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Happisburgh Cliffs (TG 380 312): Glacial lithostratigraphy, till provenance and Ice-Marginal Deposits

J.R. Lee, J. Rose, J.B. Riding, B.S.P. Moorlock and R.J.O. Hamblin

Background and Site Significance

Historically, several distinguished geologists have examined the coastal sections at Happisburgh. Clement Reid, in the late nineteenth century (Reid, 1882), was the first to establish a stratigraphy for the site, and subsequent workers have generally accepted this succession albeit applying revised nomenclature (Banham, 1968; Ranson, 1968; Lunkka, 1994). Hart (1987, 1999) by contrast, also examined the coastal sections southwards from Happisburgh towards Eccles, and identified a glacial succession comprising three tills separated by glaciolacustrine and outwash lithofacies. The succession of tills identified by Hart (1987, 1999) is interesting because the sequence does not correspond directly to the classic 'Cromer Till' succession of northeast Norfolk (Banham, 1968; Lunkka, 1994). Rather it contains stratigraphical elements from both the 'Cromer Till' succession and the Anglian stratotype area to the south in the Waveney Valley. Understanding the lithostratigraphy of this site is therefore of crucial importance to the wider stratigraphic understanding of the region and links together the stratigraphies of two areas that previously have only been tentatively correlated (Rose, 1989c). In recent years, enhanced coastal erosion of up-to 9m yr^{-1} (Poulton *et al.*, 2006) has enabled detailed logging and lithological analysis of the glacial sediments to the south of Happisburgh and this has directly helped resolve this stratigraphical problem.

The purpose of this paper is to demonstrate the succession of the Happisburgh site and its regional stratigraphic context. The sedimentology of the site is not presented in detail here and is presently being prepared for publication (Lee and Rose, unpublished data).

Lithofacies Description

The succession at Happisburgh is presented as a series of 'Lithofacies' described and distinguished on the basis of their sedimentological, geometrical and lithological properties. The sequence is summarised in a composite log (Figure 1) and cliff cross-section (Figure 2).

Lithofacies A

Lithofacies A is the basal unit and consists of a yellowish grey, massive, matrix- supported diamicton with a clayey-sand matrix texture. The diamicton is 6m thick and rises above the level of the foreshore at 300m from where it can be traced westwards along the base of the cliffs to 3500m. Pebbles are rare, being generally composed of flint and shell, with minor concentrations of chalk and non-local lithologies such as limestone, ironstone, schist and granite. In places where the foreshore has been removed, the basal contact with the underlying preglacial deposits is sharp and planar in appearance, with the upper 20cm of the preglacial sediments frequently exhibiting low-angle shear planes dipping towards the northwest. The upper surface of the diamicton is undulating, consisting of a series of elongate ridges separated by small basins.

The massive and highly homogenised nature of the diamicton indicates that it consists of sediment that has been thoroughly mixed under conditions of either high shear strain and / or elevated pore-water pressure. The sharp, planar contact between the diamicton and underlying preglacial deposits is a plane of décollement that reflects a major rheological discontinuity separating materials of ductile and brittle / ductile deformation. The association of these two deformation facies upon one another is characteristic of a subglacially deforming bed till (Boulton and Hindmarsh, 1987; Hart *et al.*, 1990; Benn and Evans, 1996). Shear plane orientations within the underlying tectonised preglacial sediments imply that ice flow was initially from the north-northwest.

Lithofacies B

Lithofacies B consists of a series of on-lapping beds of stratified clay and silt that crop-out between 300–3500m. A lower sub-facies occurs within the inter-ridge basinal areas and consists of thin intercalated beds and wedges of greyish brown sandy diamicton and olive brown coarse silt. These beds thicken towards the centre of the basins and exhibit parasitic and disharmonic folds, vertical pillar and flame structures. Overlying these, the middle sub-facies are largely unconstrained by the ridged upper surface of Lithofacies A. It consists of beds of massive silt, separated by rhythmically bedded dark grey clays and light grey silts with occasional lenticular and convolute beds. They in turn, are overlain by 20–35cm thick bed of massive brown silt with occasional discrete laminae and ripples, and small dish structures. The sediments of Lithofacies B record the progressive infilling of the inter-ridge basinal areas on top of the diamicton (Lithofacies A), and the successive growth and expansion of ponds and lakes within an ice marginal landsystem. The lower sub-facies represent the deposition of background sediment (silt) and slurries of reworked diamicton into shallow pools that formed within the basins. The middle and upper sub-facies were laid down in association with the low-energy deposition of silts and clays through the water column, perhaps in association with seasonal freezing of the lake surface and the overturn of the water column (Ashley, 1995), punctuated by episodic influxes of sand into the sedimentary system. The presence of discrete horizons of convolute bedding and dish structures, indicate that sediment availability was high and deposition at times was rapid (Reineck and Singh, 1980).

Lithofacies C

Lithofacies C consists of stratified sands that rest conformably upon the underlying silts and clays between 250–1200m before descending beneath the level of the foreshore to the south on the northern limb of a syncline. The lower horizons consist of massive and parallel laminated sand that grade upwards into sets of ripple cross-lamination and type-A and B climbing ripples, and planar cross-beds with clay drapes. These pass up into horizontal and type-A and B climbing ripple-bedded sands with occasional horizons of convolute bedding, dissected by shallow, broad channels.

