tunnels and lake water and, hence, likely oscillations in the position of the efflux point/grounding line. A similar scenario has been proposed to explain the variable sedimentological characteristics of till interbeds in the Holden Till of County Durham by Davies et al. (2009) and Evans (2018), where the North Sea Lobe oscillated at the eastern end of Glacial Lake Wear.

Given the proximity of the Filey area boreholes to the Filey Brigg section, we assume a lateral correlation between similar lithofacies and, hence, similar process-form regimes. Nevertheless, a significant difference between the Filey Brigg stratigraphic sequence and those of the Filey Gas Works and Pumping Station is the prominence of a thick stratified basal component and generally thicker stratified interbeds between diamictons, to the extent that diamictons are subordinate in the lower 40 m of the Pumping Station borehole (Fig. 4a). This occurrence of thick sequences of fine-grained stratified deposits (especially clay, silt and sand lithofacies) and their gradually increasing dominance over multiple diamictons and intervening stratified deposits in a westerly direction away from the Flamborough Head moraine (Fig. 4b) reflects the increasing influence of glacilacustrine sedimentation at the eastern end of Glacial Lake Pickering (Evans et al., 2017; Eddey et al., 2022). The occurrence of diamictons in otherwise glacilacustrine sequences at Muston and Carr Lane (Fig. 4b), because they coincide with mounds on the eastern floor of the former Lake Pickering, are likely morainic deposits created at an oscillating margin of the North Sea Lobe as it actively retreated from the LGM (Dimlington Stadial) position located further west. Similar incursions by the North Sea Lobe into increasingly proximal Lake Pickering deposits are recorded by diamictons below 15 m in the Filey Pumping Station borehole. The eastwards thickening of the diamictons in the nearby Filey Gas Works borehole and then the Filey Brigg section represents increasingly ice-proximal sedimentation, whereby sub-marginal tills and/or sediment gravity flows were interspersed with increasingly coarse glacilacustrine deposits. The generally finer-grained nature of the inter-till stratified units (architectural element I-g) in the Filey Brigg section, as outlined above, suggests a canal fill origin and, hence, the three Filey stratigraphic sequences (Fig. 4b) are positioned at the likely interface of subaqueous and subglacial sedimentation, where tunnel efflux points locally expanded into glacier sub-marginal, water-filled cavities. At such locations, the aggradation of sub-marginal tills, which were feeding ice-proximal subaqueous sediment gravity flows, was punctuated by the emplacement of sliding bed facies (canal fills) and penecontemporaneous glacilacustrine facies. Further south, the Butlins Holiday Camp borehole stratigraphy (Fig. 4a), like the Filey Brigg section, is dominated by diamictons, between which openwork boulders, boulder lags and clast-supported diamicton likely record winnowing of the tops of at least two diamictons, but otherwise finer-grained interbeds represent canal fills. Given the consistency of the stratigraphic sequences in Filey Bay, it is most likely that the boulder interbeds relate to one of two origins or a combination of them: 1) subglacial meltwater flushing or sliding bed facies, whereby the boulders represent a palimpsest lag, especially where associated with poorly-sorted gravels (*e.g.*, Davies et al., 2009); 2) excavational deformation, whereby the advection of deforming layer material from the innermost, thin ends of sub-marginal till wedges leaves remnant boulder-sized clasts with striated upper facets on a fluted surface (Boulton, 1996a; Evans and Hiemstra, 2005; Evans et al., 2016, 2018).

When assessed in the geographical context of the linear hummocky ridges in the Flamborough Head moraine (Fig. 3), the simplest interpretation of the multiple diamictons (tills) exposed in the Filey Brigg section and Filey Bay boreholes is that they represent stacked glacier sub-marginal till wedges created by incremental thickening of the subglacial deforming layer. This is a process of punctuated aggradation (sensu Brett and Baird, 1986; Eyles et al., 2011) and one that has been observed in contemporary active temperate glacier marginal environments, where the landform manifestation of the sub-marginal till wedge is a push moraine and phases of ice-marginal stability lead to the construction of composite or closely-spaced push moraines and multiple or stacked tills (Evans and Hiemstra, 2005; Evans et al., 2016, 2018; *cf.*, Leysinger-Vieli and Gudmundsson, 2010).

