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Leszczynska, K., Boreham, S. & Gibbard, P. L.: Middle Pleistocene ice-marginal sedimentation in the transitional zone between the constrained and unconstrained ice-sheet margin, East Anglia, England.

It is uncommon in the North Sea basin and north-western Europe for the ice-marginal glacial successions of the Middle Pleistocene, Anglian (Elsterian) age to be well preserved and not overridden by subsequent glaciations. The existence of extensive and thick (~20 m) Middle Pleistocene sand and gravel successions in East Anglia, England provide a unique opportunity to reconstruct and understand the palaeoenvironmental conditions in the Anglian ice-marginal zone, and further across the North Sea basin. This paper uses data from 80 sections in two sand and gravel quarries in East Anglia to provide the first evidence concerning: i) the character of the ice-marginal processes in the unique, transitional zone between the topographically-constrained and unconstrained Anglian ice-sheet margin; ii) the role of meltwater in the re-shaping of topographically-driven pre-glacial drainage; and iii) the position and the number of oscillations of the Anglian ice-sheet margin in the form of a sediment-landform assemblage. Moreover the current research adds to the discussion on the presence and extent of the pro-glacial lake in the North Sea Basin during the Anglian glaciation. The sand and gravel successions in the Anglian ice-marginal zone are primarily reworked proto-Thames sediments deposited by meltwater. At the beginning of the glaciation, the meltwater followed the pre-glacial (proto-Thames) river course. However, as the ice-sheet advanced, it was re-routed, overwhelming and abandoning the old river course and depositing an extensive ice-marginal subaqueous fan. The succession includes evidence for at least two enhanced meltwater release events, as well as indications of glaciolacustrine sedimentation. The character of the described sedimentary settings is discussed in the wider context of the presence of the North Sea Lake.

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East Anglia, England, is one of only a few areas in the North Sea basin and north-western Europe where the deposits and landforms of the Anglian age, equivalent to the Elsterian in north-western Europe (480-420 ka BP) have not been overridden by subsequent glaciation, and ice-marginal sediment-landform assemblages are preserved (Fig. 1A). Here, during the Anglian glaciation, the ice-sheet overrode the pre-existing River Thames Kesgrave Formation deposits of the pre- and early-Anglian age, contributing to the diversion of the river (Fig. 1B, C) (Bristow 1985; Gibbard & Allen 1994; Lucy 1999). At this time, the ice-front in this area abutted the significant, elongated, London Clay ridge, named the Danbury-Tiptree ridge, formed south-west of the town of Colchester. This major barrier prevented the ice from expanding further to the south-east (Bristow 1985). Parallel to the ridge, on its north-western slopes, on the stoss side towards the ice-sheet, a deep channel has been cut within the London Clay and filled with Quaternary deposits. The channel ends in the vicinity of Colchester (Bristow & Lake 1975; Bristow 1985) (Fig. 1D).

In contrast, to the north-east of Colchester, the ice-front was unconstrained: freely-flowing, not constrained by any obstruction (Ellison & Lake 1986). Here the London Clay creates a low-lying landscape, and the Anglian ice-sheet margin terminates on flat ground, allowing the meltwater to accumulate outwash deposits in a pattern of discontinuous proglacial landforms (Bristow & Lake 1975; Bristow 1985) (Fig. 1D).

The transitional zone between the constrained and unconstrained ice-sheet margin has been identified in the Birch-Stanway area, the current research area, to the south-west of Colchester. There, extensive and thick successions of Middle Pleistocene sediments, mainly sand and gravel, have been deposited (Fig. 1D, E). As this is a distinctive sedimentary setting, unlike any other within the boundaries of the Middle Pleistocene ice-sheets in north-western Europe, the site represents a valuable opportunity for the exploration of unusual environmental contexts.

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Moreover, the Birch-Stanway area is located in the south-western periphery of the North Sea basin. During the Anglian glaciation, the British and north-European ice-masses were confluent, blocking the North Sea basin in the northern part, preventing water from escaping to the North Atlantic. They created an extensive closed, freshwater body - the North Sea Lake (Fig. 1A). The lake has been drained through the Weald-Artois (Roep *et al.* 1975; Gupta *et al.* 2007; Toucanne *et al.* 2009a; 2009b). The water level in the North Sea Lake depended on the interplay between the meltwater and the north European rivers inwash, the isostatic depression of the surrounding area and elevation of the basin. The sedimentological evidence for the presence of this lake is in the form of waterlain glacial diamictons and meltwater sediments constituting delta and lake-bottom deposits in northern and eastern East Anglia (Kazi & Knill 1969; Banham 1970; Gibbard 1980; 1988; Gibbard & Zalasiewicz 1988; Banham 1988; Lunkka 1988; Eyles *et al.* 1989; Lunkka 1991; Hart 1992, 1994; Lunkka 1994; Gibbard 1995; Moreau & Huuse 2013). There is still no direct sedimentological evidence for the North Sea Lake deposits in the southern part of the North Sea at the Dutch coastline, nor in northern Germany. Instead of supposed glaciolacustrine sedimentation (Cohen *et al*. 2008) there exist extensive sub-glacial tunnel valleys (Stackebrandt 2009; Ehlers *et al.* 2011). It has been suggested that the glaciolacustrine deposits identified within the North Sea Basin represent numerous separate glacial lakes and tunnel valleys, partly filled with glaciolacustrine deposits, associated with the Anglian ice-sheet (Laban & van der Meer 2011). As the debate on the precise extent and timing of the North Sea Lake and its water level continues, knowledge of the Birch-Stanway area would provide some of the missing evidence concerning the presence of the lake.

The new sedimentological, lithological and geophysical observations presented in this paper can be used to critically evaluate existing hypotheses by illustrating the unique palaeoenvironment in which the sediments were deposited. The aims of the current study are:

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i) to investigate the sedimentary succession; ii) to reconstruct the palaeoenvironment of deposition; iii) to explore the depositional domain at the transition between the topographically constrained and unconstrained ice-front; iv) to discuss the role of the pre-existing River Thames and Anglian ice-marginal meltwater drainage in the shaping of the sedimentary succession and palaeogeography of this area; v) to reconstruct the position of the Anglian ice-sheet margin and the number of enhanced meltwater release events; and finally vi) to open the discussion concerning the possible connection between the Anglian ice-sheet margin and the North Sea glacial lake.

Study area

In the Birch-Stanway area, the ground surface is gently inclined from 61 m Ordnance Datum (OD) in the north-west, in vicinity of Birch Quarry (National Grid Reference: TL 592000 218000), to 19 m OD in the south-east near Abberton Reservoir (TL 595000 216000; Fig. 1E). The bedrock here is composed of the Tertiary (Paleogene) London Clay of the Thames Group, the surface of which dips gently to the south (Bell 1985). In the north-western part of the research area, the London Clay is overlain by ~15-26 m of unconsolidated Middle Pleistocene deposits. The Pleistocene sediments become discontinuous south-east of the B1022-Birch Quarry-Stanway Quarry line. There the London Clay forms outcrops at the surface in an area of low relief (Ambrose 1975) (Fig. 1E).

Despite the numerous accounts of the geology of the Birch-Stanway area (Ambrose 1973, 1974, 1975), the British Geological Survey (BGS) Memoir (Ellison & Lake 1986), extensive borehole data (available at the BGS) and unpublished site reports (Bell 1985; Arditto 1995; Bailey 1995), there remains no consensus regarding the palaeoenvironment of deposition of the Middle Pleistocene sediments and several hypotheses have been proposed. The deposits in the Birch-Stanway area have been interpreted to be of varying origins: i) glacial sediments of the Lowestoft Formation (Anglian age) deposited in a pro-glacial lake

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(Bell 1985; Bailey 1996); ii) fluvial sediments of the Kesgrave Formation (pre- and early-Anglian age) deposited by the pre-diversion River Thames (Arditto 1995) or iii) sediments of mixed glacial and fluvial origin (Bristow & Lake 1975; Bristow 1985; Ellison & Lake 1986).

Similarly, no definite conclusions were drawn by the research on the lithological composition and the provenance of the deposits in the Birch-Stanway area. The glacial Lowestoft Formation sand and gravel (Anglian age) and the fluvial Kesgrave Formation deposits (pre- and early-Anglian age) are not completely lithologically distinct and all differences tend to be local and site-specific (Table 1, 2) (Hey 1965, 1976; Hey & Brenchley 1977; Green & McGregor 1978; Green *et al.* 1980; 1980; 1982; Bridgland 1983a,b; McGregor & Green 1986). In the vicinity of the Birch-Stanway area, deposits correlated with the Lowestoft Formation have been described at all elevations above sea level, while those defined as Kesgrave Formation have only been found between 15 and 20 m OD (Bristow 1985; Ellison & Lake 1986).

Methods

The investigations of the sedimentary succession in the Birch-Stanway area were undertaken at two quarries (Fig. 1D, E): Stanway (Fig. 2) and Birch (Fig. 6), where the Quaternary deposits are 21 and 26 m thick, respectively. The exposures were divided into faces (continuous exposures) and sections (localised exposures within faces). In total, 80 sections (54 in 13 faces at Stanway, 26 in 13 faces at Birch) were photographed, sketched to scale and presented as vertical profile logs (Krumbein 1937; Krumbein & Pettijohn 1938; Jones *et al.* 1999; Evans & Benn 2004). All the localities were mapped and surveyed relative to Ordnance Datum (OD) using a Leica SmartNet Global Positioning System (GPS) system. Information was gathered on the primary sedimentary structures, texture, sorting of sediments, spatial relations and contacts between discrete beds. The main palaeoflow direction was determined on the basis of the dip diections of the planar cross-beds (ripples) and foresets of dunes. The

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identification of the foresets and backsets allowed the main palaeoflow direction to be determined. For the purpose of the publication, data were presented in form of photopanel, line-drawings (Figs. 2, 6) and composite logs (Figs. 3, 7) of the exposures critical for understanding the whole succession. Additional section logs and their correlation are presented as Supporting Information (Fig. S1-5).

The collected observations were used to divide the sediment into discrete sedimentary facies (Eyles *et al.* 1983; Evans & Benn 2004). The facies were coded based on Miall (1977; 1985) and Maizels (1993, 1997) (Table 3) and grouped into facies associations, herein further referred to as FA, as they occur together most often in the field (Table 4). The analysis of these associations allowed the palaeoenvironments of the deposition to be reconstructed.

The section logging at Stanway Quarry was supplemented by a ground penetrating radar (GPR) survey. The GPR was deployed in common off-set mode, with two separate transmitting and receiving shielded 100 MHz antennae. The transects were conducted according to Regli *et al*. (2002) and Beres *et al*. (1995). The raw data were post-processed using RADAN software. After the surface position adjustment (time zero drift) and surface normalization, the sequence of processing steps consisted of: i) background removal; ii) vertical and horizontal high and low pass filter; iii) migration; iv) deconvolution and v) gain adjustment. The GPR data was interpreted using radar stratigraphy (Gawthorpe *et al.* 1993; Neal 2004), based on the recognition of radar surfaces (RS) and radar facies (RF). The radar facies were used to identify the facies and their extent in unexposed or partially-exposed areas. To correlate the GPR transects with the sedimentary facies and boundaries exposed, a control transect (transect 1, Fig. 4A, B) was placed above the exposure, so that the radar facies and radar surfaces could be correlated with real sedimentary facies and boundaries of *in situ* deposits. Morover, two control boreholes were laid in line with the GPR transects (bhS1 and bhS2; Fig. 5A).

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Borehole data from the BGS archives was used to contextualise the field observations. The original descriptions of the deposits within the boreholes were unified prior to interpretation and divided into one of three main categories: i) gravelly, ii) sandy or iii) diamicton facies. Rockworks software was employed to construct geological cross-sections based on the collected borehole data (Fig. 5).

Clast lithological analysis (CLA) was used to trace the origin of the sand and gravel deposits. Samples taken from exposures were analysed at the Physical Geography Science Laboratories at the University of Cambridge, according to Bridgland (1986), with four size ranges adopted: 8-11.2, 11.2-16, 16-32 and >32 mm. These size ranges were chosen so that pebbles were clearly identifiable, but also to allow for comparison with previous research. A minimum number of 700 clasts was counted in each sample, and the typical sample size was ~15-20 kg. Based on the literature, a clast reference collection was prepared. The presence of angular, nodular and rounded flint, as well as *Rhaxella* Chert (Table 2), was interpreted as evidence for the glacial origin of deposits of the Lowestoft Formation (Hey 1976; Green *et al.* 1980). In contrast, lithologies such as quartz, quartzite, sandstone, siltstone, pinhole chert (Hey 1965, 1976), Greensand chert (Green & McGregor 1978; Bridgland 1986), volcanic and igneous rocks (Table 2), were defined as characteristic of deposits brought into the area by the proto-Thames river and its tributaries, prior to the Anglian glaciation (Hey 1965, 1976; Green & McGregor 1978; Bridgland 1986, 1988). The characteristics of all lithological types is given in Table 2 and clast lithological analysis results of this and previous research is given in Tables 1 and 5.

Sedimentary facies and depositional geometries

The deposits described from the Birch-Stanway area were characterised in terms of their lateral and vertical facies association relationships. The gravelly facies association G1 and G3 and clay, silt and sand of F1 are present only at Stanway Quarry, while the deformed sand of

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S1 and diamicton of D1 are only characteristic of the Birch Quarry exposures. The remaining gravelly G2 and sandy S1 facies associations occur at both sites. The Middle Pleistocene sand and gravel deposits at the Birch and Stanway quarries rest on a highly undulating erosional surface of Tertiary London Clay at ~15-18 m OD. The deposits, particularly the pebble to cobble fraction running throughout all the exposures/units within both sites, have a similar lithology: angular flint prevails with an admixture of rounded flint, quartz and quartzite. Other lithologies occur in negligible amounts (Table 5).

Stanway Quarry deposits

All the facies associations described from Stanway Quarry create thick, tabular persistent units and all, with the exception of facies association F1, laterally extend throughout the area of the quarry. The overall geometry of all the beds is subhorizontal. The area covers ~600 m from north to south, in the flow direction, from the ice-proximal to the ice-distal area, and ~500 m from west to east, across the direction of flow, roughly along the predicted ice-sheet margin (Fig. 2A inset). The ground surface within this area dips gently towards the south, from ~40 m OD in the northernmost to 38 m OD in the southernmost part of the Stanway Quarry. The succession overlying the London Clay at Stanway Quarry varies along the palaeoflow direction from the north-north-west to the south-south-east: i) there is a fining particle size trend within the discrete sedimentary units and ii) gravel-rich deposits pass into sandy deposits. The deposits from Stanway Quarry were described in stratigraphical order, from bottom to the top, starting with the basal gravelly facies association G1 deposited within the erosional, elongated depression located in the central area of the quarry working. In order to depict the vertical and lateral (in flow direction) changes of facies association, the description of the deposits overlying unit G1 was grouped into the description of the sediments from the northernmost part of the quarry, the middle part of the quarry (located 350

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m towards the south, in flow direction) and the southernmost part of the quarry (located 200 m towards the south, in flow direction).

The lower boundary of the lowermost, distinctive G1 gravelly facies association is not exposed and the upper boundary is only partially exposed (Fig. 2G). The GPR was deployed to describe the dimensions of unexposed unit G1 under the quarry floor. The results show that this facies association, represented by radar facies RF1, reaches 4-6 m below the base of the quarry, to ~13-15 m OD. G1 rests directly on the London Clay (transect 1 and 2, boreholes bhS1, bhS2; Fig. 4) filling an elongated erosional, channel-like depression aligned from the south-west to the north-east within the quarry. Transect 1 cuts across the feature and shows the boundary of the depression (50-60 m along transect 1; Fig. 4B). The channel is ~3-3.5 m deep and excess 60 m in width. The GPR trace of the gravelly unit G1 (RF1; Fig. 4C, D) does not show distinctive signature beside few lobe-shaped features within the transect 2 (Fig. 4C). On the contrary within the GPR trace of unit G2 (RF2 and 3) there are low-angle clinoforms (RF2; Fig. 4B) and lobe shape features defined as convex-up architectural elements (RF3; Fig. 4C) identified.

Facies association G1 comprises pebble to cobble, poorly-sorted gravel and represents the only unit where the gravel fraction >16 mm exceeds 25% of the total volume of the sample. This is the coarsest facies association in the whole succession. Moreover, this is the only unit where clay intraclasts (nodules, rip-up clasts derived from the underlying London Clat) occur.