Lithofacies C records deposition associated with a prograding glaciolacustrine delta. Parallel lamination and ripple cross-lamination record deposition from suspended sediment clouds with climbing ripples recording subtle changes in the sediment supply and flow regime. Massive sands indicate rapid sedimentation from highly concentrated suspension flows. Planar cross-beds with frequent clay drapes, record the down-current migration of straight to linguoid-crested subaqueous dunes followed by periods of low energy still-water sedimentation. Channel structures are typical of local incision by small, migrating channels and characterise the delta topsets.

Lithofacies D

Lithofacies D crops-out within the cliffs on the northern limb of a syncline between 220–245m, and consists of two beds of highly consolidated diamicton separated by beds of stratified sand that dip southwards beneath the level of the foreshore.

The lower bed of diamicton consists of a grey to olive-brown matrix-supported diamicton with a clayey sand matrix texture, whilst the upper bed of diamicton is brown in colour, matrix-supported with a sandy texture. Both beds of diamicton are clast-poor with abundant pebbles of flint and detrital shell. Examination of the base of the diamicton and upper horizons of the underlying sands at 230m demonstrates that the junction between the two deposits is not sharp but gradational and marked by a zone of intercalation and interfolding. Structurally the diamicton is largely massive in appearance but localised heterogeneity exists in the form of thin sandy stringers and rhythmically-bedded silts and clays with occasional isoclinal fold noses.

The diamicton assemblage is interpreted as being deposited in association with an advance of grounded ice into a glaciolacustrine basin. The non-planar intercalated and interfolded basal contact with the underlying sands are features typical of a subaqueous mode of sedimentation (Eyles and Eyles, 1983; Lee, 2001), however, a subglacial origin for the diamicton is suggested by its largely massive structure and highly consolidated nature. The preservation of these two quite contrasting genetic styles suggests that the till was advected subglacially with intermixing between the till and the highly saturated sands occurring as the ice flowed into the glaciolacustrine basin.

Lithofacies E

Lithofacies E consists of stratified yellow sands that are largely decalcified, but locally contain occasional horizons of detrital chalk grains. The sands crop-out on the northern limb of the syncline between 130–300m and rest abruptly, but conformably, upon the upper surface of the underlying diamicton (Lithofacies D). The basal horizons consist of inter-stratified thin beds of sand and silty sand, and these exhibit parallel bedding with sand lenses and load structures, ripple cross-lamination and climbing ripple cross-lamination, fining-up beds of sand and silt. The middle and upper sandy horizons are dominated by larger-scale bedding structures that include laterally continuous parallel bedding, ripple cross-lamination, sets of trough and planar cross-bedding and common shallow channel structures. Palaeocurrent measurements indicate a flow direction from the west and northwest. The sands of Lithofacies E are interpreted as being deposited within a delta foreset (basal) and topset

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(middle and upper). The delta foresets, characterised by parallel bedded and rippled sands and silt sandy with occasional load structures, record fluctuations within both the energy regime and sediment supply but suggest a tendency towards high sediment budgets and rates of deposition under a low to moderate energy regime. The delta topsets within the middle and upper horizons are represented by the switch to larger-scale bedforms and channel structures that record the down-current migration of lunate subaqueous bars and the lateral and vertical migration of active channels.

Lithofacies F

Lithofacies F is the highest glacial unit within the succession south of Happisburgh and crops-out between 130–180m. The lithofacies comprises highly consolidated olive yellow to grey matrix-supported diamicton with a silt-rich matrix texture. The diamicton is typically massive but in places exhibits a chaotic lithological heterogeneity comprising zones of chalk-rich and flint-rich diamicton. The base of the diamicton is generally sharp and planar in appearance, and often marked by a thin 2–3cm layer of grey clay—the base of which sometimes exhibits slickenside structures. Structural measurements taken on shear planes and slickensides, indicates the latest direction of stress application was from the northwest.

The highly-consolidated nature of the diamicton, combined with the slickenside structures and sharp planar base—interpreted as a décollement plane, are typical features associated with a subglacial till (Hart and Roberts, 1994; Benn and Evans, 1996). The local heterogeneous nature of the till with chalk- and flint-rich facies suggests localised contrasts in strain and pore water content such that homogenisation of the till constituents was not uniform across the subglacial bed.