4. Discussion

Although the style of glaciation on the East Yorkshire coast has long been understood to have been dictated by the onshore flow of the North Sea Lobe, with the construction of the prominent Flamborough Head hummocky moraine being responsible for the blocking of the eastern end of the Vale of Pickering and the damming of Glacial Lake Pickering (Farrington and Mitchell, 1951; Evans et al., 2017; Eddey et al., 2022), our knowledge of the nature of the glacial depositional environment and its implications for local ice sheet dynamics is less well-developed. Whereas Farrington and Mitchell (1951) regarded the moraine assemblage as simply an end moraine, Valentin (1957) proposed multiple ice-marginal positions, allocating what he called the Speeton moraine (the northern extension of the Flamborough Head moraine) to a "second readvance" that overrode the deposits of his "first readvance". Straw (1979) used the term "Cayton-Speeton Stage" to refer to the construction phase of the Speeton Moraine and Penny and Rawson (1969) used the term "Seamer-Flamborough Stage" for the construction of the Flamborough Head moraine. The folding of the lower sequence of multiple tills and stratified sediments and their superimposition by upper laminated and varved (*i.e.*, glacial lake) deposits and tills at Hunmanby Gap, as reported by Bisat (1940), also indicates at least two major ice advance phases. The implications here are that onshore ice flow was characterised by oscillatory behaviour, but apart from Penny and Rawson's (1969) observation that moraine linearity was due to drumlinisation, no further details on moraine morphology or any linkages to multiple tills in the area, as documented by Bisat (1940), Edwards (1981) and Evans et al. (1995), have been proposed and nor have any linkages been made stratigraphically and sedimentologically between the coastal moraine belt and glacial lake deposits inland, despite such linkages having been well documented for Holderness to the south (Boston et al., 2010; Evans and Thomson, 2010).

The Filey Bay stratigraphy clearly documents the damming of regional drainage by the onshore advance of the North Sea Lobe (Fig. 13). This is recorded in the thick sequences of predominantly fine-grained (clay, silt, sand) glacilacustrine deposits in the basal parts of the borehole records as well as the stratified diamicton (element DE-s) outcropping at the base of the Filey Brigg section. Increasing ice proximity is recorded in the vertical increase in coarse-grained lithofacies in the glacilacustrine deposits as well as the appearance of stratified diamictons emplaced by sediment gravity flow, which most likely prograded into the earliest lake within Filey Bay to form a subaqueous ice-contact fan/apron on the distal slope of a subaqueous push ridge developed in the lake sediments, akin to the "mud aprons" of Kristensen et al. (2009; *cf.*, Johnson et al., 2013).

The overriding of the mud apron by onshore flow resulted in the emplacement of a stacked sequence of tills, the earliest of which presumably correlate with the more extensive ice lobe positions in the Vale of Pickering (advance till, sensu Boulton, 1996a, 1996b; Evans and Thomson, 2010) (Fig. 13). The zone of interdigitation of tills and lake sediments thereby migrated first westward and then eastward, culminating in the emplacement of multiple tills (retreat tills, sensu Boulton, 1996a, 1996b; Evans and Thomson, 2010) and intervening canal fills (alternating deforming bed-sliding bed facies) through the process of sub-marginal incremental thickening or punctuated aggradation, when the North Sea Lobe underwent a phase of relative stability and constructed the inset push moraines on the rising slopes of Filey Bay in response to minor ice marginal oscillations. A similar depositional scenario is evident in the stratigraphic architecture of the Holderness coast glacigenic deposits (Evans and Thomson, 2010). The more substantial stratified intra-till beds in such sequences likely represent the widening of canal fills into either lake rhythmites or subaqueous fans in marginal cavities near the glacier grounding line (Fig. 13), similar to the depositional scenario envisaged for the stratified deposits associated with the Skipsea and Withernsea tills to the south (Evans and Thomson, 2010), the upper and lower tills at Upgang in North Yorkshire (Roberts et al., 2013) and in the Horden Till in northeast England (Davies et al., 2009).