Crudely horizontally-stratified gravel of G1 (Table 4) is arranged in places in faint trough cross- and solitary planar cross-stratifications (angle of 10-15°). Within generally matrix-supported sediments, units of clast-supported to open-work gravel occur, especially within solitary planar cross-beds (dip up to ~20°). Tabular and lenticular beds of massive to diffusely horizontally-bedded pebbly sand are present. Frequent erosional surfaces and scour

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fills cut the deposit. The scour fills are 0.1-0.4 m deep and laterally extend for ~20 m. They are filled with massive to cross-stratified matrix supported to openwork gravel (cross-strata dip at an angle of~15-20°). The solitary cross-strata dip towards the east and north-east and imbricated clasts with a-axis transverse and b-axis inclined - a (t) and b (i); dip towards the west. Across-flow a-transverse orientated pebbles confirm the direction of the axis of the palaeocurrent.

Filling an elongated erosional, channel-like depression, facies association G1 is not present within the whole quarry working. In the northernmost part of the quarry (for location see Fig. 2A inset), at the point most proximal to the ice-sheet margin (Fig. 2A-E), the entire thickness of the succession overlying the London Clay, consists of two juxtaposed units of gravel of facies association G2. The entire exposed thickness of the lower unit of facies association G2 here (from 21 to 33 m OD) comprises massive to horizontally diffusely-stratified gravel (Fig. 2B-D). Within the upper level of G2, massive to horizontally diffusely-stratified gravel is interbedded with massive to planar parallel-bedded sand which is only occasionally planar cross-bedded (angle of dip <20°; Fig. 2E-H). These continuous, tabular gravel and sand units laterally extend for a few hundreds of metres. Here, the beds of gravel are up to few metres thick, while the beds of sand are a few decimetres thick. Within both levels imbricated clasts are observed; they dip towards the north with a-axis transverse and b-axis inclined - a (t) and b (i). This unit of G2 is truncated at the level of 32-33 m OD by a sharp horizontal, easily distinguishable boundary associated with an erosional surface or a break in sedimentation (hereafter referred to as ES). From this level it is penetrated by two to two and a half metre-deep ice-wedge casts (Fig. 2E). These ice-wedge casts occur every 10-15 metres along the face and are present only in the northernmost part of the quarry where the succession cosists only of the overlying units of gravel of G2.

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When comparing both juxtaposed units of gravel G2, the maximum clast size in the upper unit (mean D-value between 8.8 and 9.67 mm, with 5-11% of a sample > than 16 mm) is smaller than in the lower one (mean D-value between 12.07 and 13.26 mm, with 30-46% of a sample > than 16 mm). The uppermost sediments within the upper unit of G2, which reaches up to 39.5 m OD, are red-stained. From this locality towards the south south-east of the quarry working, in the flow direction, the gravel of both, lower and upper unit of G2, becomes finer, the proportion of sand within matrix increases and sandy beds become thicker at the expense of the gravel beds (Fig. 2F and the general stratigraphy of this part of the quarry in form of the composite log SC1 in Fig. 3).

In the middle part of the Stanway Quarry, about 350 m further south of the northernmost exposures, along the palaeoflow direction, the succession consists of basal gravelly facies association G1 described from the elongated depression within the London Clay, overlain by gravel of facies association G2 (from 17.5-18 to 20-21 m OD) in places laterally gradually changing into facies association G3, both overlain by sandy facies association S1 (from 20-21 to 30 m OD), capped with sand, silt and clay facies association F1 (from 30 to 31 m OD) and again, the upper unit of gravelly facies association G2 (from 31 to 39 m, the ground surface) (photopanels in Fig. 2G-J and composite log SC2 in Fig. 3). The boundaries between all the units are gradational, with the exception of the base of the upper unit of gravel G2, which is erosional.

In exposure (Fig. 2G) and in the GPR the boundary between gravelly unit G1 (RF1) and G2 (RF2 and RF3) is undulating, sharp, but non-erosional. While the gravelly unit G2, overlying G1, displays the same characteristics described from the northernmost part of the quarry, in this area, it is thinner and reaches ~20-21 m OD. In this part of the quarry in places G2 is replaced by distinctive large-scale planar cross-stratified gravel of facies association G3 (Figs. 2M, 3). It extends laterally for >150 m (accurate lateral extent is obscured by slump

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deposits of a quarry face). Due to the inaccessibility of exposure, it was not possible to trace whether the lateral change between G2 and G3 is gradational or sharp and erosional. The unit of planar cross-bedded gravel is ~1.5 m thick. It is underlain and overlain with gravel of the lower unit of facies association G2. The lower boundary of G3 is erosional, while the upper is sharp, but non-erosional. The individual beds dip with an angle between 15-22° towards the east, and south east and west within a single outcrop.

Both gravelly facies associations G2 and G3 are overlain by sandy deposits of S1 at the level of 21 m OD (Fig. 2M-R). The high variability of sedimentary structures and the rapid transition between structures and individual beds is typical of this association. It comprises lenticular and tabular discontinuous beds of planar parallel-, planar cross- and trough cross-bedded sand with small lenses of cross-stratified granule gravel. The individual beds of planar parallel- and planar cross-bedded sand are 10 to 40 cm thick, which are only occasionally thicker and extend laterally for a few metres. The lenses of granule gravel are up to 40-50 cm thick and laterally do not exceed 2 m. The planar cross-beds within the sandy deposits dip towards the south-east with an angle of 10-12°. Multiple erosional scours and chutes-and-pools are also described from this unit (Fig. 2M-R). The chutes and pools are filled with planar to sigmoidal and concave-up, downflow-divergent cross-beds and rare boundary conformable laminae. Cross-beds within these features, which constitute backsets (based on comparison with the palaeoflow direction indicated by planar cross-beds) dip towards the north and north-west with an angle of <10°. The erosional scours are filled with sigmoidal cross-beds. Individual beds of planar parallel- and planar cross-bedded sand are 10 to 40 cm thick, thickening occasionally and extending laterally for a few metres. Likewise, erosional scours and chute-and-pools are 10 to 50 cm deep and span a few metres in lateral extent.

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At a level of ~29.6 m OD, unit F1, consisting of recurring cycles of fining-upwards sand, silt and clay (Fig. 2J-L), is identified above sandy facies association S1. Within these successions, massive or small scale planar and climbing ripple cross-laminated sand fines upwards into planar parallel-laminated to massive silt and clay. The beds of sand are between 10 and 20 cm thick, whilst the beds of silt and clay are a few cm thick. Unit F1 is absent towards the north of this locality, but gradually thickens towards the south. In places where recurring cycles of sand, silt and clay are few tens of centimetres thick, they are overlain with very stiff, massive clay and silt. This unit is overlain by an upper unit of gravel of G2 at the level of 31 m OD.

In the southernmost part of the quarry, another 200 m further towards the south in the flow direction, the exposures show a succession of the gravel of G2, overlain by the sand of S1, the sand silt and clay of F1 and again the gravel of G2 continues with only two alternations: i) the size range and the percentage of gravel particles within the upper unit of G2 decreases, and ii) the sand, silt and clay unit F1 thickens to reach >1 m (between 28.9 and 30 m OD) in the southernmost exposures of the quarry (Fig. 2K).

Along the western exposures within the quarry, the succession is similar to that presented above from the eastern part, but lack the units of the lowermost gravel of G1 and cross-stratified gravel of G3. In the western part of the quarry, as in the eastern part, the lower unit of gravel of G2 gradually changes into the sandy unit of S1. Further south, unit F1 appears between the sandy deposits of S1 and the upper unit of gravel of facies association G2. All the sedimentary characteristics of these units are as described from the eastern part of Stanway Quarry.

All the sedimentary units described above dip gently towards the south, i.e. in the direction of the palaeoflow. This is demonstrated by the dip of the base of the upper unit of

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gravel G2: from 32 m OD in the northernmost to 30 m OD in the southernmost part of the Stanway Quarry working.

Geological transects based on the borehole records are used to extend the entire sedimentary succession described from Stanway Quarry into unexposed areas (Fig. 5A, C). Three characteristics appear from the description of these transects: i) while the boreholes in the north of the transect with the north-south alignment are gravel dominated, the south of the succession is dominated by sandy deposits; ii) there is an apparent gravel unit which consistently starts at a height of ~30-31 m OD in the north-to-south aligned transect 2, boreholes 10-20 (Fig. 5A, C); iii) the presence of the two units of gravelly deposits and sandy facies between them. This pattern broadly corresponds to the succession of deposits described from the quarry.

Birch Quarry deposits

The facies associations described from Birch Quarry occur as thick continuous tabular units extending throughout the area of the quarry workings, ~300 m from the north to south, in the current direction, from the ice-proximal to ice-distal area and ~300 m from the west to the east, across the flow direction, roughly aligned along the predicted ice-sheet margin (Fig. 6A inset). The overall geometry of all the beds described within the succession is subhorizontal.

The depositional succession at Birch Quarry starts with 3-4 m-thick unit of gravelly facies association G2 (from 18 to 21-22 m OD) (Figs. 6B, 7) at the base of the whole quarry (face I and II), where exposures can be seen. The massive to horizontally diffusely-stratified gravelly beds within this unit are a few tens to a few hundreds cm thick. They are interbedded with units of massive to diffusely planar, parallel- and planar cross-bedded sand and pebbly sand. Individual beds of sand are ten to a few tens cm thick and laterally extend for more than few metres. The percentage and the size of gravel particles within gravelly beds of G2 decreases, while the sandy units thicken to reach >1 m towards the east, across the palaeoflow

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(Fig. 6C) and towards the south, parallel to the palaeoflow direction. The planar cross-beds within the sand dip towards the south and south-east with an angle of ~15°.

Towards the top of the succession, around 21-22 m OD, gravel and sand units of G2 gradually change into sandy deposits of S1 (Fig. 6C, D; 7). This unit can be traced continuously across the quarry. The sandy deposits of this unit consist of lenticular and tabular discontinuous beds of trough- and planar cross-bedded and planar-parallel pebbly sand. The sand beds display subhorizontal geometry. They are cut with multiple erosional surfaces and chutes-and-pools features, which are 50 to 60 cm deep and two to three metres wide. Planar cross-beds dip towards the south and south-east with an angle of ~15°. On the contrary, within the chutes-and-pools, sigmoidal to concave-up in places downflow divergent laminae show backset cross-stratification and dip steeply (15-20°) towards the north. Erosional scours are filled with cross-beds characterized by the dip up to 15-20°.

At the level of ~26-27 m OD, this 4-5 m-thick sandy unit (S1) is directly overlain by the gravel of G2 (Fig. 6E; 7). Similarly, as in the lower unit, gravelly beds are present, consisting of massive to horizontally diffusely stratified gravel a few tens to few hundreds cm thick. They are interbedded with units of massive to diffusely planar parallel-bedded sand up to 20 cm thick. These sandy units are discontinuous and less ubiquitous than in the lower level of G2. The upper gravelly unit G2 reaches up to 30-31 m OD and the boundary at this level is traceable throughout the quarry. As at Stanway, the gravel is disrupted by extensive (2-2.5 m-deep) ice-wedge casts at this level (Fig. 6F). Ice wedge casts occur only in the north-western part of the quarry (Fig. 6E, F, inset).

In the north-western part of the quarry, in the area proximal to the ice sheet, above 30-31 m OD, the succession starts with the massive pebble to cobble gravel of facies association G2 (Fig. 6G), the characteristics of which match those described from the lower level of gravel G2. This gravel, present above 30-31 m OD in the north-western part of the quarry

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gradually passes towards the south and south-east (along palaeoflow direction) into sandy unit S1. In the southernmost part of the quarry, distal to the ice-sheet margin, above 30-31 m OD, the sandy deposits of S1 are present instead of the gravel of G2 (Figs. 6K, L, 7).

The gravel in the north-western part of the quarry is overlain at the level of 40-41 m OD by a distinctive unit of deformed sand of S1 2-3 m-thick (Fig. 6I, J). The lower boundary of S1 is sharp and undulating. The deformation structures consist of overturned and recumbent folds, as well as small-scale convolute lamination. The axial plane of the fold described from section I and J (Fig. 6I, J) was horizontal and followed the direction north-north-west to south-south-east. Some of the folds were bounded by an erosional surface. The deformed sandy unit thins, disappearing towards the south, in the direction of flow.

The top of the succession at Birch Quarry comprises a massive diamicton of facies association D1described from both the north-western and southern part of the quarry (Fig. 6H, K, L). According to contextual observations this unit is continuous between these faces. In the north-west, D1 truncates the underlying deformed sand of S1 at a level of ~43 m OD (Fig. 6H). In the south-eastern part of the quarry, it directly overlies the sandy deposits of S1 (Fig. 6K, L). Beyond face XIII, diamicton D1 thins and finally disappears. The succession described above is presented in form of two composite logs depicting key localities within the quarry (Fig. 7).

Similarly to Stanway, in the Birch area, geological transects based on borehole evidence confirm the general characteristics of the succession described from the quarry exposures. The presence of sand interbedded with two units of gravel and the uppermost unit of diamicton D1 is confirmed in transect 1, aligned from the north-west to the south-east (Fig. 5B, D); however, the upper unit of deformed sand underlying D1 is not described from the boreholes. The units of gravel thin from the north-west to the south-east in the downflow direction, from the proximal to distal environment. In transect 2, which runs across the

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palaeoflow direction, towards the south, off the quarry area, all the boreholes confirm the presence of gravel-dominated succession and there are no significant changes in the amount of coarse-grained component along this line, with the exception of the borehole in the middle of the transect (Fig. 9B).

Birch and Stanway Quarry deposits - interpretation

Glaciofluvial Facies Association (FA G1). The GPR data confirms that the gravel of G1 present at the base of the succession at Stanway Quarry was deposited in a south-west to north-east-aligned channel eroded in the London Clay surface. The channel is ~3-3.5 m deep and excess 60 m in width. The secondary radar surface SRS1 described within RF1 is interpreted as representing either the London Clay or a local reflector associated with the presence of high concentrations of clay and silt within gravel matrix (Fig. 4).

The poorly sorted pebble to cobble, matrix-supported to openwork gravel of this facies association indicates rapid aggradation in supercritical flow conditions. Crudely horizontally stratified units are interpreted as being deposited by traction currents. The presence of imbricated clasts indicates deposition taking place as a bedload 'lag' or within longitudinal bars (Miall 1978). Tabular units of planar cross-stratifications represent the downflow transport of bedload on a braidplain as longitudinal bars (Boothroyd & Ashley 1975; Plink-Bjorklund & Ronnert 1999). Lenticular beds of massive or diffusely horizontally-bedded pebbly sand are interpreted as scour-fills associated with rapid cut-and-fill processes related to supercritical flow conditions (Winsemann *et al.* 2009; Lang & Winsemann 2013) (Fig. 2G).

However in the GPR transects there are no unequivocal indications of the palaeoflow direction within unit G1 (RF1), the palaeoflow direction indicated by solitary cross-stratification and imbricated clasts within exposures of G1 points towards the east and north-east, with the axis of the flow confirmed by the presence of a-axis transverse pebbles.

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The deposits of facies association G1 may be compared with either ice-proximal deposition within the high energy braided environment with migrating channel bars or as jet efflux sediments associated with supercritical conditions in ice-proximal environment (Winsemann *et al.* 2009; Lang & Winsemann 2013).

Subaqueous Fan Facies Association (FA G2, G3, S1). The basal portions of the gravelly facies G2 are well depicted within the GPR transects (Fig. 4). The undulating lower boundary of this unit is here confirmed. The low angle clinoforms within unit G2 (RF2) are aggradational forms, which confirm the direction of palaeoflow as described from exposures (Fig. 4B). The lobe shape features shown by the GPR traces within unit G2 (RF3) across flow are compared with features typical for fan or shallow-water delta deposits (Fig. 4C).

Facies association G2 in the northern part of both sites displays the characteristics of sediments rapidly deposited from sediment-laden flow in a high-energy environment, with high competence and discharge (Collinson & Thompson 1989) (Fig. 4B-D). The lack of erosional zones and lack of channel-like features confirm the presence of sediment overloading (Postma 1986). Such substantially thick, persistent units of matrix-supported, massive gravel, as represented by the lower unit of G2, are known to result from supercritical sheetflows (Krzyszkowski & Zielinski 2002), non-cohesive debris flow (Shanmugam 2000) or rapid sedimentation from sediment density flow (Postma 1986). Horizontally diffusely-stratified gravel was deposited from traction in lower concentration portions of the flow (Plink-Bjorklund & Ronnert 1999) or gravelly antidunes (Lang & Winsemann 2013). The poor sorting and coarse character of the deposits indicate a short transport path. The presence of imbricated clasts indicates palaeoflow towards the south.

Beds of massive sand within facies association G2 were deposited from the sandy debris flow, from suspension, following the deceleration of high-velocity sediment-laden flow (Maizels 1993; Shanmugam 2000; Bennett *et al.* 2002; Tucker 2006; Winsemann *et al.* 2009).