Lithostratigraphy

The stratigraphy of the Happisburgh cliff sections (South) can be determined by comparing the properties of the six glacial lithofacies to those of the regional stratigraphic model (Lee *et al.*, 2004b). Within this scheme, as with others, till lithofacies form distinctive lithostratigraphical units that can be defined and mapped over wide areas on the basis of their bulk lithology as this changes little in space
(Banham, 1968; Lunkka, 1994; Lee *et al.*, 2004b; Hamblin *et al.*, 2005) (Figure 3). Three tills are present within the Happisburgh succession—Lithofacies A, D and F. Lithofacies A is correlated with the Happisburgh Till Member of the Happisburgh Formation based upon its grey colouration, sandy matrix texture and clast content dominated by flint, vein quartz and shell. This till unit crops-out northwards from the site to Walcott, and then from Trimingham to Overstrand and is equivalent to the First Cromer Till (Banham, 1968) and Happisburgh Diamicton (Hart, 1987; Lunkka, 1994). The brown colour, sandy matrix texture, low calcium carbonate content and flint-rich clast assemblage of Lithofacies D is typical of the Corton Till Member. This till unit can be mapped southwards from Happisburgh towards Norwich Great Yarmouth and Lowestoft where it crops-out within the flanks of the Waveney and Wensum valleys and in coastal sections such as Scratby and Corton. The highest till within the succession is the chalk-rich Lithofacies F, and this is correlated with the Walcott Till Member of the Lowestoft Formation based upon the high silt-content of the matrix. This till is equivalent to the Second Cromer Till of Banham (1968) and Walcott Diamicton of Lunkka (1994). The Lowestoft Till Member, the principal till unit of the Lowestoft Formation, by contrast exhibits a clay-rich matrix texture consisting of reworked Kimmeridge Clay derived from the Fenland Basin. The silts and clays of Lithofacies B equate to the Ostend Clay Member and can be traced northwards discontinuously to Sidestrand— previously these formed part of the 'Intermediate Beds' of Banham (1968) and 'Happisburgh Clays' of Lunkka (1994). The stratified sands of Lithofacies C correspond to the Happisburgh Sand Member and crops-out only within the Happisburgh area. Lithofacies E equate to the Corton Sand Member based upon heavy mineral composition (Lee, 2003; Lee *et al.*, 2004b). These sands form an extensive sand deposit that can be mapped to the west of Norwich, and southwards into the Waveney Valley (Hopson and Bridge, 1987; Moorlock *et al.*, 2002).

Provenance of Till lithofacies

Lithofacies A—Happisburgh Till Member, Happisburgh Formation

All lithological data are summarised in Table 1, whilst palynomorph data is shown in Table 2. Clast lithologies and derived palynomorphs from the Happisburgh Till Member at Happisburgh were examined to determine the provenance of the till unit (Lee, 2003; Lee *et al.*, 2002). Clasts from the 4–8mm and 8–16mm fractions are dominated by lithologies derived locally from the reworking of pre-existing Crag sediments (white / brown flint, vein quartz, quartzite, shell and wood) and Cretaceous strata (chalk, black flint, sandstone) in the North Sea. Amongst the distinctive non-crystalline lithologies are Magnesian Limestone from northeast England, and Carboniferous Limestone and coal from northern England or the Midland Valley of Scotland, and Devonian Old Red Sandstone from the Midland Valley. Crystalline lithologies are relatively abundant (up-to 8.6%) and include lavas from the Devonian and Carboniferous of the Midland Valley of Scotland, low-grade metamorphic rocks from the Southern Uplands and Central Scotland, and Whin Sill dolerite from Northumberland and granite and granodiorite from Central Scotland. Significant 'over-sized' lithologies include rhomb porphyry (Hoare *et al*., 2006) and larvikite (Lee *et al*., 2006b) from Oslofjord in Norway.

An abundant and diverse allochthonous palynomoprh association was derived from the till matrix. Key provenance markers include several palynomorphs from Jurassic (Redcar Mudstone Formation) and Lower Cretaceous (Speeton Clay Formation) strata within the Yorkshire Basin, and spores that include Carboniferous taxa such as *Cingulisporites* spp., *Densosporites* spp., *Lycospora pusila*, *Radiizonates* sp. and *Tripartites trilinguis*.

Lithofacies D—Corton Till Member, Happisburgh Formation

Clast lithologies and derived palynomorphs from the Corton Till Member at Happisburgh were examined to determine the provenance of the till unit (Lee, 2003; Lee *et al*., 2002). Lithologies derived from the reworking of pre-existing Pleistocene deposits, namely flint, vein quartz, quartzite and shell are the dominant clast types, with lesser proportions of Cretaceous (black flint and chalk) and Jurassic lithologies (ironstone, sandstone, oolite). Other persistent lithologies include Magnesian Limestone from the Permian of northern England, Carboniferous chert and coal from northern England or the Midland Valley, Devonian Old Red Sandstone from the Midland Valley of Scotland, schistose grit from northern Scotland, and basic and acidic porphyries from Carboniferous and Devonian strata in the Midland Valley.

This diamicton matrix has a moderately abundant organic content, consisting mainly of wood fragments and plant tissues, and relatively common, although poorly preserved, allochthonous palynomorphs (Table 2). Amongst those that can be provenanced with precision include a range of Carboniferous spores derived from the Viséan-Namurian (*Tripartites vetustus*) and Westphalian A and B (*Cristatisporites connexus*) (Clayton and Butterworth, 1984) strata of northern England and the Midland Valley of Scotland. The Jurassic component is largely comprised of Mid-Late Jurassic miospores such as *Callialasporites* spp, *Cerebropollenites macroverrucosus* and *Classopollis classoides*. Jurassic dinoflagellate cysts are more biostratigraphically significant with *Gonyaulacysta jurassica* subsp. *adecta* characteristic of the Callovian Stage, and most other species, including *Cribroperidinium globatum* and *C. longicorne,* typical of the Kimmeridgian (Riding and Thomas 1988).