The landform-sediment assemblages of Filey Bay and the eastern end of the Vale of Pickering, as described and explained above, record the dynamic nature of the North Sea Lobe as it impinged on the eastern English coast. Recent developments in the construction of a chronology for ice sheet behaviour in the North Sea (Roberts et al., 2018; Evans et al., 2021; Clark et al., 2022) have identified North Sea Lobe oscillations at a regional scale, with their ice sheet limits 1–4 impacting specifically on the Filey Bay area. Limit 1 was the earliest North Sea Lobe incursion

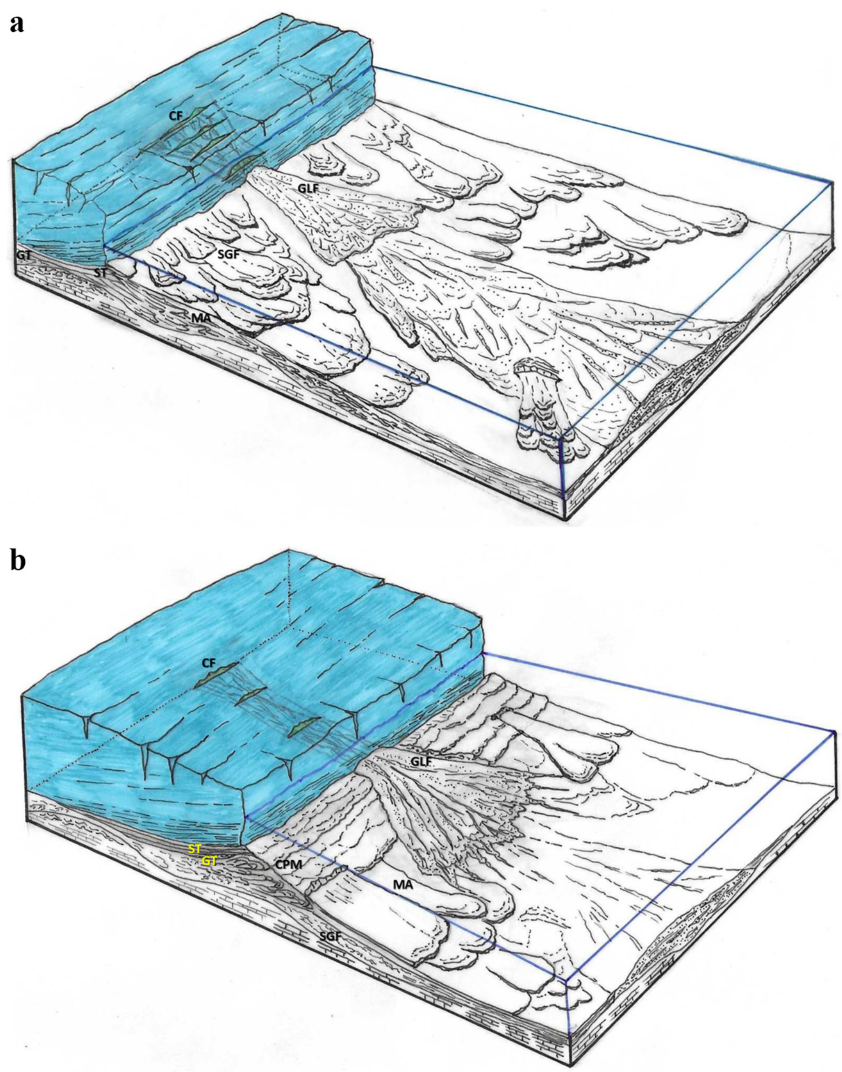


Fig. 13. Idealised reconstruction of the depositional setting in Filey Bay based on a combination of the sedimentology presented in this paper and from previous research on the Holderness lowlands. To ensure clarity and emphasis on diamicton production, the diagrams do not depict interflow and overflow plumes or iceberg activity but such processes would have been operating. Panel A shows the situation when the North Sea Lobe had moved far enough onshore to dam a proglacial lake over Filey Bay and the Vale of Pickering. Ice margin oscillation leads to the progradation of overprinted subaqueous sediment gravity flows (SGF) and grounding line fans (GLF) and it depicts snout stabilisation after a phase of recession. The diamictic nature of the sediment gravity flows (mud apron MA) is dictated by their delivery to the ice margin *via* subglacial traction tills (ST) with fine-grained matrices imparted by glacitectonised marine muds (GT). Alternatively, canal fills (*CF*) connect with, and deliver sands and gravels to, the grounding line fans. Panel B shows the situation after a further period of snout advance, during which the subaqueous sediment gravity flow deposits are overrun, glacitectonised (GT) and remobilised into further debris flows (mud apron) at the front of the resulting composite push moraine (CPM).