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The laminated sand was deposited by traction from lower concentration turbidity flows or flush floods under the conditions of an upper flow regime with a plane bed (Miall 1977). Small-scale cross-beds present in places within the sand indicate deposition within migrating sandy bars or dunes. Stacked successions of gravelly facies and massive, laminated and cross-bedded sand may also be interpreted as antidunes or humpback dunes. The downcurrent dip of the planar-cross beds indicates the palaeocurrent direction towards the south-east, as predicted for the meltwater from the Anglian ice sheet in this part of England, and roughly perpendicular in relation to gravel of G1.

Within both levels of facies association G2 at both sites, an apparent downcurrent and upward-fining trend can be seen. The decreasing size of clasts and percentage amount of gravel within the deposit towards the south-east (Fig. 2F) is evidence for two possible scenarios: i) a downcurrent flow transition, i.e. a rapid decrease of flow competency and energy of transport associated with flow splitting during fan/delta aggradation, or ii) a progressive decline in a sediment load, i.e. rapid deposition of the coarse-grained component at the beginning of the transport path, after/during a hydraulic pulse (Marren 2001; Bennett *et al.* 2002). The smaller maximum clast size in the upper unit of G2 is evidence of relatively lower energy of transport and deposition than in the lower unit of G2, or a longer distance with respect to the source area, in this case the ice front. The presence of well-developed ice-wedge casts (Fig. 2E)at the level of 30-31 m OD within the uppermost part of the unit G2, indicates sub-aerial exposure of the deposits in a dry and cold climate.

The well-developed cross-stratification within the gravel of G3 in the southern part of Stanway Quarry (Fig. 2M), dipping towards the south-east and west, may be interpreted as i) the shallow-water mouthbar delta (Ashley & Smith 1985; Glanville 1997) or ii) the remnants of migrating two- or three-dimensional dunes. In the first, most probable scenario, the variety of palaeocurrent directions, which fit to the geometry of a delta lobe, results from the fact that

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the delta can prograde into a water body both longitudinally and laterally in relation to the delta apex. In pro-glacial conditions, its orientation is independent of the ice-front orientation (Clemmensen & Houmark-Nielsen 1981). The lateral extent of the foresets (a few hundreds of metres) precludes a large scour-fill origin for these foresets. In the second case, the migration of dunes requires constant discharge conditions for a long time period (Reineck & Singh 1980; Mulder & Alexander 2001; Benn & Evans 2002). As the wavelength of dunes influencing the size of developed cross-stratification is scaled to water depth, the significant thickness of the G3 bed in the 1.5 m range may indicate a significant depth of flow (Fielding 2006).

Facies association S1 is characterized by the high variability and rapid transitions between various sedimentary structures (Fig. 2N-R). These are caused by changes in the physical properties of the flow. Here, the fluctuating hydraulic conditions are related to either intrinsic variations of depth and velocity typical of transcritical and supercritical flow, or varying supplies of sediment and flow density (Miall 1977; Reineck & Singh 1980; Miall 1985; Alexander *et al.* 2001; Benn & Evans 2002). The presence of planar cross- and trough cross-bedded sand and pebbly sand with lenses of cross-stratified granule gravel is interpreted as the remnants of migrating two- and three-dimensional dunes (Church & Gilbert 1975; Smith 1985; Alexander *et al.* 2001; Marren 2001; Russell & Arnott 2003). These unconfined large-scale migrating bedforms are typical of a subaqueous setting with sustained high energy currents. Chute-and-pools filled by planar to sigmoidal cross-beds dipping upstream, towards the north and north-west (the paleocurrent direction confirmed by tabular units of planar cross-beds) are scoured upflow submerged hydraulic jumps, under conditions of dilution, reduced velocity and competence of flow. The backset cross-stratification may also be evidence for downflow-migrating humpback dunes (Massari 1996; Duller *et al.* 2008; Cartigny *et al.* 2012) typical of transcritical flow conditions (Lang & Winsemann 2013).

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Fine-grained glaciolacustrine Facies Association (FA F1). The distinctive fine character of facies association F1 (Fig. 2I-L) indicates deposition in a lower flow regime setting. Planar parallel-laminations are associated with deposition from traction in conditions of decelerating/expanding flow, while climbing cross-stratification indicates high rates of sedimentation under conditions of waning flow (Ashley *et al.* 1982). The uppermost part of this facies association, comprising stiff, massive to faintly planar-parallel laminated silt and clay, represents deposits of waning, low density turbidity currents or sedimentation from suspension within an extensive water body, i.e. a glaciolacustrine environment. Similarly, the apparent cyclic pattern of depositon presented by sandy silt and clay facies association F1 in pro-glacial conditions is typical of a lake setting with minimal meltwater discharge (Jopling & Walker 1968; Rust & Romanelli 1975; Reineck & Singh 1980; Collinson & Thompson 1989; Russell & Arnott 2003).

Glacial diamicton FA D1. The two uppermost facies associations described from the north-western part of the Birch Quarry, deformed sand facies S1 (Fig. 6H-J) and diamicton D1 (Fig. 6H, K, L), are interpreted as direct evidence of liquefaction of desposits and the presence of an ice-mass in form of glacial ice-lobe in this locality. Facies D1, present only at Birch Quarry, is interpreted as a diamicton deposited by i) solifluction or ii) directly from the ice sheet. The diamicton of unit D1 marks the maximum extent of the ice sheet in this area.

Synthesis and discussion

The succession described from the two quarries at Birch-Stanway area are illustrated in the schematic cross sections in Fig. 8 (Supporting Information Fig. S6 – with location of sections). There are several common features of both sites: i) the facies associations create thick, tabular, laterally continuous units, which indicate high aggradation rates and stable flow and discharge conditions within the time-space of a single water-release; ii) discrete bed dips are only in a range of few degree – the overall large scale geometry is subhorizontal; iii) an

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erosional boundary/break in sedimentation surface associated with periglacial features divides the succession at 30-31 m OD; iv) the deposits within all the facies associations fine down-current, from ice-proximal to ice-distal environment (from the north to the south). Features unique to the the Stanway Quarry comprise: i) a south-west to north-east aligned erosional depression in the London Clay surface filled by crudely horizontally, trough cross- to solitary planar cross-bedded clast and matrix-supported gravel of facies association G1; ii) facies association F1 consisting of recurrent successions of normally graded sand, silt and clay and stiff, massive clay and silt. Two typical features are present only in the Birch Quarry: i) deformed sand facies association S1 and ii) the massive structureless diamicton of facies association D1. As mentioned above, the succession in the Birch-Stanway area was previously interpreted as being of glacial (Bell 1985; Bailey 1996), fluvial (proto-Thames origin, Arditto 1995) and of partly glacial, partly fluvial origin (Bristow & Lake 1975; Bristow 1985; Ellison & Lake 1986).

Some of the characteristics of gravel unit G1, such as: i) the alignment of the channel in a south-west to north-east line; ii) the palaeocurrent direction towards the north-east indicated by sedimentary structures within exposures; iii) the altitude of deposits (between 13-15 to 17.5-18 m OD) and iv) the presence of lithologies characteristic of the Kesgrave Formation (quartz, quartzite, sandstone, pinhole and Greensand chert), coincide with characteristics predicted for the proto-Thames river and its deposits in this area (Gibbard 1995). However, at the same time gravelly facies association G1 including (i) a high percentage of the typical Lowestoft Formation lithologies (mainly angular flint); (ii) the pebble to cobble size of gravel; (iii) the presence of clay intraclasts derived from the underlying London Clay, and iv) poor sorting, closely resemble sediments deposited by the Anglian ice sheet meltwater. Following from this, the gravel of facies association G1 is interpreted as being deposited by meltwater, which flowed through the channel previously

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occupied by the pre-existing River Thames (Figs. 1B, 9A). Sedimentary features interpreted as deposited from traction, as a bedload lag, within longitudinal bars or minor channels indicate deposition within the braided river environment of the ice-proximal setting. At the initial stage of the Anglian glaciation, this channel became the main evacuation route for the glacial meltwater. The pre-existing Kesgrave Formation gravel, including material exotic to the area, was remobilised. Reworked clasts were diluted within the lithological components transported by the meltwater of the Anglian ice sheet and re-deposited in the Birch-Stanway area.

With time, as the Anglian ice sheet advanced closer to the Birch-Stanway area, the channel could no longer evacuate the excessive amount of meltwater. The water associated with the Anglian ice sheet began to flow across the valley towards the south-east and south, as predicted for the meltwater in this part of England (Fig. 9B). It deposited overlying sediments of facies association G2, S1 and F1. The lithological characteristics of this succession (mainly G2 and S1), i.e. the presence of clasts characteristic of the fluvial proto-Thames formation (quartz, quartzite, sandstone, pinchole and greensand chert) among lithological components typical of glacial affinities (flint, mainly angular), confirm that the deposits of the Kesgrave Formation gravel were reworked and re-deposited by water associated with the Anglian ice sheet. A similar view was proposed for the interpretation of the sand and gravel deposits from other areas of eastern England by Wood (1868), Clayton (1957), Bristow & Cox (1973) and Whiteman *et al*. (1995), including the Banham Sand and Gravel Member (glacigenic deposits described in the area north-west of Diss in Norfolk) by Mathers *et al*. (1987).

While considering various types of sedimentary environments within the pro-glacial domain, the Birch-Stanway succession shares many characteristics with an extensive subaqueous fan or a series of coalescing subaqueous fans and deltaic deposits within a glaciolacustrine setting (Ashley & Smith 1985; Winsemann *et al.* 2009; Lang & Winsemann

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2013). This interpretation partially supports the glacial interpretations previously advocated by Bell (1985) and Bailey (1996). The units of gravel G2, described from the northern and north-western parts of Birch and Stanway quarries, are the product of maximum sediment transfer in a gravel-dominated environment deposited close to the source area (ice margin), i.e. an ice-proximal setting (Miall 1977; Reineck & Singh 1980; Miall 1985; Smith 1985; Benn & Evans 2002). These sediments are dominated by highly aggradational supercritical flow, sheetflow, debris flow and traction deposits, but lacking easily identifiable channels and erosional surfaces (Blair & McPherson 1994). These features, together with the coarse and massive character of these deposits, indicate their deposition occurred during catastrophic floods. In the case of a pro-glacial setting, this type of event is associated with phases of peak meltwater discharge directly from the ice-masses or from beneath them (Rust & Romanelli 1975; Winsemann *et al.* 2009).

The gradational change from the north and north-west to the south and south-east, from gravel-dominated to sand-dominated deposits (from facies association G2 to S1) represents a progressive change from an ice-proximal to an ice-distal environment within the subaqueous fan setting. This area is characterised by a lateral flow transition associated with a decrease in flow competency and decline in sediment load. The lateral and the upward fining of the sediments from gravelly to sandy deposits is associated with the flow splitting at the mouth of the conduit(Winsemann *et al.* 2009; Lang & Winsemann 2013). The dominant well-developed cross-, trough cross-bedded and planar parallel-bedded sandy deposits of the upper portions of the facies association S1, are associated with large-scale, unconfined, migrating bedforms (dunes) - typical for the zone of established flow in a subaqueous fan setting (Lang & Winsemann 2013).

The two main levels of gravel and sand deposits in the Birch-Stanway area, divided by erosional surface ES at 30-31 m OD, associated with periglacial conditions, represent two

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main depositional events separated by a period of quiescence. The deposition of both units of G2 is interpreted as evidence for enhanced sediment transfer associated with intense ablation, interpreted as being caused by the retreat of the ice margin. As the meltwater within the ice-domain is transported via sub-, en- and supra-glacial conduits for long distances, its retreat and loss of ice-mass may not necessarily directly affect the closest vicinity of the Birch Stanway area, but may be of a more regional or distant local scale. The non-depositional event/hiatus in a pro-glacial environment may indicate halted ablation arising from deteriorating climatic conditions, as well as the associated standstill of the ice margin or even its advance (Smith 1985). The presence of periglacial features (ice-wedge casts within gravelly units G2), associated inherently with the subaerial exposure is also the evidence for the absence of glaciolacustrine conditions, following from the temporal, partial lake drainage. The lake drainage may be associated with palaeogeographical changes elsewhere or a negative drainage/inflow ratio – with dominance of drainage on inflow.

The direct evidence for a glaciolacustrine environment in the Birch-Stanway area is represented by fine deposits of sand, silt and clay of facies association F1 at the southernmost part of Stanway Quarry. The evidence for the close proximity of the ice-front to the Birch-Stanway area is present in the form of diamicton facies association D1. It is interpreted as having been deposited by the glacial ice and marks the southern and south-easternmost extent of the ice sheet in this area. The deformation structures within the underlying S1, indicate stress from the north-west, what is presumed direction of the ice-sheet advance in this part of East Anglia (Allen *et al.* 1991).

The absence of reworked glacial debris within the succession described from the Birch-Stanway area are atypical of subaqueous fans. This may be caused by i) the shallow water depth into which the meltwater deposited the gravel and sand and/or ii) an excessive

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amount of sediment transported by meltwater which were distributed evenly in the pro-glacial zone.

The subaqueous fan described from the Birch-Stanway area is interpreted to have been aggraded by a conduit-focused sedimentation (Fyfe 1990). The main source of meltwater is likely to have been a deep channel ('tunnel valley') cut within the London Clay on the north-western slopes of the Danbury-Tiptree ridge, to the south-west of the Birch-Stanway area (Bristow & Lake 1975; Bristow 1985) (Fig. 1D). The meltwater evacuated from the Anglian ice-sheet margin could not escape towards the south-east since that direction was blocked by the ridge. The lateral ice-marginal drainage was therefore deflected towards the north-east, parallel to the topographical barrier. At the north-eastern end of the ridge, meltwater was able to escape via the Birch-Stanway area portal, depositing substantial volumes of sand and gravel as a proglacial subaqueous fan system. The slightly variable palaeocurrent directions, with all generally trending towards the south-east, is caused by the flow splitting at the conduit mouth during fan aggradation(Winsemann *et al.* 2009) or less likely variable position of the water supply associated with multiple sub-glacial outlets (portals, conduits) separate for the Birch and Stanway quarry areas.

A regional perspective

The Birch-Stanway subaqueous fan complex was an ice-marginal meltwater evacuation route, which initially adopted the pre-existing course of the pre-diversion River Thames to some extent. The geographical situation of the Birch-Stanway subaqueous fan system, in the south-eastern part of East Anglia, implies that it potentially formed a linkage between the Anglian ice sheet margin and the lake formed by the ponding of pro-glacial waters by the ice sheet in the southern North Sea basin, as noted by Gibbard (1988, 1995, 2007) and Cohen *et al.* (2005) (Fig. 1A). These authors suggest that at its maximum, the water level of the lake reached ~30 m OD at the Dover Straits col; Gibbard & van der Vegt (2012) also confirm that levels in

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excess of 32 m are represented in northern East Anglia (Corton Member sediments). Following from this, the deposits of unit F1 at Stanway Quarry, interpreted as glaciolacustrine accumulation, occuring at the 30-31 m OD, intermediate between two discrete pulses of the sand and gravel deposition, may be direct evidence of the presence of the North Sea lake in this locality. The correspondence of these levels to those of the North Sea lake implies that it is likely that the Birch-Stanway subaqueous fan aggraded directly into this water body.

The conclusion that the Anglian ice-marginal zone was in direct contact with the contemporary North Sea lake in the Birch-Stanway area, as suggested by the sedimentology and elevation of the glaciolacustrine sediments within Stanway Quarry, represents an exciting opportunity for further detailed study of this proglacial system. The fruits of these studies would resolve some of the complexities arising from the correlation between the British and north-European successions and would contribute further to large-scale reconstructions of palaeogeographical evolution, including changes in water-level, isostatic adjustments, and erosion and deposition, through the Anglian/Elsterian glaciation (Gibbard 1988, 1995; Moreau & Huuse 2013). So far, attempts to link fine-grained deposits from the Birch-Stanway area with those of the North Sea lake by clay mineralogical analysis have confirmed the overwhelming influence of the background signal within the samples (Leszczynska *et al.*, 2010). The mineralogical composition of the clay samples from the Birch-Stanway area, which were dominated by mica (illite) with a mixed-layer micaceous smectite and minor kaolinite, has also been observed in analyses from other sites in East Anglia: from Aldeburgh in Suffolk (Huggett & Knox 2006) and the Dengie Peninsula in Essex(Gibbard *et al.* 1996). The mineralogical composition of all these samples is associated with the London Clay that underlies the succession in southern East Anglia.