Lithofacies F—Walcott Till Member, Lowestoft Formation

The clast assemblage shows a marked similarity between both 4–8 and 8–16mm fractions. These are composed almost exclusively of locally derived lithologies from the reworking of pre-existing Pleistocene strata (brown and white flint, vein quartz and quartzite) and Cretaceous bedrock in the area of the North Sea (chalk and black flint). Additionally, the samples contain a small number of clasts of Jurassic (oolitic sandstone, limestone, mudstone), Permian (Magnesian Limestone), Carboniferous (coal and limestone) and Devonian (Old Red Sandstone) provenance. Crystalline lithologies, totalling 1.5–1.8% of the total sample, are composed of Dalradian schist, basic porphyry and granite.

An abundant, diverse and well-preserved palynoflora was derived from the matrix of the diamicton (Moorlock *et al*., 2000; Lee, 2003). Carboniferous spores are prominent and include several long ranging taxa that range from the late Viséan to Westphalian and is suggestive of derivation form northern England or the Midland Valley. Unequivocal Jurassic palynomorphs are also common. These include Early Jurassic forms such as *Nannoceratopsis deflandrei*, a species typical of the late Pleiensbachian and Toarcian (Riding and Thomas, 1992), and the pollen grain *Chasmatosporites*. Upper Jurassic forms, specifically those characteristic of the Kimmeridgian are also prominent and include *Cribroperidinium globatum*, *Glossodinium dimorphum*, *Gonyaulacysta jurassica* subsp. *jurassica* and *Senoniasphaera jurassica*. The association of the Early and Upper Jurassic forms is typical of input from the Yorkshire Basin.

Significance of clast and palynomorph assemblages

There are a number of similarities between the clast and palynomorph assemblages. Each of the three tills exhibit far-travelled clast associations that can be traced as far north as the Midland Valley (Carboniferous and Devonian sedimentary and igneous lithologies), and low-grade metamorphic clasts

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derived from the Southern Uplands and southern sector of the Central Highlands. Carboniferous input from either the Midland Valley or County Durham is also supported by the association of Viséan, Namurian and Westphalian palynomorphs. Permo-Triassic input from the County Durham is demonstrated by the presence of Magnesian Limestone and red sandstone whilst the various Jurassic and Lower Cretaceous erratics and palynomorph associations are sourced from the Yorkshire Basin. The remaining clast associations are derived from either the erosion of ice flowing across the Chalk surface in the area of the North Sea offshore from Norfolk, Lincolnshire and Yorkshire, and from the local reworking of pre-existing Pleistocene lithologies. Of critical importance in terms of provenance, are the presence of the Carboniferous lithologies and the Magnesian Limestone that demonstrates unequivocally a British provenance for all three tills, as neither crop-out at surface between northern East Anglia and southern Norway. Two Scandinavian erratics have been recovered *in situ* from the Happisburgh Till Member at Happisburgh. Their presence however does not overrule the overwhelming evidence for the British provenance of the tills. Instead workers consider that their presence in the Happisburgh Till Member is due to the reworking of Scandinavian erratics in the North Sea Basin by British Ice (Hoare *et al.*, 2006; Lee *et al.*, 2006b).

Palaeoenvironmental Reconstruction

The glacial sequence exposed in the cliffs to the south of Happisburgh exhibits two distinctive glacial subdivisions—the Happisburgh and Lowestoft formations.

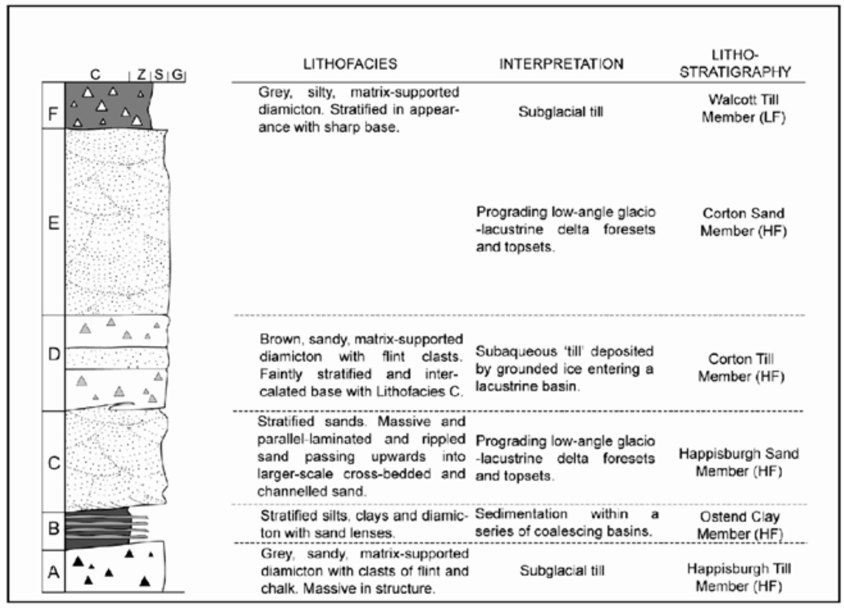
The Happisburgh Formation at this site, consists of a relatively thick sequence of subglacial and proglacial sediments that record successive oscillations in the margin of the British Ice Sheet. The Happisburgh Till Member is the basal member of the Happisburgh Formation, and was deposited by grounded ice that flowed across the locality from the northwest. Detailed analysis of the lithology of the till demonstrates that it was deposited by British ice that flowed down the present North Sea coast from central Scotland (Lee *et al.*, 2002) as far south as Happisburgh and Eccles (Hart, 1987, 1999; Lee *et al.*, 2004b). As the ice margin retreated northwards upon ice wastage, a proglacial lake system developed on the undulating upper surface of the till. Examination of the form of this till surface reveals it to be a relict ice-marginal land-surface consisting of a range of subglacial and ice-marginal landforms including crevasse-fill ridges (Lee, 2003), flutes and small terminal moraines (Hart, 1987; Lunkka, 1994). These ancient landforms have been preserved because they were buried quickly by the Ostend Clay Member which accumulated within a series of coalescing proglacial ponds and lakes. A change in the ice-marginal sediment dynamics led to the accretion within this proglacial lake basin of a delta characterised by the Happisburgh Sand Member. An ice-marginal readvance into this lake basin is represented by the Corton Till Member. This till sheet is considerably more extensive than that of the Happisburgh Till and has been mapped extensively across through the Norwich, North Walsham area and southwards into the Waveney Valley where it is diachronous consisting of several distinctive mappable beds separated by sand. It represents a second, more extensive advance of the British Ice Sheet into Norfolk. Reworked till clasts from this till found within Bytham River deposits at Leet Hill provide a stratigraphical link between the glacial and fluvial sequences, and a river terrace generation model has been used to suggest a pre-Anglian MIS 16 age for the deposit and glaciation (see Lee *et al.*, this guide). Following the retreat of this second ice advance, deglaciation resulted in the deposition of the Corton Sand Member at Happisburgh and more extensively throughout southern Norfolk and northern Suffolk (Hopson and Bridge, 1987; Lee, 2001). Largely this deposit was laid-down as part of a distal glaciofluvial outwash plain however local elements, such as at Happisburgh, have minor deltaic constituents.