into Filey Bay and dated 25.8–24.6 ka, initiating the first impoundment of drainage. Limit 2 represents the furthest west incursion of ice into the Vale of Pickering and its proglacial lake and dated 23.5–22.2 ka. Limit 3 records the recession of the lobe back towards Filey Bay at 21.5–20.8 ka. The positioning of the lobe margin offshore is represented by limit 4 at 19.7–19.5 ka, thought to be coeval with the emplacement of the Withernsea Till on southern Holderness. This broad temporal scale of oscillatory behaviour is compatible with the landsystem signature on Holderness, as reported by Eyles et al. (1994), Boston et al. (2010) and Evans and Thomson (2010). Although such dynamism has been related to possible surge behaviour (Lamplugh, 1911; Eyles et al., 1994) and the operation of multiple ice flow units within the North Sea Lobe (Boston et al., 2010), the emplacement of multiple tills and inset push moraines by glacier sub-marginal accretion and thickening, as recorded at Filey, is also compatible with non-surging, active temperate glacier behaviour (Evans and Hiemstra, 2005). Nevertheless, Evans et al. (2021) acknowledge that the ice-marginal instability indicated by their palaeoglaciological reconstruction can be explained by either surging behaviour and/or increased ice lobe dynamism due to changes to the topographic configuration of the southern North Sea Basin brought about by glacitectonic disruption of Dogger Bank (Phillips et al., 2017; Roberts et al., 2018; Phillips et al., 2022) after ~23 ka.

5. Conclusions

Sequences of >40 m of horizontally layered, multiple diamictons and associated stratified sediments at Filey Bay represent the localised accretion and thickening of glacigenic deposits to form the Holderness/Flamborough Head coastal moraine belt, which was constructed at the onshore flowing oscillatory and dynamic margin of the North Sea Lobe of the BIIS between ~25.8 and ~19.7 ka. The stratigraphy records first the damming of regional drainage by onshore ice advance, specifically in thick basal sequences of predominantly fine-grained glacilacustrine deposits, with increasing ice proximity being recorded in the vertical increase in coarse-grained lithofacies and the appearance of stratified diamictons emplaced by sediment gravity flow. The latter likely prograded into the earliest lake dammed within Filey Bay as the deposits of a subaqueous ice-contact fan/apron on the distal slope of a subaqueous push ridge. Later overriding of the mud apron by south-westerly-flowing ice is recorded in a stacked sequence of tills that interdigitated with lake sediments inland. A zone of till-lake sediment interdigitation migrated first westward during North Sea Lobe advance and then eastward during its retreat, into and out of Glacial Lake Pickering, respectively. Multiple tills and intervening canal fills at Filey represent alternating deforming bed-sliding bed facies emplaced by sub-marginal incremental thickening or punctuated aggradation that constructed inset push moraines, the last of which appear as inset linear hummocky terrain on the inland slopes of Filey Bay. More substantial stratified intra-till beds likely represent the widening of canal fills into either lake rhythmites or subaqueous fans in marginal cavities near the former glacier grounding line. Although this landform-sediment assemblage is compatible with former ice lobe surging behaviour it can also be related to non-surging, active temperate glacier imprints.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Acknowledgements

Lotte Evans provided able field assistance at Filey Brigg. Figure 9, Figure 10 and Figure 12 were drawn by ERP and the remaining figures in this paper were drafted by Chris Orton of the Department of Geography, Durham University. ERP publishes with permission of the Director of the British Geological Survey.

References

Bateman, M.D., Evans, D.J.A., Buckland, P.C., Connell, E.R., Friend, R.J., Hartmann, D., Moxon, H., Fairburn, W.A., Panagiotakopulu, E., Ashurst, R.A., 2015. Last glacial dynamics of the Vale of York and North Sea lobes of the British and Irish Ice Sheet. Proceedings of the Geologists' Association 126, 712–730.

Bateman, M.D., Evans, D.J.A., Roberts, D.H., Medialdea, A., Ely, J.C., Clark, C.D., 2018. The timing and consequences of the blockage of the Humber Gap by the last British-Irish Ice Sheet. Boreas 47, 41–61.

Benn, D.I., 1994. Fabric shape and the interpretation of sedimentary fabric data. Journal of Sedimentary Research A 64, 910–915.