Stratigraphical correlations

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Based on the i) general sedimentary and lithological characteristics; ii) the topographical altitude of the units and, most importantly, iii) the relationship of these units to the erosional boundary at 30-31 m OD at both sites, it is proposed that a relationship exists between Birch and Stanway quarries with regard to their sand and gravel deposits. It is suggested that the sand and gravel units of G2 and S1 below the 30-31 m OD level at Stanway Quarry are a counterpart of the sand and gravel deposits of G1 and S1 below that level at Birch Quarry. The lithostratigraphical term ‘Birch-Stanway Lower Sand and Gravel’ is proposed for this unit. Similarly the sand and gravel deposits overlying the 30-31 m OD boundary, namely the upper unit of G2 at Stanway Quarry and the uppermost unit of G2 at Birch Quarry, are correlated on the same basis to be the ‘Birch-Stanway Upper Sand and Gravel’. They are interpreted to represent two discrete depositional events associated with enhanced meltwater release and possibly the retreat of the Anglian ice sheet and associated partial lake drainage and subaerial exposure of the deposits (periglacial features). These deposits are therefore members of the Lowesoft Formation (Bristow 1985).

The basal gravel described from the Stanway Quarry, which differs sedimentologically and lithologically from all the overlying deposits, is proposed to represent a separate unit, named hereafter the ‘Stanway Basal Gravel’. It represents the final course of the lower reaches of the proto-Thames River before the diversion to its current position and after the onset of the Anglian glaciation in East Anglia. On the basis of similar lithological properties, the altitude, and its tentative/stratigraphical chronology, the Stanway Basal Gravel is proposed as a counterpart of the Hertfordshire Westmill Gravel, the youngest member of the Kesgrave Formation (Gibbard 1977).

Conclusions

- This investigation of a 15-20 m thick succession of well-preserved Middle Pleistocene deposits in the Birch-Stanway area represents an important opportunity at the scale of

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north-western Europe to reconstruct the palaeoenvironmental conditions and character of the ice margin at the Anglian ice sheet periphery within the European context. The main results are summarized below.The sedimentary succession described from the Birch-Stanway area, East Anglia, consists of major units of laterally extensive gravelly deposits dissected by an erosional boundary or a non-depositional event. They are interbedded with sandy facies associations and grade into sandy deposits laterally, in a down-current direction, from an ice-proximal to an ice-distal environment, from the north to the south. In the northern and north-western part of the area they are capped with deformed sand and diamicton, while in the south there is a unit of fine-grained deposits inserted between sand and the upper unit of gravel.

- The depositional palaeoenvironment of sand and gravel in the Birch-Stanway area consists of two or more, laterally overlapping subaqueous fan features. Palaeocurrent trends from the north and north-west towards the south and south-east indicate a direction of flow from the ice sheet margin towards the proglacial zone. The fining trend in particle size from the north and north-west towards the south and south-east indicates the change of depositional sub-environments from proximal to distal, respectively. The presence of glacial damicton capping the succession indicates the proximity of the ice sheet margin. The break in sedimentation dividing the deposits into two separate successions indicates at least two cycles of evolution of the system.
- The location of substantially thick sand and gravel successions at Birch-Stanway area was determined by a) the excessive amount of sand and gravel transported from the area where deposition in the pro-glacial zone was restricted by topographical obstruction, the Danbury-Tiptree ridge; b) the presence of accommodation space associated with the transition from a constrained to an unconstrained ice-front and c) the pre-existing proto-Thames river channel. It was the presence of the extensive

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Danbury-Tiptree topographical ridge, protruding towards the south-west of the Birch-Stanway area and blocking the passage of the Anglian ice sheet and its meltwater, that created a unique set of topographical conditions for the deposition of glacial sediments in this locality. In the case of a freely flowing ice margin, the meltwater sediments would only create a flat outwash plain, in the whole length of the pro-glacial zone.

- The proto-Thames early Anglian course towards the east, described from Birch-Stanway area (Stanway Basal Gravel at Stanway Quarry) has been established as an initial evacuation route for the meltwater from the pro-glacial zone. When the Anglian ice sheet advanced closer to the Birch-Stanway area, the channel was abandoned and an excessive amount of meltwater was flowing across the channel towards south and south-east. Pre-existing river deposits supplied the material, which was later reworked and deposited together with sediments associated with the Anglian ice sheet within the ice-contact fan succession.
- The Birch-Stanway subaqueous fan complex is evidence for the position of the Anglian ice sheet margin in this part of East Anglia. It has not been overridden by a subsequent glaciation and it marks the southernmost reach of the ice sheet. The fan succession indicates fluctuations of the ice front associated with at least two periods of enhanced meltwater release and following from that, possibly ablation and retreat, as well as possible partial lake drainage.
- Fine-grained facies F1 in the southern part of the Stanway Quarry, on the basis of sedimentary characteristics as well as the altitude, is interpreted as glaciolacustrine deposits, which may be, together with the subaqueous fan, contemporaneous to the glacial lake in the North Sea Basin. This proposal remains to be further confirmed.

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FIGURES:

Fig. 1. A. The North Sea Lake, the Anglian (Elsterian) glaciation extent and drainage pattern in north-western Europe. Light grey = ice-sheet, dark-grey = water, white = land masses. Black arrows indicate the direction of drainage. Dashed-and-dotted line indicate position of the Anglian ice-sheet margin. Dashed line links the area shown in Fig. 1B with the outline on the map in Fig. 1C. Question marks indicate areas where the evidence for the presence and extent of the North Sea Lake is missing. Based on Cohen *et al.* (2005), Ehlers *et al.* (2011), Laban & van der Meer (2011) and Roskosch *et al.* (2011).

B. Pre-Anglian course of the River Thames and Medway. Based on Bridgland (1995).

C. Diverted River Thames and the Anglian ice-sheet margin (dashed line). Based on Bridgland (1995).

D. The geological map of East Anglia, England. The black box indicates the Birch-Stanway research area. BQ = Birch Quarry; SQ = Stanway Quarry. Contour lines (grey, every 30 m) and shoreline after Ordnance Survey of Great Britain.

E. A detailed geological map of the Birch-Stanway area. Stars mark the location of Birch and Stanway quarries.

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Fig. 2. Photopanels depicting facies associations and large scale geometry of the deposits at Stanway Quarry (SQ). Scale bars are 1 m long.

A. Panorama of the northernmost face at SQ. The black box indicates the location of photopanel B. Inset: location of photopanels within the quarry.

B. Two overlying units of G2 divided by erosional/non-deposition boundary (thick, black line) in the northern part of SQ. Massive to horizontally diffusely-stratified gravel interbedded with massive to planar parallel-bedded sand.

C. A view of the two overlying units of G2. The black box indicates the location of photopanels D, E.

D. A detailed view of the lower gravelly unit of G2. Massive to horizontally diffusely-stratified gravel interbedded with massive to planar parallel-bedded sand.

E. Ice-wedge cast within the lower gravelly unit of G2 composed of horizontally diffusely-stratified gravel interbedded with massive sand.

F. Gradual vertical transition between massive to horizontally diffusely-stratified gravel interbedded with massive to planar cross-bedded sand of G2 and tabular beds of massive to planar parallel-bedded with lenses of granule gravel of S1.

G. The lowermost unit of G1 – crudely horizontally-stratified gravel with solitary planar cross-stratification, with visible erosional surface.

H. A sharp but non-erosive horizontal boundary between the lower unit of gravel G2 arranged in tabular cross-beds and unit S1 of tabular beds of planar parallel-bedded to massive sand.

I. Details of transition between S1 tabular and lenticular beds of massive to planar parallel- and planar cross-bedded sand and overlying recurring cycles of fining upward sand, silt and clay arranged in small scale planar-laminations and climbing ripple cross-laminations of unit F1 in the southern part of SQ.

J. Large-scale geometry of tabular beds of planar parallel-bedded to massive sand of S1, recurring cycles of fining upwards planar and climbing ripple cross-laminated sand, silt and clay of F1 and tabular and lenticular beds of massive gravel G2 in the southern part of SQ.

K. L. Details of transition between F1 and overlying G2 in the southern part of SQ. Note the erosional lower boundary of the gravel unit G2.

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M. The horizontal boundary between unit G3 of well-defined planar cross-bedded gravel and of tabular and lenticular beds of massive to planar parallel-, trough and cross-bedded sand of S1 with some chutes-and-pools deposits.

N. Photopanel depicting unit S1 in the southern part of SQ, comprising tabular and lenticular beds of planar-parallel and planar-cross and trough-cross bedded sand with some chutes-and-pools deposits. Position of detailed images O, P, R.

O. Tabular planar-cross and trough-cross bedded sand deposits.

P and R. Tabular planar-parallel and planar-cross and trough-cross bedded sand deposits with chute-and-pools deposits.

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Fig. 3. Composite log depicting general succession of facies associations in Stanway Quarry (SQ). For location of SQ see Fig. 1.

Fig. 4. Uninterpreted (upper) and interpreted (lower) GPR transects and boreholes from Stanway Quarry. A. Location map of transects. B. Transect 1, borehole bhS1. Note the multiple lobe-shaped features (dip ~10°) defined as convex-up architectural elements and erosional troughs, identified as concave-up features across flow direction C. Transect 2, borehole bhS2. Note the low-angle clinoforms in the direction of flow.

Fig. 5. Geological cross-sections based on borehole data from the vicinity of the Birch and Stanway quarry. A. Stanway Quarry borehole (1-9 and 10-20) locations. B. Birch Quarry borehole (1-7 and 8-14) locations. C. Stanway Quarry geological cross-section. D. Birch Quarry geological cross-section.

Fig. 6. Photopanels depicting large scale geometry of the deposits at Birch Quarry (BQ). Scale bars are 1 m long.

A. Panorama of the north-western part of BQ. Black boxes indicate the location of photopanels Inset: location of photopanels.

B. Lowermost gravelly unit G2.

C. Vertical transition between G2 and S1.

D. Sandy unit S1.

E. Vertical transition between units S1 and G2.

F. The erosional/non-depositional surface at 30-31 m OD with two ice-wedge casts and overlying unit G2.

G. Upper unit G2.

H. Undulating erosional boundary between uppermost unit G2 and diamicton of D1.

I. J. Details of deformation structures within sandy unit S1 below diamicton D1.

K. L. Boundary between sandy unit S1 and overlying unit of diamicton D1 in the southernmost part of BQ.

Fig. 7. Composite log depicting general succession of facies associations in Birch Quarry (BQ).

Fig. 8. Schematic drawing of the lithofacies associations described from the Birch-Stanway area. Black boxes indicate locations depicted in details by photopanels. A. Stanway Quarry deposits. Letters A-P indicate the photopanels within Fig. 2, where detailed images of the selected exposures from Stanway Quarry are presented. B. Location of the Stanway Quarry cross-section. C. Location of the Birch Quarry cross-section. D. Birch Quarry deposits. Letters A-L indicate the

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photopanels within Fig. 6, where detailed images of the selected exposures from Birch Quarry are presented.

Fig. 9. A schematic drawing of Birch-Stanway complex fan. A. Black arrows indicate the direction of pre-Anglian Thames river flow. B. Black arrows indicate the generalized palaeocurrent direction of Anglian meltwater flow in the area of the subaqueous fan described from the Birch-Stanway area. The black dashed line marks the Anglian ice-sheet margin, and the transparent white marks, the area of the Birch-Stanway complex fan.

Tables:

Table 1: Lithological composition of the Kesgrave Formation and Lowestoft Formation samples – overview of published research.

Table 2: Overview of the provenance of lithological components of sand and gravel from the Birch-Stanway area.

Table 3: Facies identification codes and descriptions as used in the current research.

Table 4: Facies associations and their characteristics as used in the current research.

Table 5: Clast lithological analysis results: B1-B12 – Birch Quarry samples, S1-S14 - Stanway Quarry samples.

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Supporting Information:

Fig. S1. A. Birch Quarry plan. Note: sections – black dots, cross-sections BQ1-BQ2 and BQ3-BQ4 (on-line support material 2 and 3) – grey dashed lines, cross-section M-N (Fig. 10) – grey line.

Fig. S2. Geological cross-section BQ1-BQ2 based on vertical profile logs from Birch Quarry. For location see Fig. S1.

Fig. S3. Geological cross-section BQ3-BQ4 based on vertical profile logs from Birch Quarry. For location see Fig. S1.

Fig. S4. Geological cross-section SQ1-SQ2 based on vertical profile logs from Stanway Quarry. For location Fig. S1.

Fig. S5. Geological cross-section SQ3-SQ4 based on vertical profile logs from Stanway Quarry. For location see Fig. S1.

Fig. S6. Schematic drawing of the facies associations described from the Birch-Stanway area A. Stanway Quarry deposits. Black boxes indicate locations depicted in details by section logs. B. Birch Quarry deposits. Black boxes indicate locations depicted in details by section logs.

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Reference	Stratigraphic interpretation/ formation or member	Site/location	% of flint	% of quartz and quartzite
Hey (1980) and Whiteman (1992)	Glacial gravel	Tiptree	83	15.1
	Glacial gravel	Great Dunmow	70.6	28.4
Rose *et al*. (1999)	Various members of the Kesgrave Formation in Essex, Suffolk and south Norfolk	not known	64.9 - 83.3	12 - 29.8
Green & McGregor (1999)	Gravel of the Kesgrave Formation type in northern Suffolk and Norfolk	not known	68.2 - 84.5	8 - 15.6
	Kesgrave Formation type	not known	43.1 - 74.8	11.9 – 32
Green *et al*. (1982)	Glacial gravel	not known	79.4	-

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Lithology	Provenance	Reference
Associated with glacial origin of deposits		
Flint (angular and nodular)	Directly from chalk underlying the London Clay bedrock; Reworked from the local Tertiary pebble beds;	Green & McGregor (1978)
	Upper and Middle Chalk	Bridgland (1986)
	London Basin Tertiary; Chalk;	Hey (1965, 1967, 1976)
Rounded flint	London Basin Tertiary beds	Hey (1967, 1965)
	Kesgrave Formation	Rose *et al*. (1977) Rose & Allen (1977)
Rhaxella Chert	Northern British provenance	Green *et al*. (1980
	Corralian Beds of the Upper Jurassic in east Yorkshire; North-east of Oxford; Red Crag near Ipswich;	Hey (1976)
associated with non-glacial, fluvial (proto-Thames) origin of deposits		
Quartz	Bunter Pebbles Beds of English Midlands; Palaeogene formations within the present catchment of the Thames;	Green & McGregor (1978)
	Mesozoic rocks of western and northern Britain; The Devonian conglomerates of the Welsh borderlands; Various Permo-Triassic conglomerates and breccia of the West Midlands; Mesozoic pebble-beds of the south Midlands	Bridgland (1986)
	Reading Beds of East Anglia; Bunter and Lower Carboniferous of the southern Penines;	Hey (1965, 1967, 1976)
	Belgium (historical view)	Prestwich (1890)
Quartzite	Bunter Pebble Beds of Midlands; Permo-Triassic beds of Midlands; Devonian conglomerates of the Welsh borderlands; Precambrian and Paleozoic beds of the Midlands-Welsh borderlands;	Bridgland (1986)
	Bunter Pebble Beds of English Midlands	Hey (1965, 1967, 1976) Hey & Brenchley (1977)
Sandstone and siltstone	Bunter Pebbles Beds of English Midlands;	Green & McGregor (1978)
	The Dengie Peninsula north of the Thames	Bridgland (1986) Bridgland (1988)
	Corralian Beds of the Upper Jurassic in east Yorkshire; North-east of Oxford; Red Crag near Ipswich;	Hey (1976)
Pinhole Chert	The Lower Greensand of the northern margin of the Weald; Southern Penines;	Hey (1967, 1976)
Greensand Chert	South-Eastern Essex	Gregory (1915), Green & McGregor (1978) Green *et al*. (1980)
	Hythe Beds in Kent, west of Sevenoaks and western Weadland; Folkestone Beds and Bargeat of Sandgate Beds of Surrey; Lower Greensand of the Farington district of Oxfordshire; Upper Bagshot and Pebble Beds of northern Surrey;	Bridgland (1986) Bridgland (1988)
Volcanic rocks	Ordovician beds of North Wales	Hey & Brenchley (1977, 1978) Green & McGregor (1978) McGregory & Green (1978) Green *et al*.(1980)
	The Cretacerous beds of the southern and south-eastern Midlands	Salter (1905), Gregory (1922)
Igneous rocks	Wales; Welsh Borderlands; West Midlands;	Bridgland (1986)
	Bunter Pebble Beds of Midlands	Hey (1976)

