Age and Relationships of the Chillesford Clay (Early Pleistocene: Suffolk, England)

J. A. Zalasiewicz, S. J. Mathers, P. L. Gibbard, S. M. Peglar, B. M. Funnell, J. A. Catt, R. Harland, P. E. Long and T. J. F. Austin

Phil. Trans. R. Soc. Lond. B 1991 **333**, 81-100
doi: 10.1098/rstb.1991.0061

Age and relationships of the Chillesford Clay (early Pleistocene: Suffolk, England)

J. A. ZALASIEWICZ[1], S. J. MATHERS[1], P. L. GIBBARD[2], S. M. PEGLAR[3], B. M. FUNNELL[4], J. A. CATT[5], R. HARLAND[1], P. E. LONG[6] AND T. J. F. AUSTIN[7]

[1] *British Geological Survey, Keyworth, Nottingham, NG12 5GG, U.K.*
[2] *Subdepartment of Quaternary Research, Botany School, University of Cambridge, Downing Street, Cambridge CB2 3EA, U.K.*
[3] *Botanisk Institutt, Bergen Universitet, Allegaten 41, N-5007 Bergen, Norway*
[4] *School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, U.K.*
[5] *Soil Science Department, Rothamsted Experimental Station, AFRC Institute of Arable Crops Research, Harpenden, Hertfordshire AL5 2JQ, U.K.*
[6] *Botany Department, University of Leicester, Leicester LE5 5UH, U.K.*
[7] *36 College Road, Norwich NR2 3JL, U.K.*

CONTENTS

Phil. Trans. R. Soc. Lond. B (1991) **333**, 81–100
Printed in Great Britain

SUMMARY

The distribution, lithology, palaeontology (pollen and spores, foraminifera, molluscs and dinoflagellate cysts), heavy mineral content and palaeomagnetic properties of the Chillesford Clay Member of the Norwich Crag Formation are described, and compared with those of the Easton Bavents Clay that outcrops further north. The Chillesford Clay is a discrete unit forming the top of the marine Plio-Pleistocene sequence between Aldeburgh and Orford, Suffolk; it rests conformably on the Chillesford Sand. Pollen spectra are dominated by non-arboreal pollen. Two local pollen assemblage biozones are recognized; the lower is similar to that of the Baventian, and the upper to that of the Pre-Pastonian *a*. A deterioration in climate from cool oceanic to cold is indicated. Foraminifera assemblages preserved in one sequence suggest a decline from temperate to cool conditions. Restricted mollusc assemblages found in one sequence may signify low temperatures. Dinoflagellate cyst floras differ from those of the Chillesford Sand and Easton Bavents Clay, and in all these deposits suggest warmer conditions than the other biological indicators, although their absence from part of the Chillesford Clay may indicate low temperatures. Heavy mineral suites from the Chillesford Clay, Easton Bavents Clay, Chillesford Sand and Red Crag Formation are similar and are more diverse than those of the overlying fluviatile Middle Pleistocene Kesgrave Formation; thus, the earlier concept of a distinctive mineralogy of the Easton Bavents Clay is refuted. Palaeomagnetic measurements were inconclusive.

The Chillesford Clay is interpreted as a temporal correlative of the Easton Bavents Clay. Both deposits are thought to have been deposited in high intertidal conditions during the major marine regression that accompanied transition from the Bramertonian Stage (warm) to the Baventian cold Stage and Pre-Pastonian *a* cold Substage. This suggests that these two cold stages/substages are more closely related in time than previously thought, and that the relative stratigraphical positions of the Bramertonian and Baventian stages are the reverse of those originally envisaged. The Baventian to Pre-Pastonian *a* interval probably correlates with the Tiglian C4c Substage of the Netherlands sequence, and should be considered as part of a single cold stage, for which the Baventian has nomenclatural priority.

1. INTRODUCTION

Stages within the British Plio-Pleistocene cannot always be satisfactorily related because many are defined at different type sites, the deposits are laterally variable and there is often no evidence of superposition. In East Anglia, there are special problems associated with the mainly arenaceous Red Crag and Norwich Crag formations. Some biostratigraphically important fossil groups (pollen, dinoflagellate cysts) are not normally preserved in these deposits, and others (molluscs, foraminifera) can be difficult to interpret because of abrasion and reworking. Thus, clay beds within the Crag sequences assume considerable stratigraphic importance, as they contain relatively complete, undisturbed fossil assemblages and have measurable palaeomagnetic properties. Because of this they provide some of the most complete insights available into the nature of climatic and environmental change during the pre-glacial Pleistocene of the southern North Sea Basin.