Benn, D.I., Evans, D.J.A., 1996. The interpretation and classification of subglacially-deformed materials. Quaternary Science Reviews 15, 23–52.

Benn, D.I., Lukas, S., 2021. Macrofabric. In: Evans, D.J.A., Benn, D.I. (Eds.), A Practical Guide to the Study of Glacial Sediments, Second edition Quaternary Research Association, London, 125–154.

Bisat, W.S., 1939. The relationship of the "basement clays" of Dimlington, Bridlington and Filey bays. The Naturalist (Hull) 133–135, 161–168.

Bisat, W.S., 1940. Older and newer drift in East Yorkshire. Proceedings of Yorkshire Geological Society 24, 137–151.

Boston, C.M., Evans, D.J.A., Cofaigh, Ó., C., 2010. Styles of till deposition at the margin of the Last Glacial Maximum North Sea lobe of the British-Irish Ice Sheet: an assessment based on geochemical properties of glacigenic deposits in eastern England. Quaternary Science Reviews 29, 3184–3211.

Boulton, G.S., 1996a. Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. Journal of Glaciology 42, 43–62.

Boulton, G.S., 1996b. The origin of till sequences by subglacial sediment deformation beneath mid-latitude ice sheets. Annals of Glaciology 22, 75–84.

Boulton, G.S., Dobbie, K.E., 1993. Consolidation of sediments by glaciers: relations between sediment geotechnics, soft bedded glacier dynamics and subglacial ground-water flow. Journal of Glaciology 39, 26–44.

Boulton, G.S., Dobbie, K.E., 1998. Slow flow of granular aggregates: the deformation of sediments beneath glaciers. Philosophical Transactions of the Royal Society of London A 356, 2713–2745.

Boulton, G.S., Hindmarsh, R.C.A., 1987. Sediment deformation beneath glaciers: rheology and geological consequences. Journal of Geophysical Research 92, 9059–9082.

Boulton, G.S., Dobbie, K.E., Zatsepin, S., 2001. Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. Quaternary International 86, 3–28.

Boyce, J.I., Eyles, N., 2000. Architectural element analysis applied to glacial deposits: internal geometry of a late Pleistocene till sheet, Ontario, Canada. Bulletin of the Geological Society of America 112, 98–118.

Brandes, C., Le Heron, D.P., 2010. The glaciotectonic deformation of Quaternary sediments by fault-propagation folding. Proceedings of the Geologists' Association 121, 270–280.

Brett, C., Baird, G.C., 1986. Symmetrical and upward shallowing cycles in the Middle Devonian of New York state and their implications for the punctuated aggradational cycle hypothesis. Paleoceanography 1, 431–445.

Busfield, M.E., Lee, J.R., Riding, J.B., Zalasiewicz, J., Lee, S.V., 2015. Pleistocene till provenance in East Yorkshire: reconstructing ice flow of the British North Sea lobe. Proceedings of the Geologists' Association 126, 86–99.

Catt, J.A., 1991. The Quaternary history and glacial deposits of east Yorkshire. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), Glacial Deposits in Great Britain and, Ireland. Balkema, Rotterdam, 185–191.

Catt, J.A., 2007. The Pleistocene glaciations of eastern Yorkshire: a review. Proceedings of Yorkshire Geological Society 56, 177–207.

Catt, J.A., Penny, L.F., 1966. The Pleistocene deposits of Holderness, East Yorkshire. Proceedings of Yorkshire Geological Society 35, 375–420.

Clark, C.D., Ely, J.C., Hindmarsh, R.C.A., Bradley, S., Igneczi, A., Fabel, D., Ó Cofaigh, C., Chiverrell, R.C., Scourse, J., Benetti, S., Bradwell, T., Evans, D.J.A., Roberts, D.H., Burke, M., Callard, S.L., Medialdea, A., Saher, M., Small, D., Smedley, R.K., Gasson, E., Gregoire, L., Gandy, N., Hughes, A.L.C., Ballantyne, C., Bateman, M.D., Bigg, G.R., Doole, J., Dove, D., Duller, G.A.T., Jenkins, G.T.H., Livingstone, S.L., McCarron, S., Moreton, S., Pollard, D., Praeg, D., Sejrup, H.P., van Landeghem, K.J.J., Wilson, P., 2022. Growth and retreat of the last British–Irish Ice Sheet, 31 000 to 15 000 years ago: the BRITICE-CHRONO reconstruction. Boreas 51, 699–758.