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Facies code	Description
Gmm	Massive, matrix-supported, poorly sorted, pebble to cobble gravel; matrix is fine to coarse sand
Gmp	Planar cross-stratified, poorly sorted, granule to pebble, matrix-supported gravel; matrix is fine to coarse sand; occasionally normally graded
Gmt	Trough cross-stratified, poorly sorted, granule to pebble, matrix-supported gravel; matrix is fine to coarse sand; multiple scour-fills, erosional and recurrent surfaces
Gmh	Diffusely horizontally stratified, poorly sorted, pebble to cobble, matrix-supported gravel; matrix is fine to coarse sand; horizontal stratifications with conformable bases
Gcm	Massive, poorly sorted, pebble to cobble, clast-supported gravel
Gcp	Solitary or planar cross-stratified, poorly sorted, pebble to cobble, clast-supported (openwork) gravel
Sm	Massive, poorly sorted, fine to coarse sand, may be with isolated pebbles
Sh	Horizontally stratified (occasionally diffusely horizontally stratified), poorly sorted, fine to coarse sand, with occasional pebble trains, often occurs together with facies Sm
Sp	Solitary or planar cross-bedded, poorly sorted, fine to coarse sand, with occasional pebble trains; ultiple erosional surfaces and occasional scour-fills and chutes-and-pools with planar to sigmoidal and concave-up, downflow-divergent cross-beds – backsets (bed dip less than 10 degrees) and rare boundary conformable laminae
St	Trough cross-bedded, poorly sorted, fine to coarse sand with occasional pebble trains; multiple erosional surfaces and scour-fills
Sd	Poorly sorted, fine to coarse sand with deformed bedding, mainly deformed horizontal stratification
Fm	Massive silt and clay, very stiff
Fl	Finely laminated silt and clay, in places diffusely, occasionally graded
Fsl	Small scale planar cross-stratified sand silt and clay
Dm	Massive diamict which consists of sandy silty clay with stones

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Facies association	Component facies	Description	Geometry and dimensions	Interpretation
G1 Crudely horizontally and solitary planar cross-bedded clast and matrix supported gravel	Gmm Gmp Gcm Gcp Shp	Throughout the whole thickness of the facies, clay inatraclasts (rip-up clasts) are abundant; sedimentary structures: crudely horizontally stratified, planar to solitary cross-stratified matrix-supported, clast supported and open-work gravel; multiple scour-fills, erosional and recurrent surfaces; discontinuous, tabular beds of horizontally and diffusely horizontally stratified sand; imbricated and a-transverse oriented pebbles are present bed contact: erosive	Forms long, tabular units a few metres thick and few tens of metres long which consist of 0.2-1 m thick lenticular beds with frequent scour fills filled with massive or cross-stratified gravel; scours are 0.1-0.4 m deep and laterally extend for few to ~20 m; sandy beds are 0.2-0.3 m thick	Indicates transport of fluvial bedload on a braidplain as bars (Boothroyd & Ashley, 1975, Plink-Bjorklund & Ronnert, 1999) or downflow migration of 2D (tabular cross-stratification) and 3D (trough cross-stratification) dunes (Harms *et al.* 1975, Allen 1982, Russel & Arnott 2003) (subcritical flow conditions); the presence of solitary cross-stratification, together with imbricated and a-transverse-oriented pebbles, is a reliable indication of palaeocurrent direction (Evans & Benn 2004); abundant presence of intraclasts is evidence for erosion of the underlying London Clay
G2 Horizontally diffusely stratified and massive gravel and sand	Gmh Gmm Sh Sm	Sedimentary structures: horizontally or diffusely-stratified gravel and sand; occasionally planar cross-stratified, planar parallel stratified (with granules and pebbles as horizontal trains within sandy beds) or massive; bed contact: erosive or sharp but non-erosive	Gravel a few tens of centimetres to few metres thick; sand 0.1-1 m thick; both extend laterally for a few tens of metres; sand beds thicken where gravel beds thin	Traction deposition from high-density turbidity currents (Church & Gilbert 1975, Russel & Arnott 2003); sand deposited from non-turbulent flow of sandy debris in conditions of high sediment supply from suspension following deceleration of high-velocity sediment-laden flow (Tucker 1982, Maizels 1993, Sihne *et al.* 1997, Shanmugam 2000, Bennet *et al.* 2002, Winsemann *et al.* 2009); thick and laterally extensive beds suggests that these depositional conditions sustained for longer periods of time (Kneller & Branley, 1995; Winsemann *et al.* 2007, 2009); current research regards diffusely-stratified bedforms as being antidune deposits, associated with supercritical flow conditions (Lang & Winsemann 2013)

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G3 large scale, planar cross-stratified gravel	Gmp	Sedimentary structures: well defined planar-cross stratification, concave-up to convex-up; occasionally normal grading occurs; individual beds dip with an angle between 15 and 22 degrees; wide range of dip directions, from the south-east to west; basal contact: tangential to angular; bed contact: erosive	Individual bed is 0.5 m to few metres thick and extend laterally for more than 50 m; within discrete depositional unit, usually occurs only one bed of this characteristics	Cross-stratification represent migrating 2 or 3D dunes associated with high turbulent flows and constant discharge from longer periods of time; the dimension and angles of the bed dip indicate the formation of shallow-water delta mouthbars or large scou-fills (Winsemann *et al.* 2009)
S1 planar cross-bedded and trough cross-bedded sand with pebbles	Sp St Sm Gmp	Gmp occurs very occasionally as solitary sets of cross-beds; sedimentary structures: lenticular and planar beds of cross-stratified sand; lenticular beds of trough-stratified sand; multiple erosional and reactivation surfaces and scour fills; bed contact: sharp, but non-erosive or erosive	Beds of planar cross-stratified sand are 0.2-0.5 m thick and laterally extend up to several m; troughs of cross-bedded sand are 0.2 to 0.5 m thick and 2-10 m wide, planar to sigmoidal and concave-up, downflow-divergent cross-beds (backsets, dipping to the north and north-west with an angle of less than 10°) and rare boundary-conformable laminae; erosional scours are filled with sigmoidal cross-beds; both chutes-and-pools and erosional scours are 10 to 50 cm deep and a few m in lateral extent	Planar and trough cross-bedded sand reflects downflow migration of 2D and 3D dunes, respectively; reactivation surfaces indicate flow and discharge variability (Collinson 1970; Marren 2004), thick successions indicate that these subcritical depositional conditions persisted for longer periods of time (Mulder & Aleksander 2001, Kneller 2004); chutes-and-pools are evidence of supercritical flow conditions (Lang & Winsemann 2013)

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F1 normally graded sand, silt and clay	Fsl Fl Fm	Sedimentary structures: recurring successions of massive or normally-graded sand that fines upwards into massive, planar-parallel or small-scale climbing ripple and climbing planar cross-laminated silt and clay; bed contact: sharp	Tabular beds of sand are <10 cm thick and grade into silt and clay beds which are 2-20 cm thick; both extend laterally for few tens of metres; when stiff massive clay and silt-tabular beds are 0.05 to few tens of cm thick, they laterally extend for a few metres to a few tens of m	Lower flow regime; fining upward successions of sand, silt, clay indicate the waning stage of the flow of surge-like turbidity currents (Bouma, 1962, Plink-Bjorklund & Ronnert 1999, Mulder & Alexander 2001) or conditions of expanding flow of density underflows (Walker 1992); low-energy current ripples and climbing planar cross-lamination indicates the migration of low-energy current ripples and combined deposition form traction and suspension, occurring as the flow decelerates, losing transport capacity (Ashley *et al.* 1982, Jopling & Walker 1968); massive silty-clay is deposited from waning low density turbidity currents (Russel & Arnott, 2003) or suspension sedimentation within glacilacustrine basin (Collinson & Thompson 1989, Gilbert 1997, Reineck & Singh 1980) massive clay deposited in conditions of no meltwater discharge, winter (Russel & Arnott 2003)
D1	Dm	No sedimentary structures – massive, tructurless; bed contact: undulating, erosive	Tabular units with undulating lower contact are few metres thick and laterally extend for a few hundred m	The presence of weathered chalk granules indicates that the diamict is genetically associated with the ice-sheet (Allen 1991); deposited as a solifluction or directly from the ice-sheet as till

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sample ID	% angular flint	% rounded flint	% nodular flint	% quartz	% quartzite	% sandstone	% igneous	% pinhole chert	% greensand chert
B1	70.1	12.9	0.00	9.1	3.9	1.3	1.0	1.6	0.00
B2	61.6	15.2	0.16	14.1	4.6	1.7	0.5	2.0	0.00
B3	73.1	10.3	0.15	9.4	2.3	1.6	0.1	2.9	0.00
B4	43.6	28.9	0.44	15.8	9.3	0.6	0.3	1.0	0.00
B5	56.2	18.1	0.09	11.5	10.6	2.1	0.4	0.8	0.09
B6	62.5	15.3	0.00	13.6	5.5	1.7	0.2	0.9	0.24
B7	61.0	14.7	0.13	13.5	5.8	2.3	0.4	2.2	0.00
B8	62.7	12.3	0.00	18.1	4.4	1.1	0.1	1.2	0.00
B9	59.3	17.9	0.28	10.9	8.9	1.7	0.1	0.8	0.00
B10	68.4	14.6	0.64	10.7	4.0	0.6	0.2	0.6	0.16
B11	52.5	16.0	1.66	8.8	17.7	1.7	1.1	0.5	0.00
B12	73.0	8.5	0.44	9.0	4.17	3.5	0.2	1.1	0.00
S1	59.8	16.9	2.3	8.4	11.1	0.5	0.5	0.5	0.0
S2	49.7	26.3	0.6	11.8	10.0	0.2	0.4	1.1	0.0
S3	40.5	34.0	0.9	14.0	9.8	0.3	0.2	0.2	0.0
S4	50.8	27.4	0.0	11.7	8.1	0.5	0.7	0.8	0.0
S5	43.3	25.6	0.4	15.3	12.7	0.5	0.7	1.5	0.0
S6	51.3	18.9	0.0	15.7	10.2	0.6	1.1	2.2	0.0
S7	53.2	22.3	0.1	16.6	7.7	0.0	0.0	0.0	0.0
S8	59.1	13.0	0.0	10.9	14.6	1.0	0.1	1.4	0.0
S9	66.5	16.5	0.0	3.7	9.6	2.7	0.0	1.1	0.0
S10	73.0	7.1	0.6	6.3	5.0	6.1	0.4	1.5	0.0
S11	55.4	26.0	0.4	9.0	6.8	1.5	0.0	0.9	0.0
S12	39.5	32.5	0.4	13.3	10.1	1.5	0.9	1.7	0.0
S13	62.4	14.6	0.0	11.5	8.3	2.0	0.4	0.8	0.0
S14	61.0	14.8	0.4	15.7	3.8	4.4	0.0	0.0	0.0

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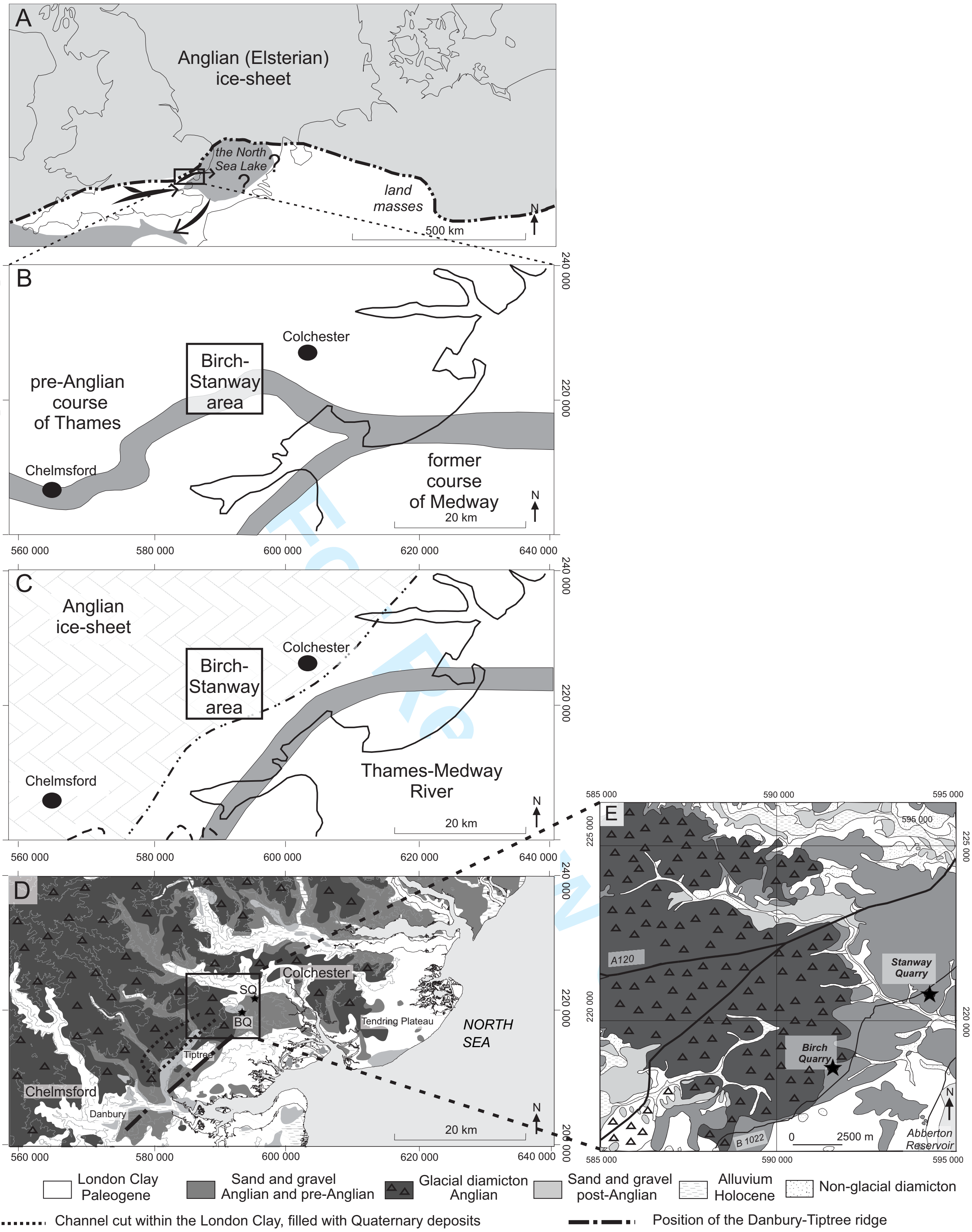

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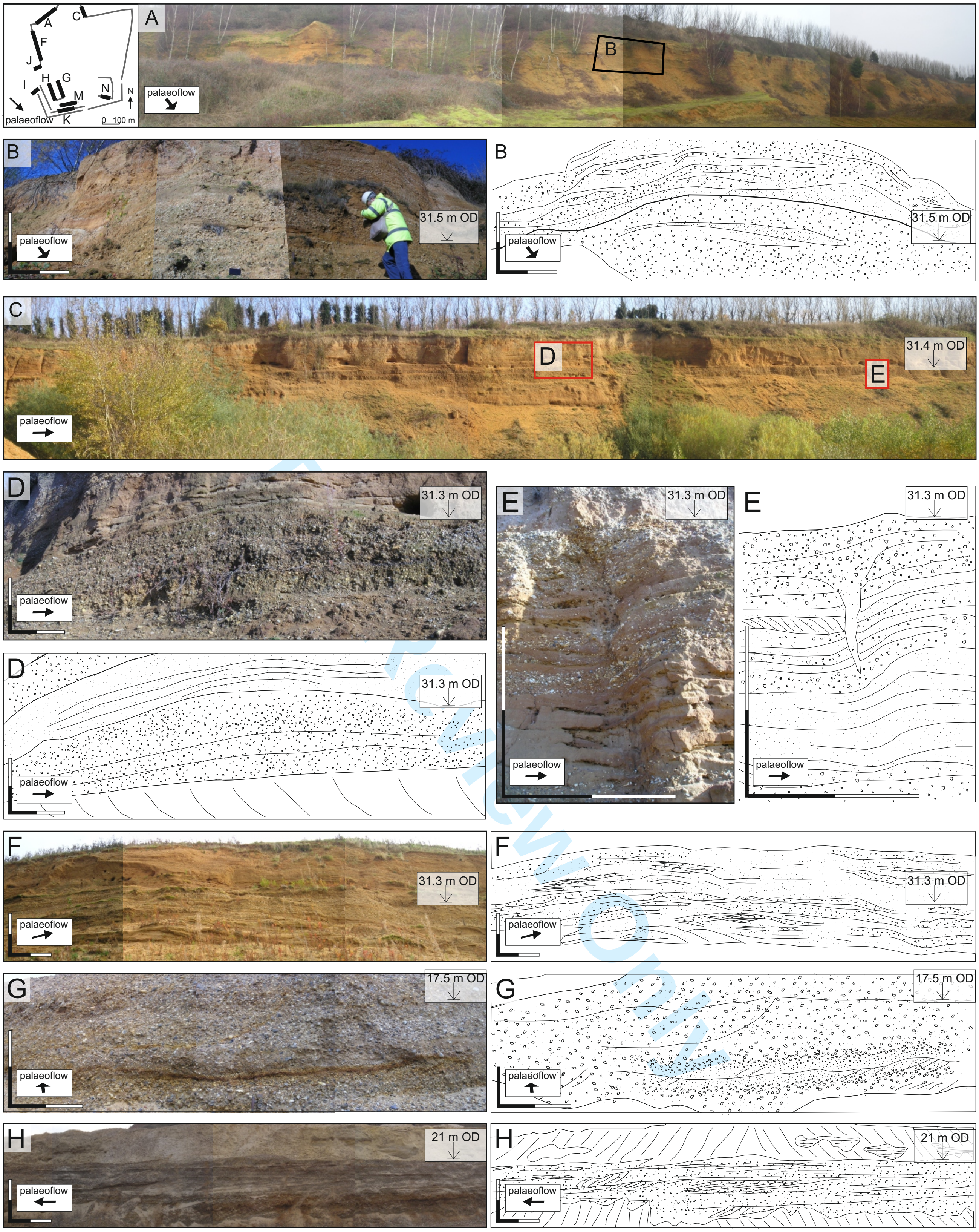