The final ice advance across the area is marked by the deposition of the Walcott Till Member of the Lowestoft Formation. This was laid down subglacially by British ice flowing locally from the northwest. Comparison with the regional stratigraphy indicates that a marked unconformity exists between the Happisburgh and Lowestoft formations that span several additional warm and cold stages (Lee *et al.*, this guide).

Conclusions

- Middle Pleistocene glacial deposits at Happisburgh belong to the Happisburgh and Lowestoft formations and record two separate episodes of glaciation.
- The Happisburgh Formation consists of two tills separated by glaciolacustrine deposits, whilst the Lowestoft Formation at the site consists of a single till.
- The three tills examined at Happisburgh—the Happisburgh Till, Corton Till and Walcott Till members, were deposited by British ice rather than Scandinavian ice as previously considered.

- The succession at Happisburgh is critical in the glacial story of Norfolk in that it directly links the classical glacial sequences of the northeast Norfolk coast with the sequences of the Anglian stratotype in the Waveney Valley.



	LITHOFACIES	INTERPRETATION	LITHO-STRATIGRAPHY
F	Grey, silty, matrix-supported diamicton. Stratified in appearance with sharp base.	Subglacial till	Walcott Till Member (LF)
E		Prograding low-angle glacio-lacustrine delta foresets and topsets.	Corton Sand Member (HF)
D	Brown, sandy, matrix-supported diamicton with flint clasts. Faintly stratified and intercalated base with Lithofacies C.	Subaqueous 'till' deposited by grounded ice entering a lacustrine basin.	Corton Till Member (HF)
C	Stratified sands. Massive and parallel-laminated and rippled sand passing upwards into larger-scale cross-bedded and channelled sand.	Prograding low-angle glacio-lacustrine delta foresets and topsets.	Happisburgh Sand Member (HF)
B	Stratified silts, clays and diamicton with sand lenses.	Sedimentation within a series of coalescing basins.	Ostend Clay Member (HF)
A	Grey, sandy, matrix-supported diamicton with clasts of flint and chalk. Massive in structure.	Subglacial till	Happisburgh Till Member (HF)

Figure 1. Composite log of the glacial deposits at Happisburgh.