Cowan, D.S., 1985. Structural styles in Mesozoic and Cenozoic melanges in the western cordillera of North America. Geological Society of America Bulletin 56, 451–462.

Davies, B.J., Roberts, D.H., O' Cofaigh, C., Bridgland, D.R., 2009. Subglacial and ice marginal controls on sediment deposition during the last glacial maximum: interlobate ice sheet dynamics at Whitburn Bay, county Durham, England. Boreas 38, 555–578.

Dove, D., Evans, D.J.A., Lee, J.R., Roberts, D.H., Tappin, D.R., Mellett, C.L., Long, D., Callard, S. L., 2017. Phased occupation and retreat of the last British-Irish Ice Sheet in the southern North Sea: geomorphic and seismostratigraphic evidence of a dynamic ice lobe. Quaternary Science Reviews 163, 114–134.

Drozdowski, E., 1987. Surge moraines. In: Gardiner, V. (Ed.), International Geomorphology. Wiley, Chichester, 675–692.

Eddey, L.J., Bateman, M.D., Livingstone, S.J., Lee, J.R., 2022. New geomorphic evidence for a multi-stage proglacial lake associated with the former British–Irish Ice Sheet in the Vale of Pickering, Yorkshire, UK. Journal of Quaternary Science 37, 1407–1421.

Edwards, C.S., 1981. Lake Pickering – the lake that never was. Geology Teaching 6, 20–24.

Evans, D.J.A., 2018. Till: A Glacial Process Sedimentology. Wiley-Blackwell, Chichester (390 pp.).

Evans, D.J.A., Benn, D.I., 2021. Facies description and the logging of sedimentary exposures. In: Evans, D.J.A., Benn, D.I. (Eds.), A Practical Guide to the Study of Glacial Sediments, Second edition Quaternary Research Association, London, 17–78.

Evans, D.J.A., Hiemstra, J.F., 2005. Till deposition by glacier submarginal, incremental thickening. Earth Surface Processes and Landforms 30, 1633–1662.

Evans, D.J.A., Ó Cofaigh, C., 2003. Depositional evidence for marginal oscillations of the Irish Sea ice stream in Southeast Ireland during the last glaciation. Boreas 32, 76–101.

Evans, D.J.A., Thomson, S.A., 2010. Glacial sediments and landforms of Holderness, eastern England: a glacial depositional model for the North Sea Lobe of the British–Irish Ice Sheet. Earth Science Reviews 101, 147–189.

Evans, D.J.A., Owen, L.A., Roberts, D., 1995. Stratigraphy and sedimentology of Devensian (Dimlington Stadial) glacial deposits, East Yorkshire, England. Journal of Quaternary Science 10, 241–265.

Evans, D.J.A., Roberts, D.H., Evans, S.C., 2016. Multiple subglacial till deposition: a modern exemplar for Quaternary palaeoglaciology. Quaternary Science Reviews 145, 1–21.

Evans, D.J.A., Bateman, M.D., Roberts, D.H., Medialdea, A., Hayes, L., Duller, G.A.T., Fabel, D., Clark, C.D., 2017. Glacial Lake Pickering: stratigraphy and chronology of a proglacial lake dammed by the North Sea Lobe of the British-Irish Ice Sheet. Journal of Quaternary Science 32, 295–310.

Evans, D.J.A., Roberts, D.H., Hiemstra, J.F., Nye, K.M., Wright, H., Steer, A., 2018. Submarginal debris transport and till formation in active temperate glacier systems: the Southeast Iceland type locality. Quaternary Science Reviews 195, 72–108.

Evans, D.J.A., Roberts, D.H., Bateman, M.D., Clark, C.D., Medialdea, A., Callard, L., Grimoldi, E., Chiverrell, R.C., Ely, J., Dove, D., Ó Cofaigh, C., Saher, M., Bradwell, T., Moreton, S.G., Fabel, D., Bradley, S.L., 2021. Retreat dynamics of the eastern sector of the British-Irish Ice Sheet during the last glaciation. Journal of Quaternary Science 36, 723–751.

Eyles, N., Sladen, J.A., Gilroy, S., 1982. A depositional model for stratigraphic complexes and facies superimposition in lodgement tills. Boreas 11, 317–333.