One of the most important clay units is the Chillesford Clay of southeast Suffolk. Originally described by Prestwich (1849) from localities around Chillesford, it was subsequently correlated with other clays, in particular the Easton Bavents Clay of north Suffolk and Norfolk (Prestwich 1871 *a*, *b*). This correlation was accepted during the original geological survey of East Anglia (see Reid 1890), but it was queried during the stratigraphical revision resulting from the micropalaeontological studies of West (1961) and Funnell (1961). The Chillesford Clay was first assigned to the Pastonian (West & Norton 1974) but subsequently to the Bramertonian (warm) Stage (Funnell *et al.* 1979). The Easton Bavents Clay provided the type section for the Baventian (cold) Stage (Funnell & West 1962; West *et al.* 1980). In addition, the two clays were thought to be mineralogically different (Solomon in Funnell & West (1962)).

The Baventian was thought to precede the Bramertonian partly because the deposits that underlie the type Baventian contain a temperate pollen assemblage that differs from that of the Bramertonian and resembles instead that of the earlier Antian Stage. In addition, at the Bramertonian stratotype (Bramerton Common), the post-Bramertonian deposits contain a cold climate pollen assemblage assigned to the Pre-Pastonian *a* Substage. However, both type sections (Bramerton Common and Easton Bavents) contain palaeontological evidence for only two stages (a warm stage followed by a cold), whose relationships to older and younger stages are uncertain: at Bramerton Common, the Bramertonian deposits rest unconformably on Chalk; at Easton Bavents, the Baventian deposits are overlain by the unfossiliferous Westleton Beds. There is no single, unambiguous way of correlating the stages represented at these two type sites.

Recent investigations have cast further doubt upon the proposition that the Bramertonian post-dates the Baventian. First, mapping in southeast Suffolk showed that all of the deposits in the Chillesford area from which West & Norton (1974) obtained Bramertonian pollen assemblages were the upper silty part of the Chillesford Sand (Zalasiewicz & Mathers 1985); the overlying Chillesford Clay itself had not been analysed palaeontologically. Second, studies of microtine (vole) teeth by Mayhew (1985) and Mayhew & Stuart

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

(1986) indicated that the Bramertonian deposits may be older, and not younger, than the Baventian deposits. Funnell (1987) accepted this possibility, noting that 'nowhere is the Bramertonian found overlying the Antian, or the Baventian', and some subsequent authors (see, for example, Bowen *et al.* (1986)) have now placed the Baventian above the Bramertonian.

This study describes the distribution, lithology, heavy mineral composition, magnetic polarity, and pollen and spore, foraminifera, mollusc and dinoflagellate cyst assemblages of the Chillesford Clay in an attempt to clarify its stratigraphic position. Implications for the relations of the Bramertonian, Baventian and Pre-Pastonian stages are discussed.

2. LITHOSTRATIGRAPHY

(*a*) *Description*

(i) *Chillesford Clay*

The Chillesford Clay Member (Zalasiewicz & Mathers 1985) is one of a number of discrete clay bodies which locally occur at or near the top of the Norwich Crag Formation in southern East Anglia (Allen 1984; Funnell & West 1962; West *et al.* 1980; figure 1, this paper). Its distribution, stratigraphical relations and lithology are shown in figures 2–5 (see also Zalasiewicz & Mathers (1985), figures 4 and 5), together with the locations of recorded sections and samples for bio- and chronostratigraphical data and mineralogical analysis. The clay is a lenticular body up to 5 m thick with a transitional contact into the underlying Chillesford Sand Member (figure 5). Its elliptical distribution, aligned N.E.–S.W., measures 12 km × 4 km. Its base, at *ca.* +14 m O.D. in the southwest, gradually descends to *ca.* +10 m O.D. in the northeast. The type section, chosen by Zalasiewicz & Mathers (1985) from Prestwich's original (1849) list of described sites, is at Chillesford Brickyard (TM 38805258) (figures 2 and 5).