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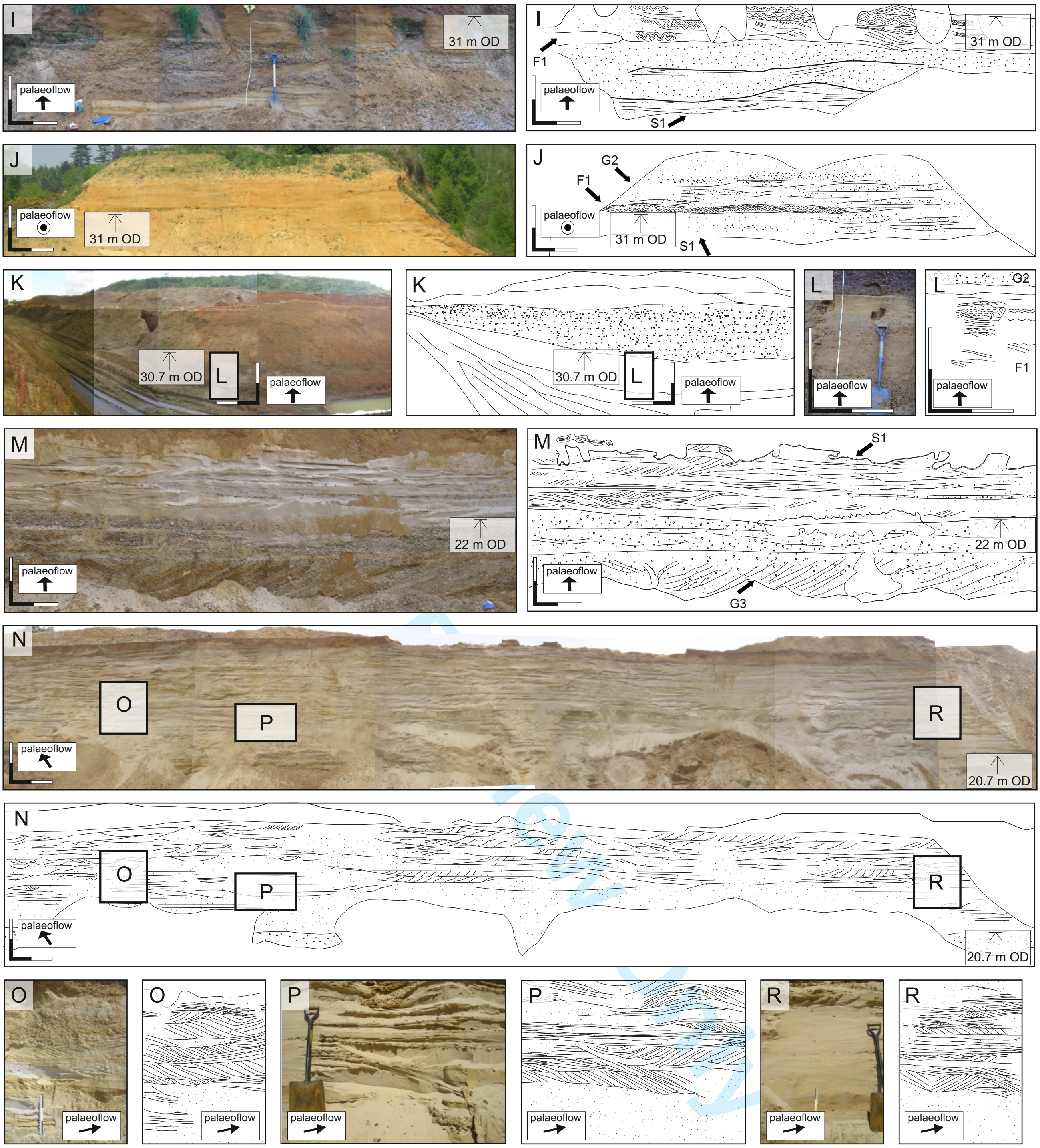

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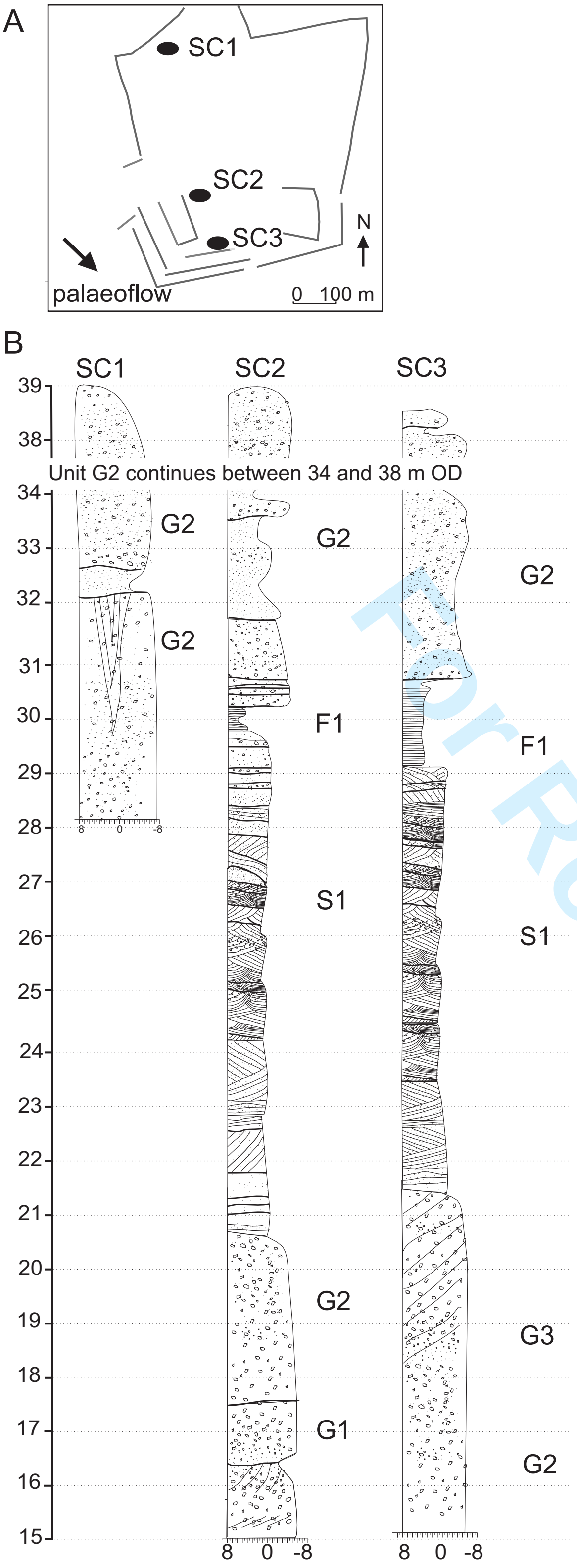

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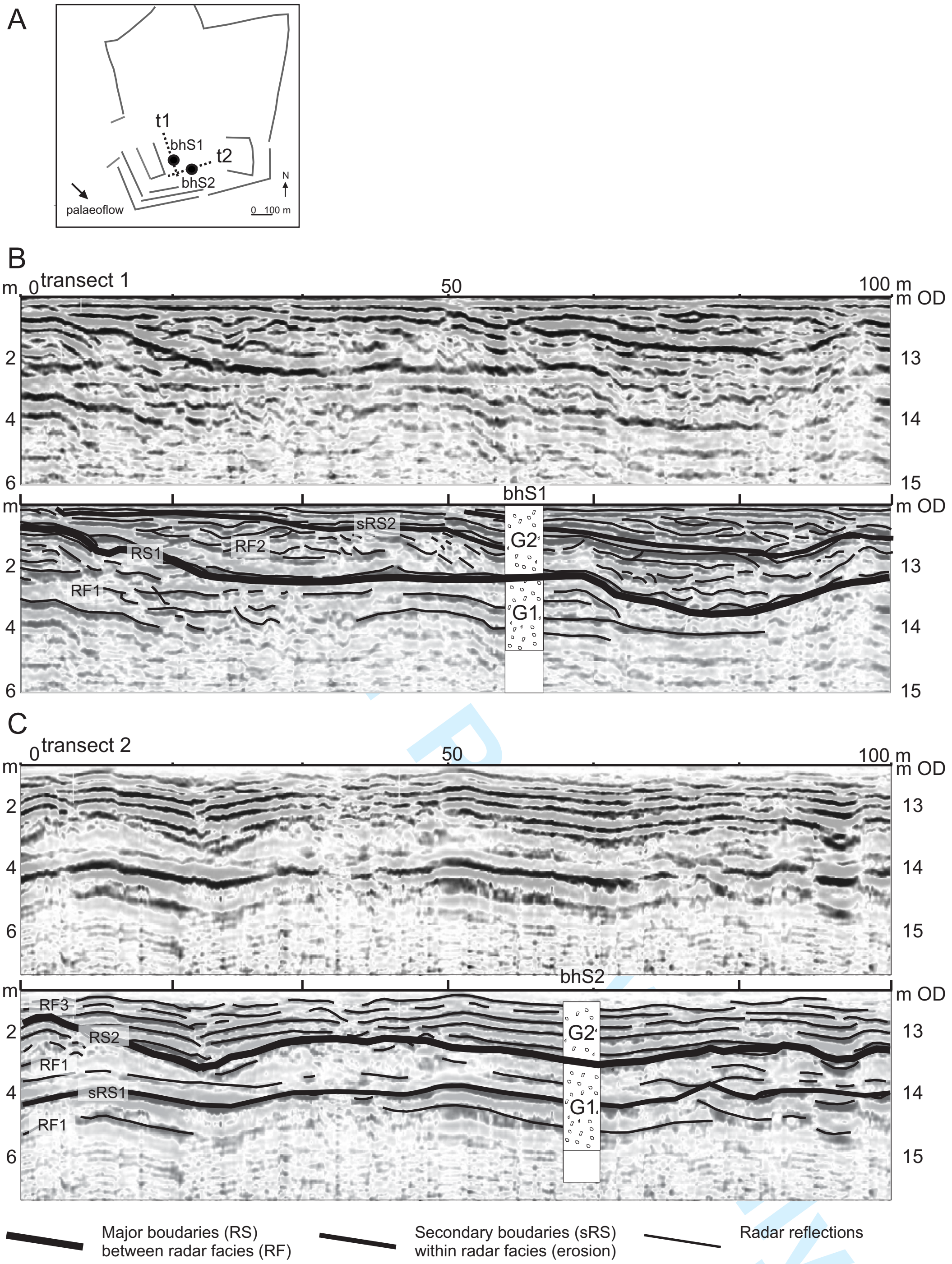

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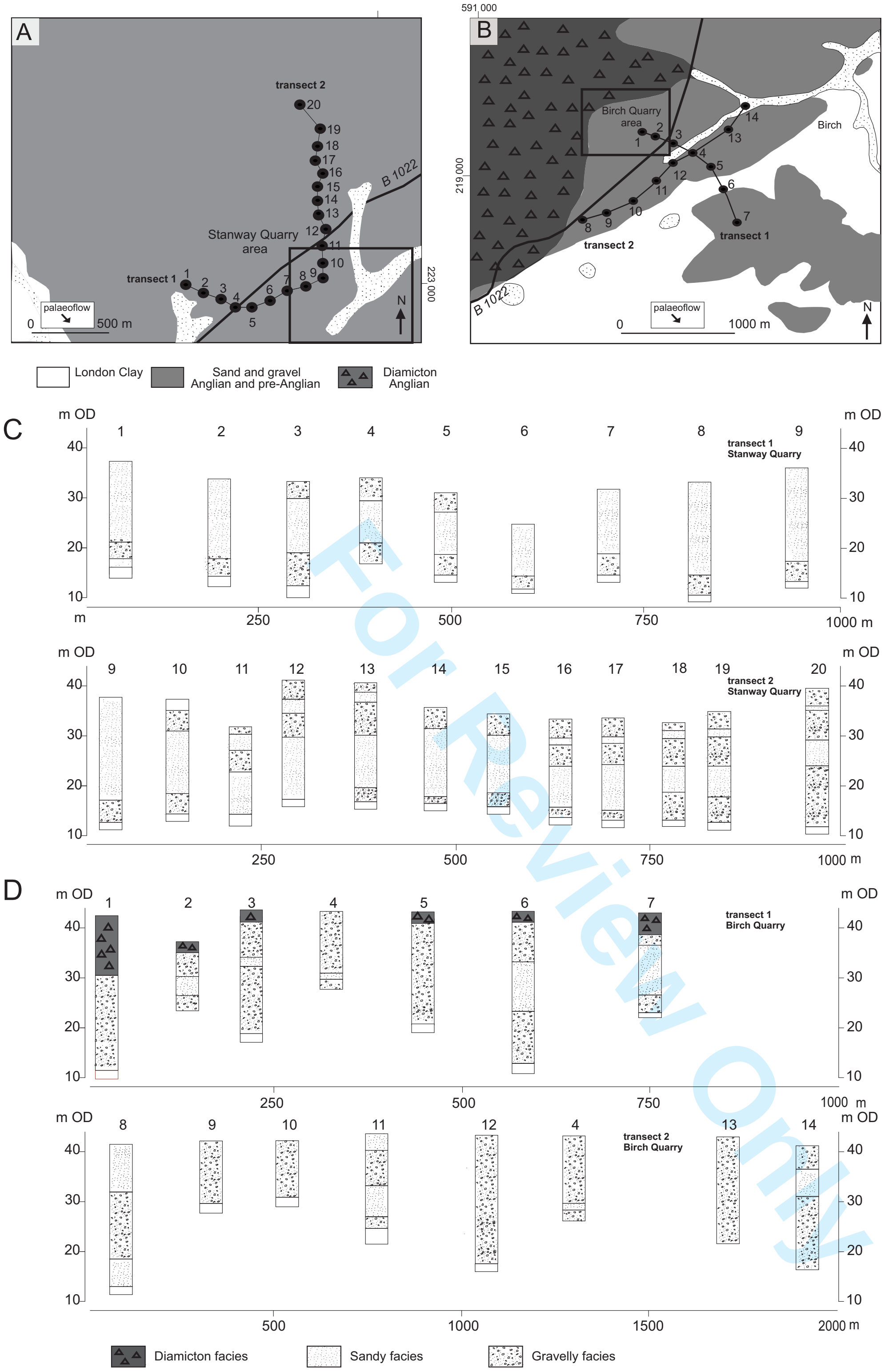