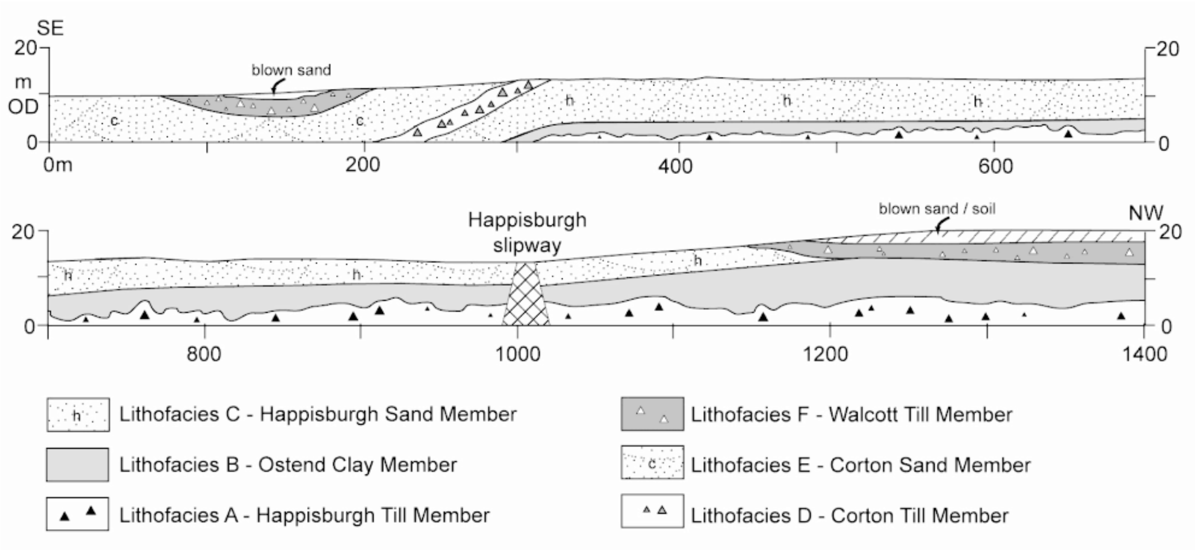


Figure 2. Generalised cross-section of the deposits exposed in coastal sections at Happisburgh.

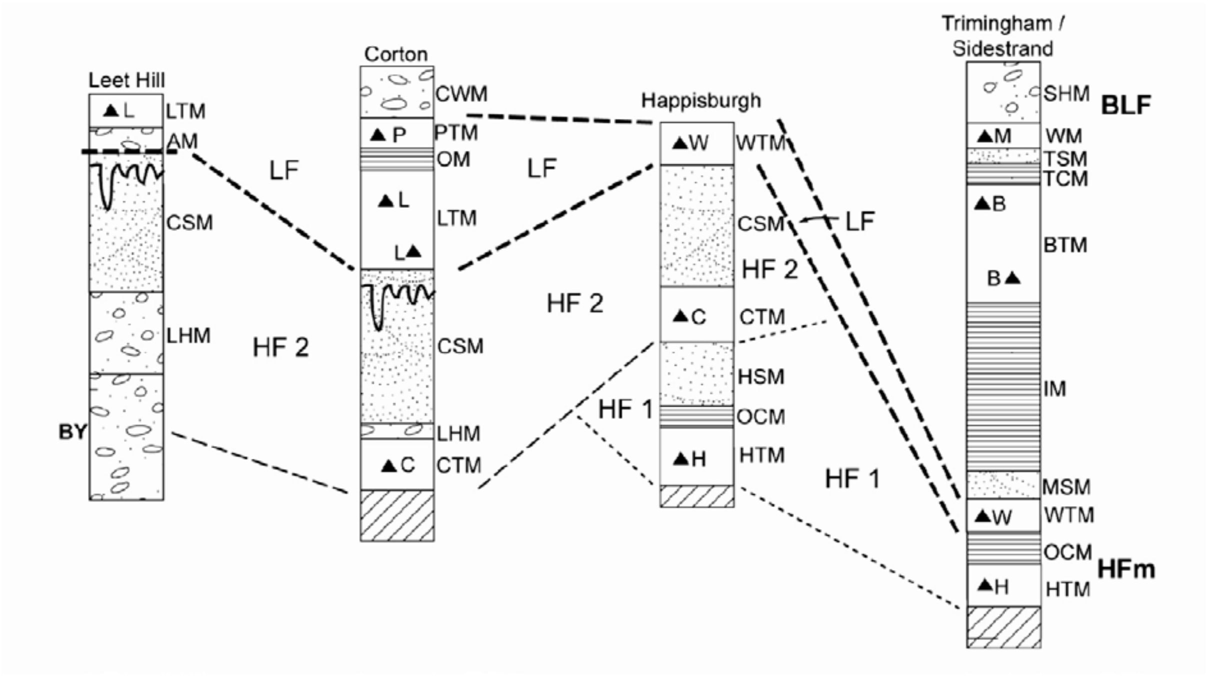
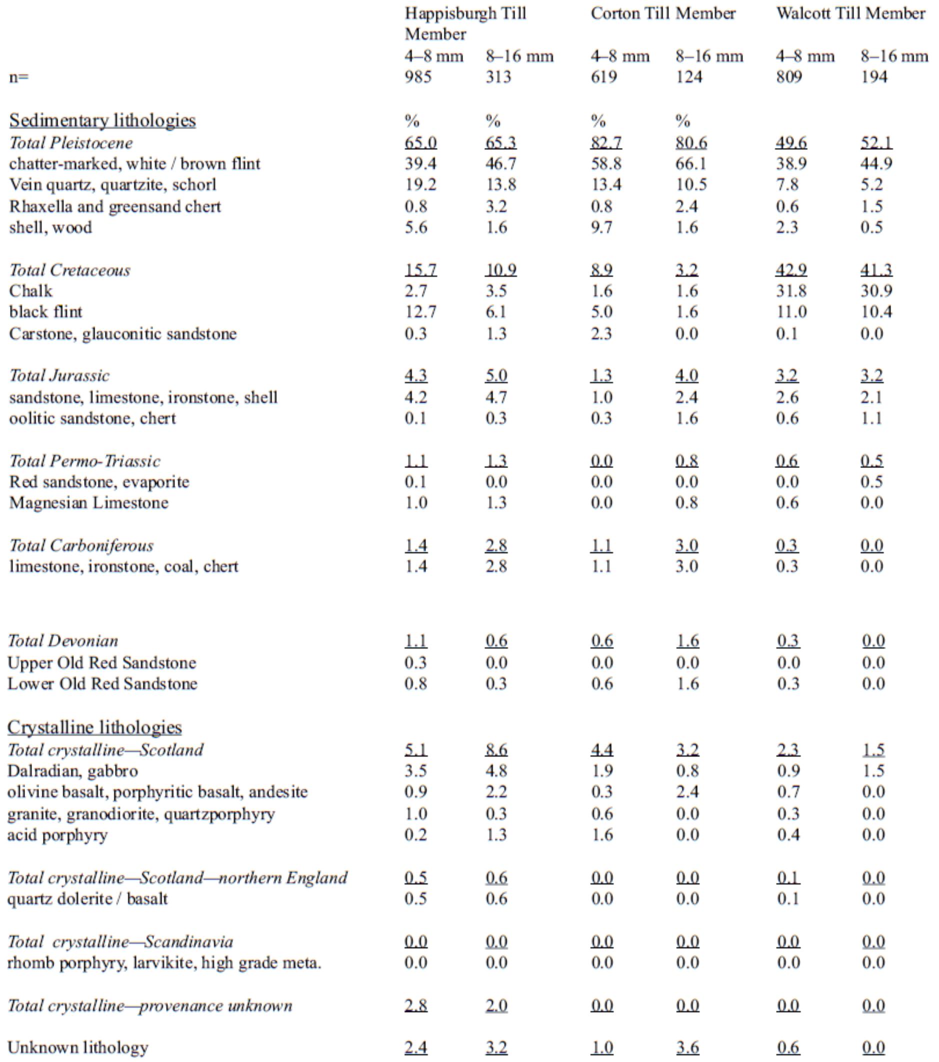