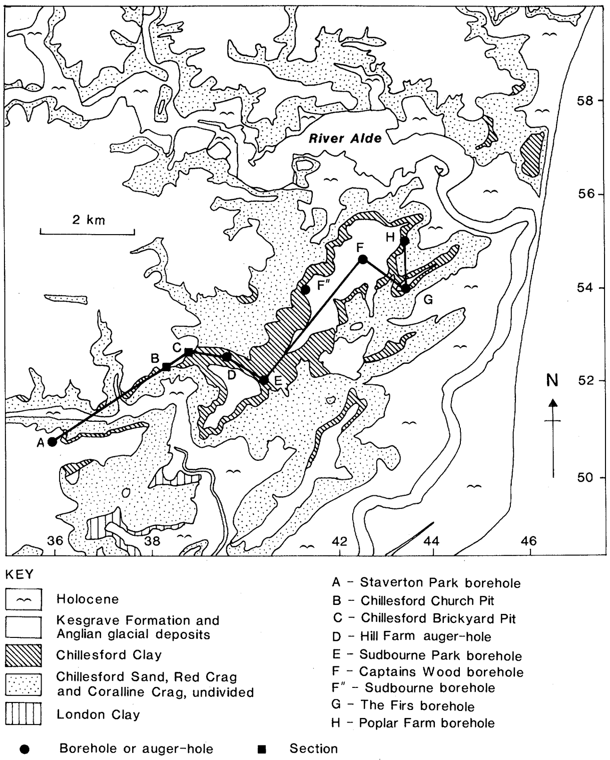

Figure 2. Simplified geological map, and location of sites described in the test. A, TM 35765050; B, TM 38295231; C, TM 38805258; D, TM 39655242; E, TM 40365193; F, TM 42375455; F″, TM 41425409; G, TM 43915390; H, TM 43405496.

The Chillesford Clay is typically a pale to medium grey clay with ochreous staining and scattered laminae of silt and fine sand; locally, there are thin intervals of

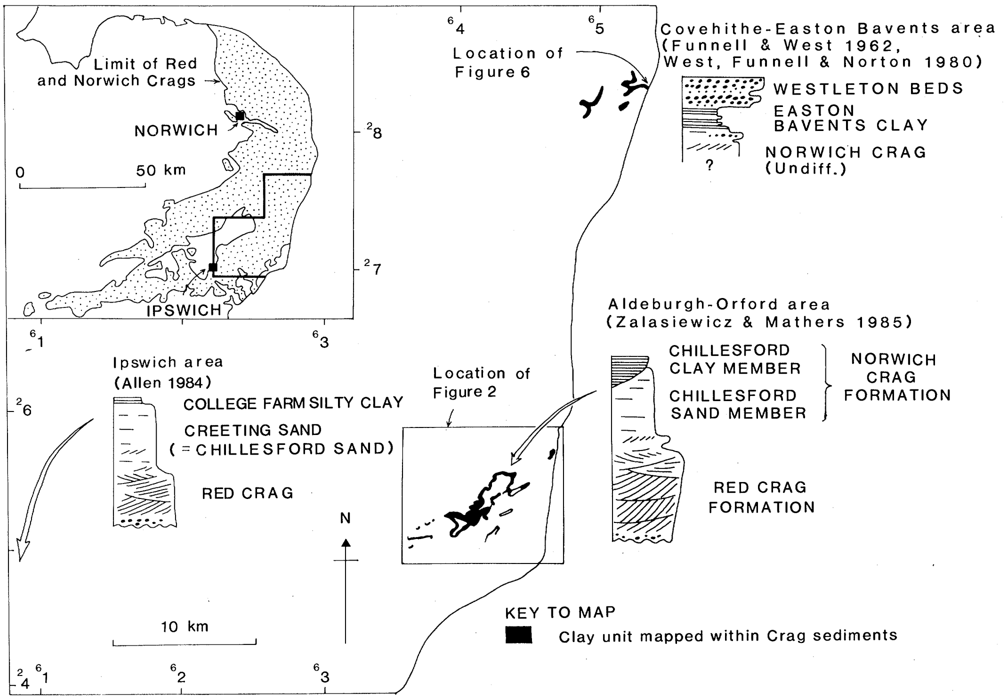

Figure 1. Location of area, and generalized location and stratigraphy of clay units in the upper part of the Norwich Crag Formation of southern East Anglia.