Eyles, N., McCabe, A.M., Bowen, D.Q., 1994. The stratigraphic and sedimentological significance of Late Devensian ice sheet surging in Holderness, Yorkshire, UK. Quaternary Science Reviews 13, 727–759.

Eyles, N., Eyles, C.H., Menzies, J., Boyce, J., 2011. End moraine construction by incremental till deposition below the Laurentide Ice Sheet: southern Ontario, Canada. Boreas 40, 92–104.

Farrington, A., Mitchell, G.F., 1951. The end moraine north of Flamborough Head. Proceedings of the Geologists' Association 62, 100–106.

Hooyer, T.S., Iverson, N.R., 2000. Diffusive mixing between shearing granular layers: constraints on bed deformation from till contacts. Journal of Glaciology 46, 641–651.

Ildefonse, B., Mancktelow, N.S., 1993. Deformation around rigid particles: the influence of slip at the particle/matrix interface. Tectonophysics 221, 345–359.

Ingólfsson, Ó., Benediktsson, Í.Ö., Schomacker, A., Kjær, K.H., Brynjólfsson, S., Jónsson, S.A., Korsgaard, N.J., Johnson, M.D., 2016. Glacial geological studies of surge-type glaciers in Iceland — research status and future challenges. Earth Science Reviews 152, 37–69.

Iverson, N.R., Hooyer, T.S., Thomason, J.F., Graesch, M., Shumway, J.R., 2008. The experimental basis for interpreting particle and magnetic fabrics of sheared till. Earth Surface Processes and Landforms 33, 627–645.

Johnson, M.D., Schomacker, A., Benediktsson, Í.Ö., Geiger, A.J., Ferguson, A., Ingólfsson, Ó., 2010. Active drumlin field revealed at the margin of Múlajökull, Iceland: a surge-type glacier. Geology 38, 943–946.