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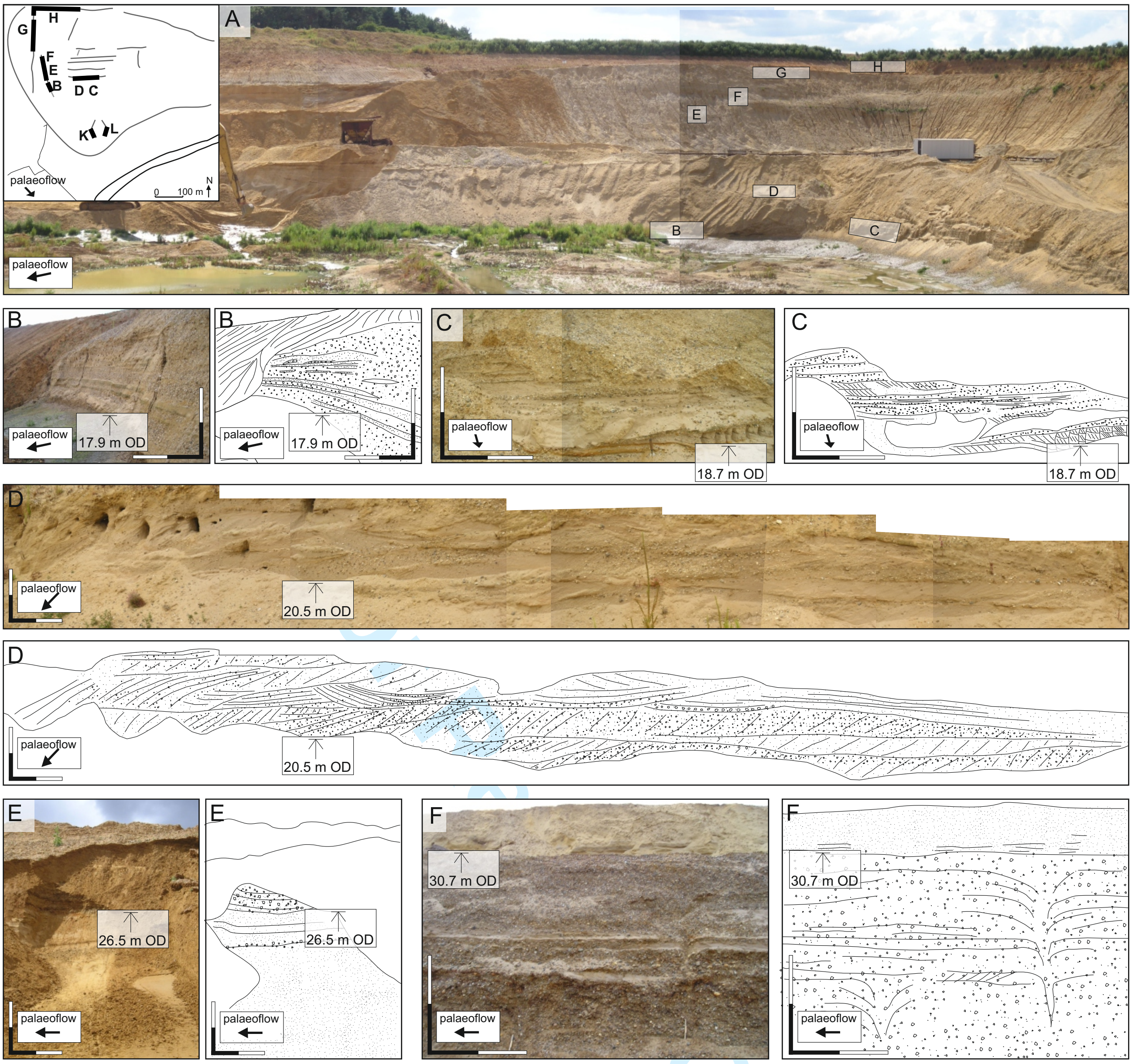

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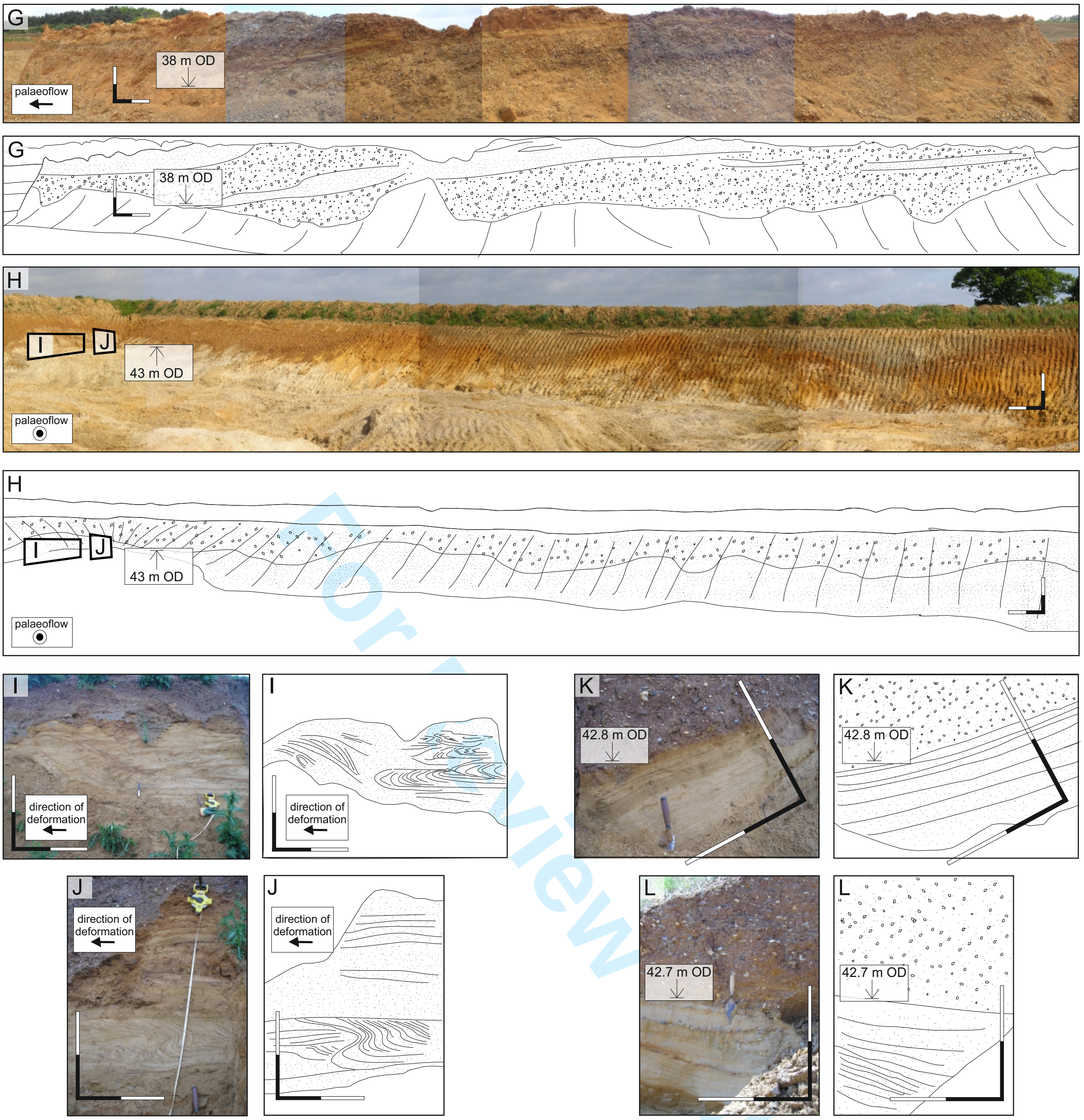

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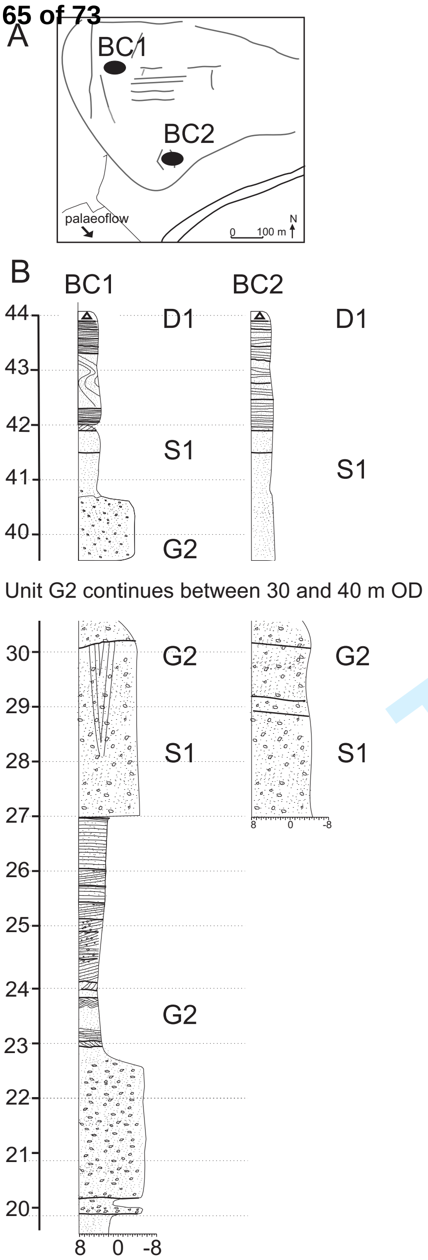

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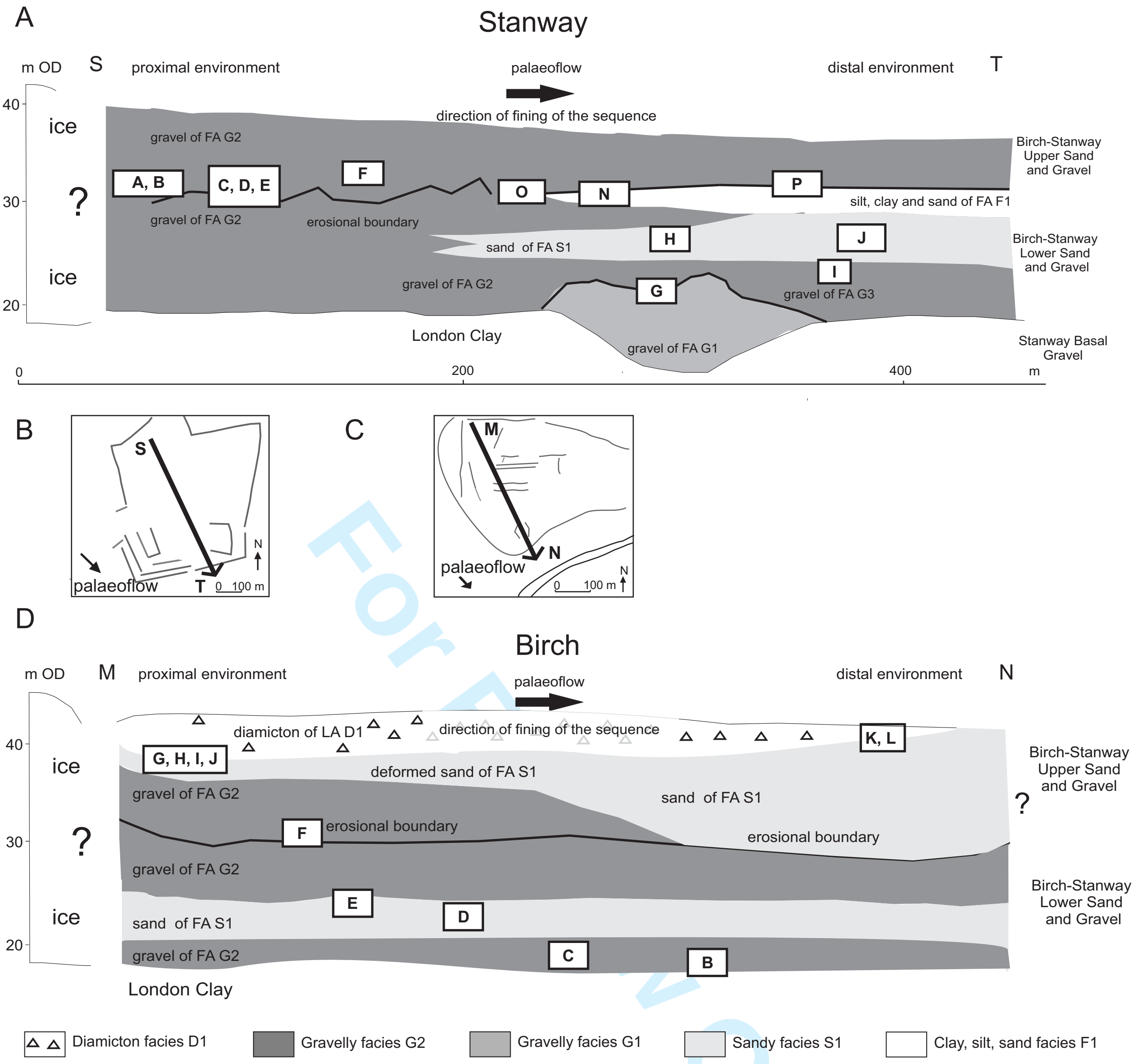

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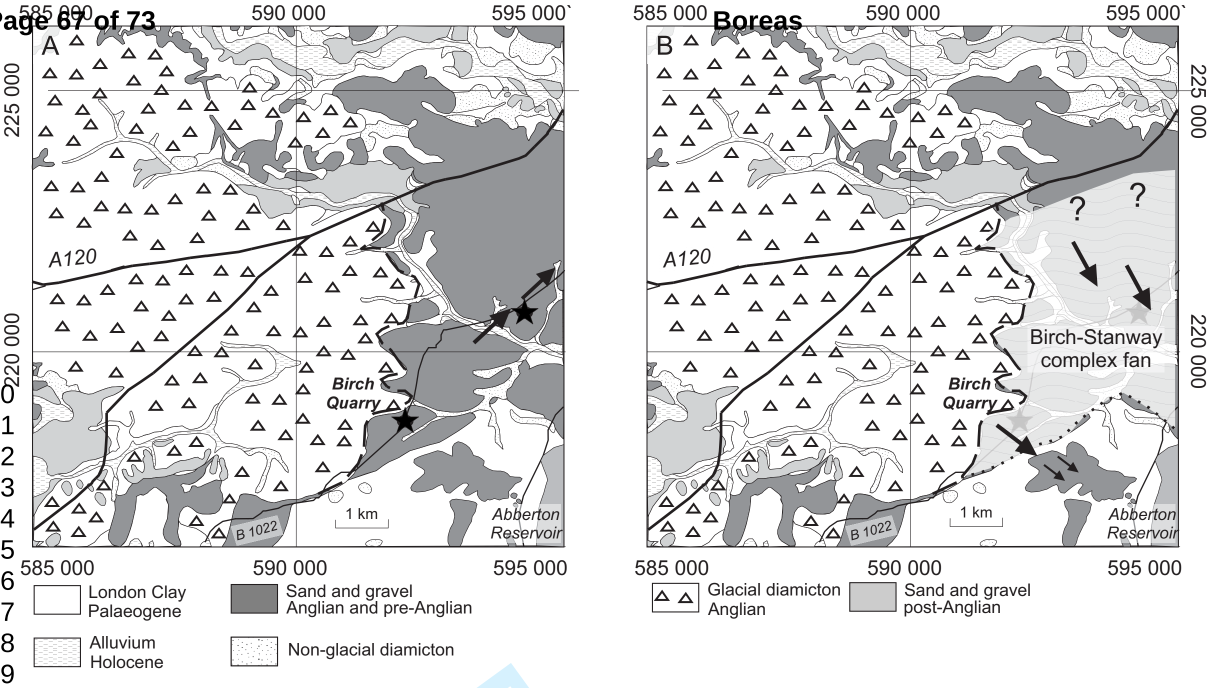

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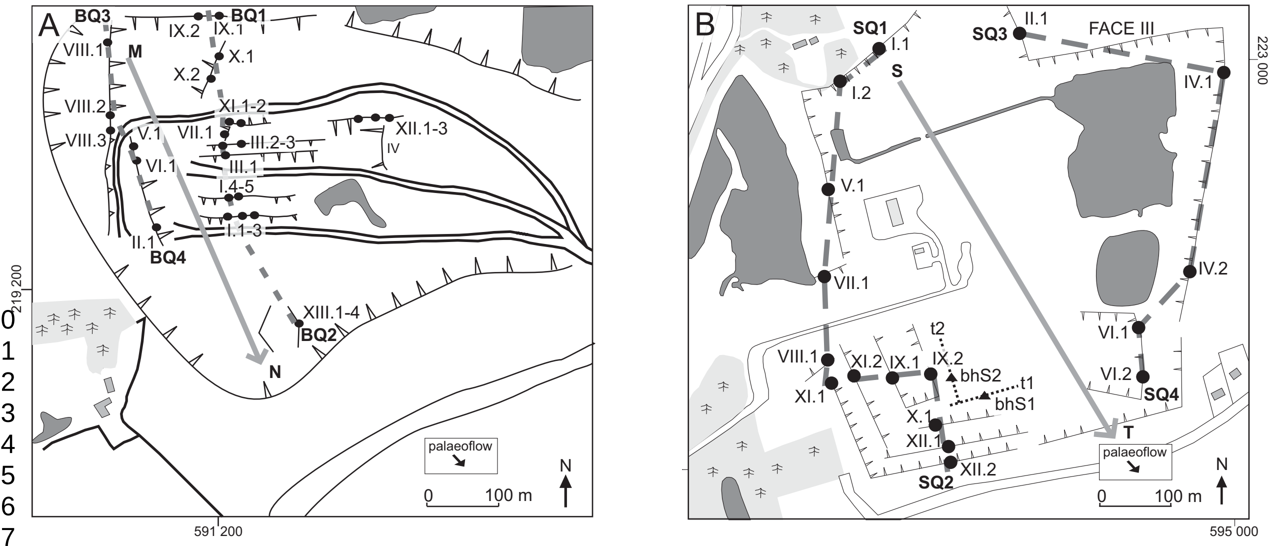