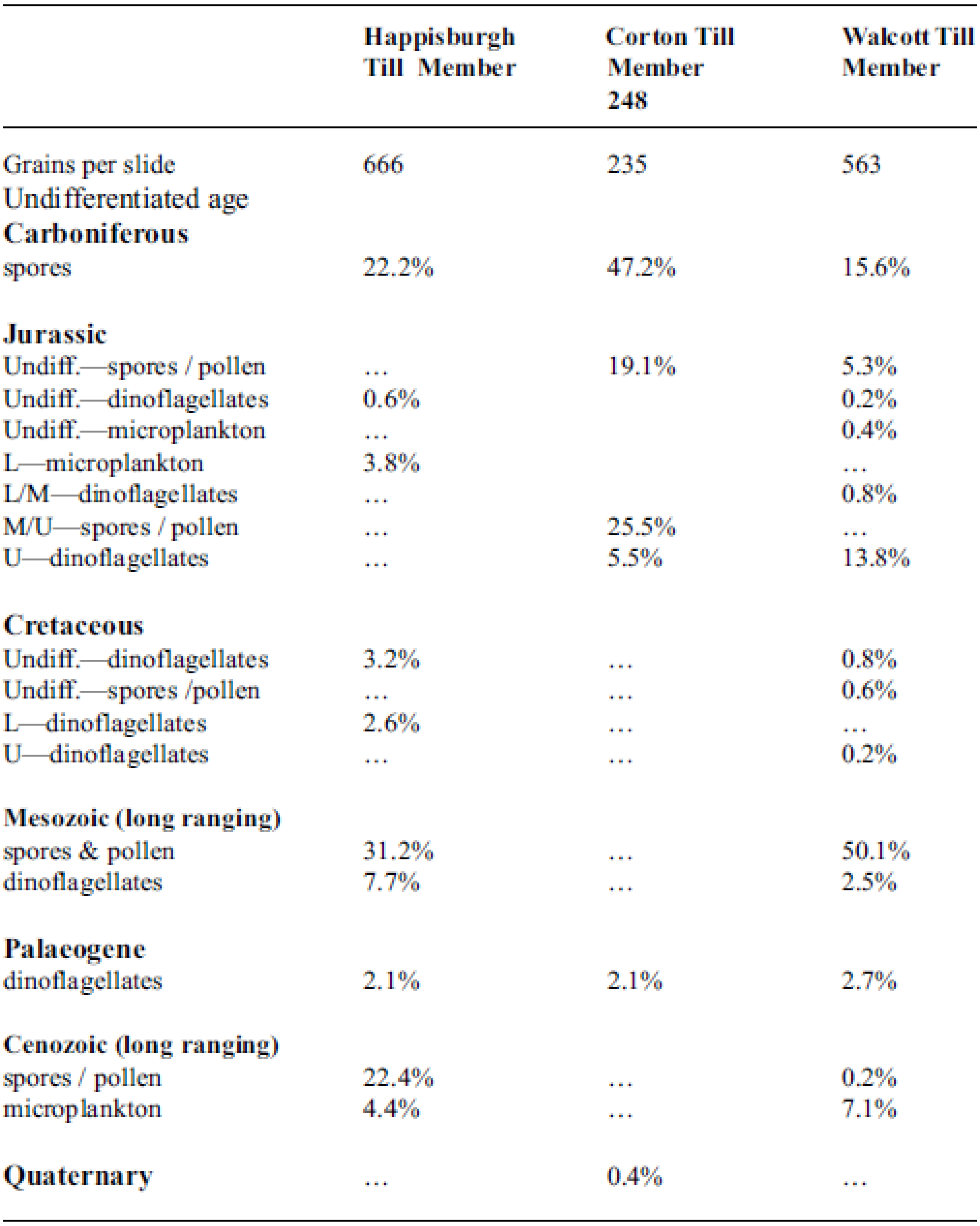
Figure 3. Fence diagram showing the correlation of Happisburgh to Corton in the Waveney Valley and Sidestrand in northeast Norfolk.