Johnson, M.D., Benediktsson, I.O., Bjorklund, L., 2013. The Ledsjö end moraine—a subaquatic push moraine composed of glaciomarine clay in Central Sweden. Proceedings of the Geologists' Association 124, 738–752.
Kendall, P.F., 1902. A system of glacier-lakes in the Cleveland Hills. Quarterly Journal of the Geological Society 58, 471–571.
King, C.A.M., 1965. British Landscapes Through Maps: The Scarborough District. Geographical Association, Sheffield.
Kristensen, L., Benn, D.I., Hormes, A., Ottesen, D., 2009. Mud aprons in front of Svalbard surge moraines: evidence of subglacial deforming layers or proglacial glaciotectonics. Geomorphology 111, 206–221.
Krüger, J., 1993. Moraine ridge formation along a stationary ice front in Iceland. Boreas 22, 101–109.
Krüger, J., 1994. Glacial processes, sediments, landforms and stratigraphy in the terminus region of Myrdalsjokull, Iceland. Folia Geographica Danica 21, 1–233.
Krüger, J., 1996. Moraine ridges formed from subglacial frozen-on sediment slabs and their differentiation from push moraines. Boreas 25, 57–63.
Lamplugh, G.W., 1911. On the shelly moraine of the Sefstromglacier and other Spitsbergen phenomena illustrative of the British glacial conditions. Proceedings of Yorkshire Geological Society 17, 216–241.
Leysinger-Vieli, G.J.M.C., Gudmundsson, G.H., 2010. A numerical study of glacier advance over deforming till. The Cryosphere 4, 359–372.
March, A., 1932. Mathematische theorie der regelung nach der korngestalt bei affiner deformation. Zeitschrift für Kristallographie 81, 285–297.
Matthews, J.A., McCarroll, D., Shakesby, R.A., 1995. Contemporary terminal moraine ridge formation at a temperate glacier: Styggedalsbreen, Jotunheimen, southern Norway. Boreas 24, 129–139.
Mills, H.H., 1991. Three Dimensional Clast Orientation in Glacial and Mass Movement Sediments. USGS Open File Report pp. 90–128.
Ó Cofaigh, C., Evans, D.J.A., 2001. Sedimentary evidence for deforming bed conditions associated with a grounded Irish Sea glacier, southern Ireland. Journal of Quaternary Science 16, 435–454.
Passchier, C.W., Trouw, R.A.J., 1996. Microtectonics. Springer, Berlin.
Penny, L.F., Rawson, P.F., 1969. Field meeting in East Yorkshire and North Lincolnshire. Proceedings of the Geologists' Association 80, 193–216.
Penny, L.F., Coope, G.R., Catt, J.A., 1969. Age and insect fauna of the Dimlington Silts, East Yorkshire. Nature 224, 65–67.
Phillips, E., 2006. Micromorphology of a debris flow deposit: evidence of basal shearing, hydrofracturing, liquefaction and rotational deformation during emplacement. Quaternary Science Reviews 25, 720–738.
Phillips, E., Merritt, J.W., Auton, C.A., Golledge, N.R., 2007. Microstructures developed in subglacially and proglacially deformed sediments: faults, folds and fabrics, and the influence of water on the style of deformation. Quaternary Science Reviews 26, 1499–1528.
Phillips, E., van der Meer, J.J.M., Ferguson, A., 2011. A new 'microstructural mapping' methodology for the identification, analysis and interpretation of polyphase deformation within subglacial sediments. Quaternary Science Reviews 30, 2570–2596.
Phillips, E., Cotterill, C., Johnson, K., Crombie, K., James, L., Carr, S., Ruiter, A., 2017. Large-scale glacitectonic deformation in response to active ice sheet retreat across Dogger Bank (southern Central North Sea) during the Last Glacial Maximum. Quaternary Science Reviews 179, 24–47.
Phillips, E., Carter, G., Teasdale, D., 2022. Microscale evidence of the role of water during the emplacement of mass flows in glacial environments. Quarterly Journal of Engineering Geology and Hydrogeology 55, 2021–2026. https://doi.org/10.1144/qjegh2021-026.
Reinardy, B.T.I., Lukas, S., 2009. The sedimentary signature of ice-contact sedimentation and deformation at macro- and micro-scale: a case study from NW Scotland. Sedimentary Geology 221, 87–98.
Roberts, D.H., Evans, D.J.A., Lodwick, J., Cox, N.J., 2013. The subglacial and ice-marginal signature of the North Sea Lobe of the British–Irish Ice Sheet during the Last Glacial Maximum at Upgang, North Yorkshire, UK. Proceedings of the Geologists' Association 124, 503–519.
Roberts, D.H., Evans, D.J.A., Callard, S.L., Clark, C.D., Bateman, M.D., Medialdea, A., Dove, D., Cotterill, C.J., Saher, M., Ó Cofaigh, C., Chiverrell, R.C., Moreton, S.G., Fabel, D., Bradwell, T., 2018. Ice marginal dynamics of the last British-Irish Ice Sheet in the southern North Sea: ice limits, timing and the influence of the Dogger Bank. Quaternary Science Reviews 198, 181–207.
Roberts, D.H., Grimoldi, E., Callard, L., Evans, D.J.A., Clark, C.D., Stewart, H.A., Dove, D., Saher, M., Ó Cofaigh, C., Chiverrell, R.C., Bateman, M.D., Moreton, S.G., Bradwell, T., Fabel, D., Medialdea, A., 2019. The mixed-bed glacial landform imprint of the North Sea Lobe in the western North Sea. Earth Surface Processes and Landforms 44, 1233–1258.
Rose, J., 1985. The Dimlington Stadial/Dimlington Chronozone: a proposal for naming the main glacial episode of the Late Devensian in Britain. Boreas 14, 225–230.
Sharp, M.J., 1988. Surging glaciers – geomorphic effects. Progress in Physical Geography 12, 533–559.
Straw, A., 1979. The Devensian glaciation. In: Straw, A., Clayton, K.M. (Eds.), The Geomorphology of the British Isles: Eastern and Central England. Methuen, London, 21–45.
Thomas, G.S.P., Chiverrell, R.C., 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, G.S.P., Chiverrell, R.C., 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.
Valentin, H., 1957. Glaziamorphologische Untersuchungen in Ostengland. Abhandlungen Geographischen Institute Freien Universitat Berlin, 4 pp. 1–84.
van der Wateren, F.M., Kluiving, S.J., Bartek, L.R., 2000. Kinematic indicators of subglacial shearing. In: Maltman, A.J., Hubbard, B., Hambrey, M.J. (Eds.), Deformation of Glacial Materials, Geological Society of London, Special Publication, 176, 259–278.