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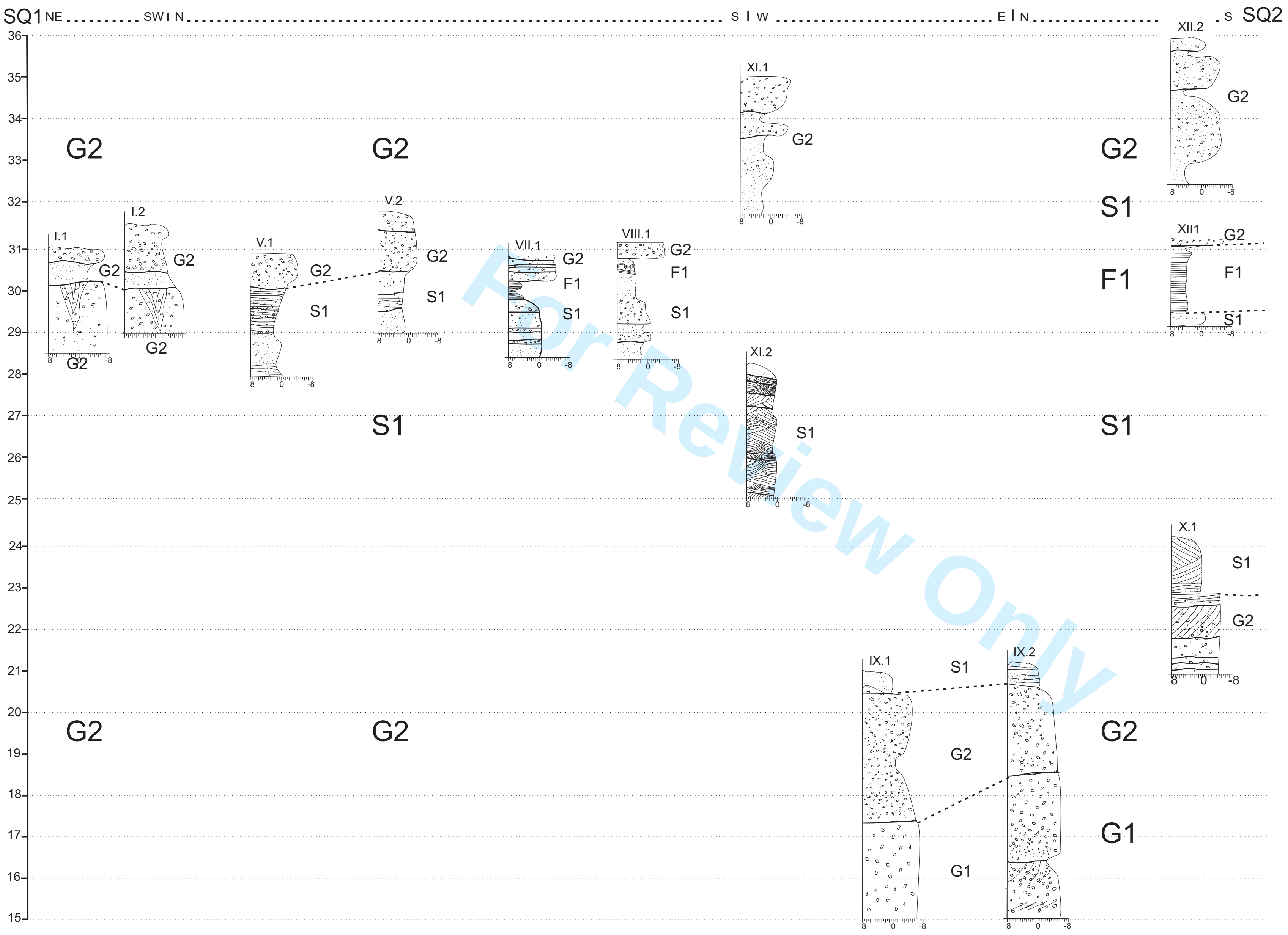

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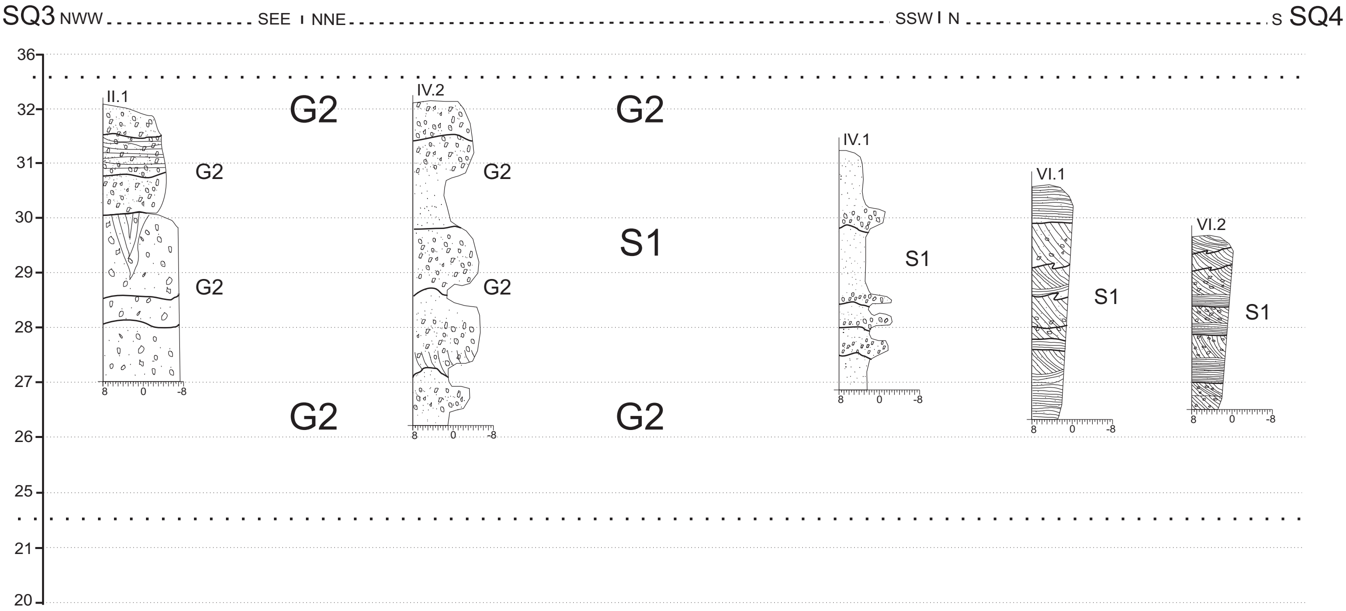

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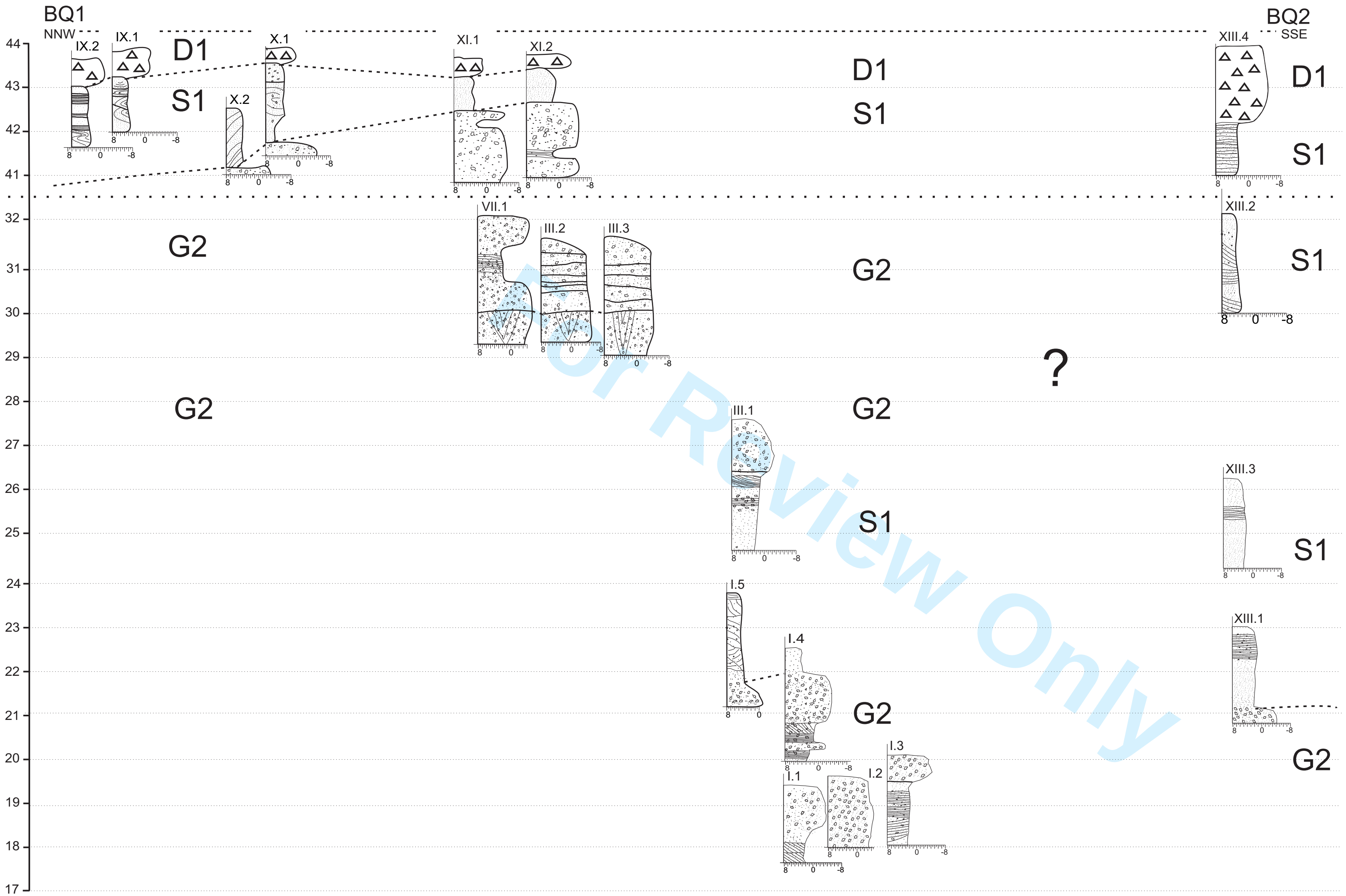

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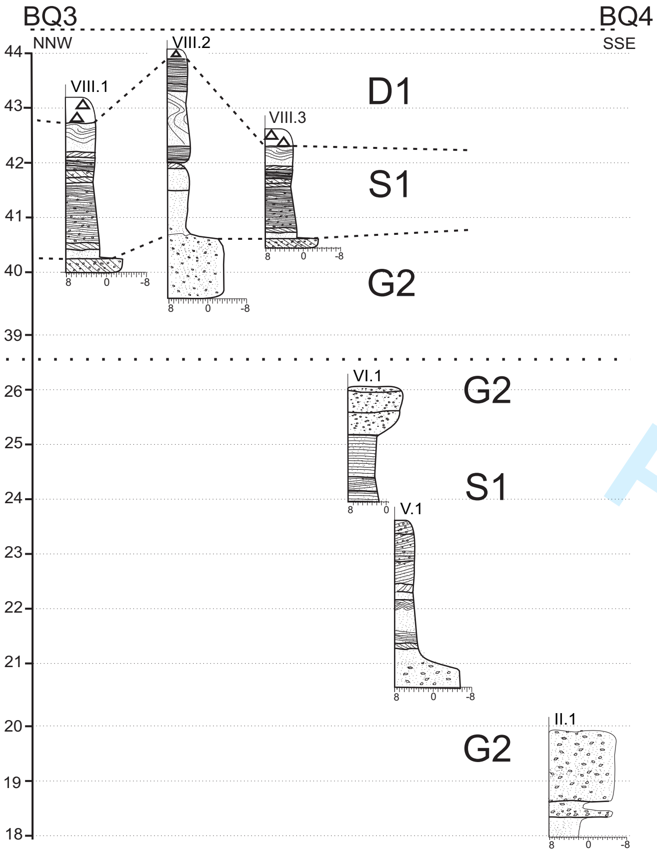

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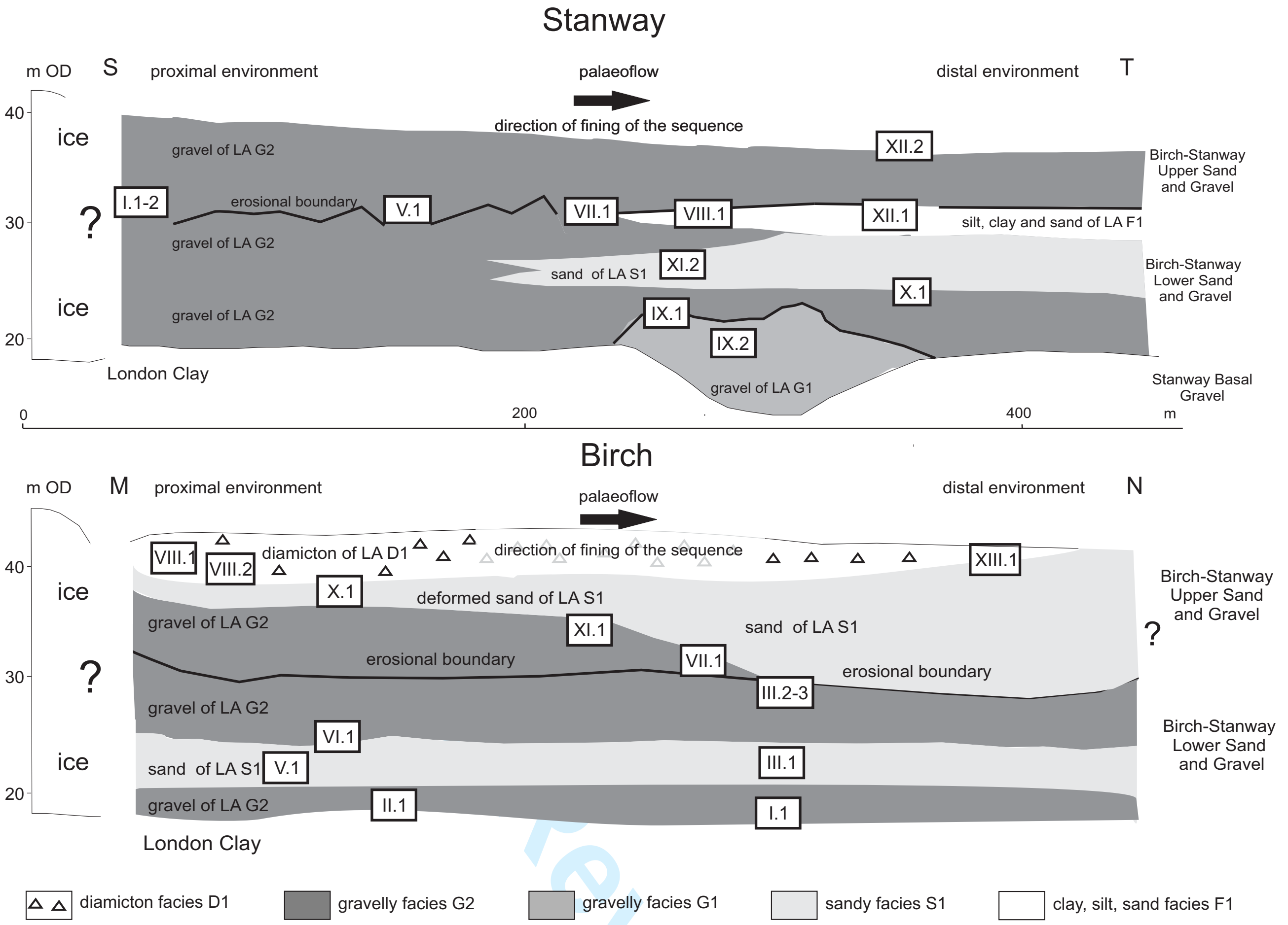
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sandy facies S1
clay, silt, sand facies F1

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