	Happisburgh Till Member		Corton Till Member		Walcott Till Member	
	4–8 mm	8–16 mm	4–8 mm	8–16 mm	4–8 mm	8–16 mm
n=	985	313	619	124	809	194
Sedimentary lithologies	%	%	%	%		
Total Pleistocene	65.0	65.3	82.7	80.6	49.6	52.1
chatter-marked, white / brown flint	39.4	46.7	58.8	66.1	38.9	44.9
Vein quartz, quartzite, schorl	19.2	13.8	13.4	10.5	7.8	5.2
Rhaxella and greensand chert	0.8	3.2	0.8	2.4	0.6	1.5
shell, wood	5.6	1.6	9.7	1.6	2.3	0.5
Total Cretaceous	15.7	10.9	8.9	3.2	42.9	41.3
Chalk	2.7	3.5	1.6	1.6	31.8	30.9
black flint	12.7	6.1	5.0	1.6	11.0	10.4
Carstone, glauconitic sandstone	0.3	1.3	2.3	0.0	0.1	0.0
Total Jurassic	4.3	5.0	1.3	4.0	3.2	3.2
sandstone, limestone, ironstone, shell	4.2	4.7	1.0	2.4	2.6	2.1
oolitic sandstone, chert	0.1	0.3	0.3	1.6	0.6	1.1
Total Permo-Triassic	1.1	1.3	0.0	0.8	0.6	0.5
Red sandstone, evaporite	0.1	0.0	0.0	0.0	0.0	0.5
Magnesian Limestone	1.0	1.3	0.0	0.8	0.6	0.0
Total Carboniferous	1.4	2.8	1.1	3.0	0.3	0.0
limestone, ironstone, coal, chert	1.4	2.8	1.1	3.0	0.3	0.0
Total Devonian	1.1	0.6	0.6	1.6	0.3	0.0
Upper Old Red Sandstone	0.3	0.0	0.0	0.0	0.0	0.0
Lower Old Red Sandstone	0.8	0.3	0.6	1.6	0.3	0.0
Crystalline lithologies						
Total crystalline—Scotland	5.1	8.6	4.4	3.2	2.3	1.5
Dalradian, gabbro	3.5	4.8	1.9	0.8	0.9	1.5
olivine basalt, porphyritic basalt, andesite	0.9	2.2	0.3	2.4	0.7	0.0
granite, granodiorite, quartzporphyry	1.0	0.3	0.6	0.0	0.3	0.0
acid porphyry	0.2	1.3	1.6	0.0	0.4	0.0
Total crystalline—Scotland—northern England	0.5	0.6	0.0	0.0	0.1	0.0
quartz dolerite / basalt	0.5	0.6	0.0	0.0	0.1	0.0
Total crystalline—Scandinavia	0.0	0.0	0.0	0.0	0.0	0.0
rhomb porphyry, larvikite, high grade meta.	0.0	0.0	0.0	0.0	0.0	0.0
Total crystalline—provenance unknown	2.8	2.0	0.0	0.0	0.0	0.0
Unknown lithology	2.4	3.2	1.0	3.6	0.6	0.0

Table 1. Clast lithological composition of the Happisburgh Till, Corton Till and Walcott Till members (after Lee, 2003; Lee et al., 2002, 2004b).

LEE, J R, ROSE, J, RIDING, J B, MOORLOCK, B S P, AND HAMBLIN, R J O. 2008. Happisburgh Cliffs (TG 380 312) : glacial lithostratigraphy, till provenance and ice-marginal deposits. 137-150 in *The Quaternary of northern East Anglia : field guide.* CANDY, I, LEE, J, AND HARRISON, A (editors). *Quaternary Research Association. Field Guide.* (Quaternary Research Association.)



	Happisburgh Till Member	**Corton Till Member 248**	**Walcott Till Member**
Grains per slide	666	235	563
Undifferentiated age			
Carboniferous			
spores	22.2%	47.2%	15.6%
Jurassic			
Undiff.—spores / pollen	…	19.1%	5.3%
Undiff.—dinoflagellates	0.6%		0.2%
Undiff.—microplankton	…		0.4%
L—microplankton	3.8%		…
L/M—dinoflagellates	…		0.8%
M/U—spores / pollen	…	25.5%	…
U—dinoflagellates	…	5.5%	13.8%
Cretaceous			
Undiff.—dinoflagellates	3.2%	…	0.8%
Undiff.—spores /pollen	…	…	0.6%
L—dinoflagellates	2.6%	…	…
U—dinoflagellates	…	…	0.2%
Mesozoic (long ranging)			
spores & pollen	31.2%	…	50.1%
dinoflagellates	7.7%	…	2.5%
Palaeogene			
dinoflagellates	2.1%	2.1%	2.7%
Cenozoic (long ranging)			
spores / pollen	22.4%	…	0.2%
microplankton	4.4%	…	7.1%
Quaternary	…	0.4%	…

Table 2. Table showing the percentages of palynomorphs of different groups and ages. Long-ranging taxa are excluded since these are deemed to be forms that cannot be confined to era level.