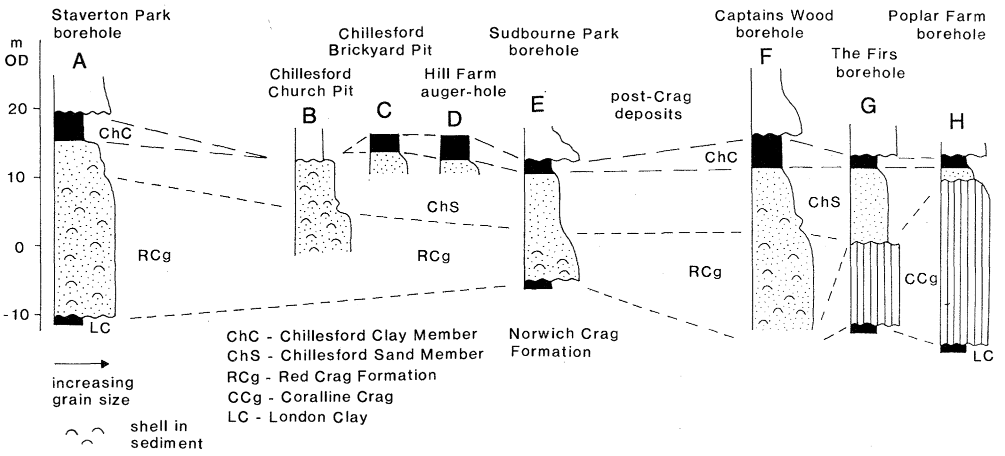

Figure 3. Correlation of sections and boreholes through the Chillesford Clay (for locations see figure 2).

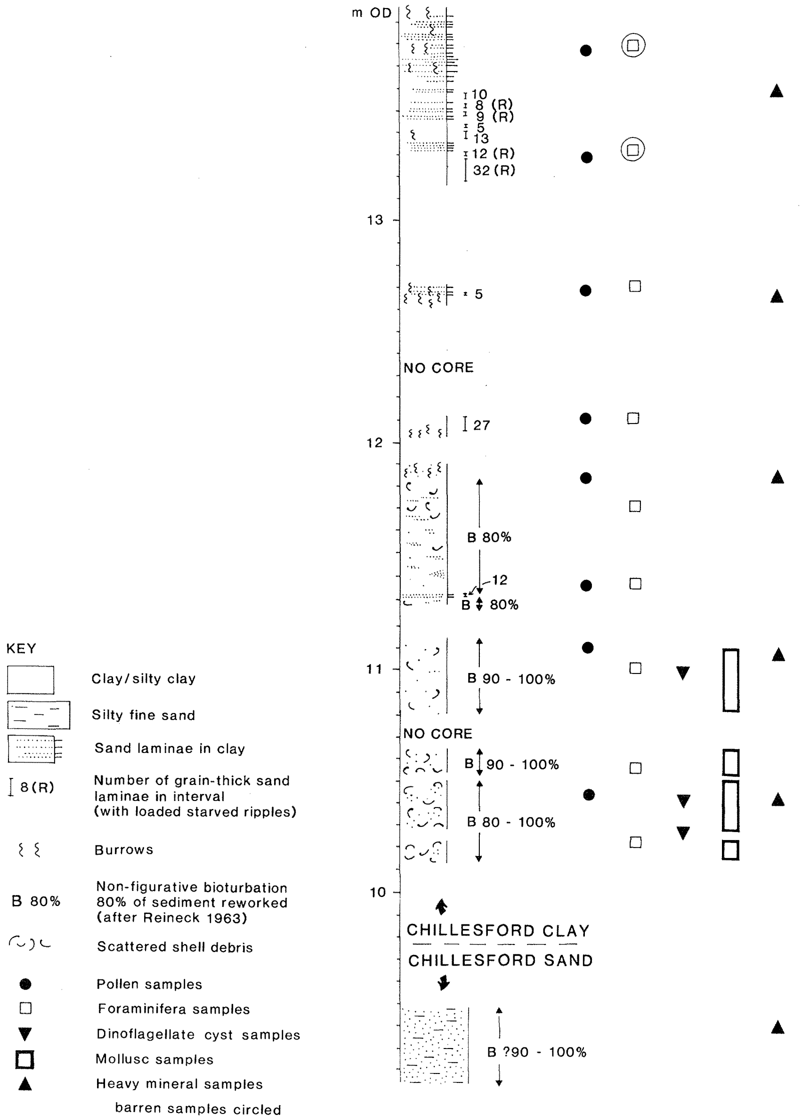

Figure 4. Diagrammatic graphic section of the Chillesford Clay in the Captain's Wood borehole (for location see figure 2) showing sampled intervals.

fine sand with clay laminae (e.g. figure 5). The thickest sequence recorded is from the Captain's Wood borehole (figure 4) where the basal 2–3 m consists of dark grey, sparsely shelly and strongly bioturbated clay. The upper part of the sequence at Captain's Wood is pale grey, probably from post-depositional weathering (R. D. Wilmot, personal communication). Macrofossils, except in the basal part of the Captain's Wood

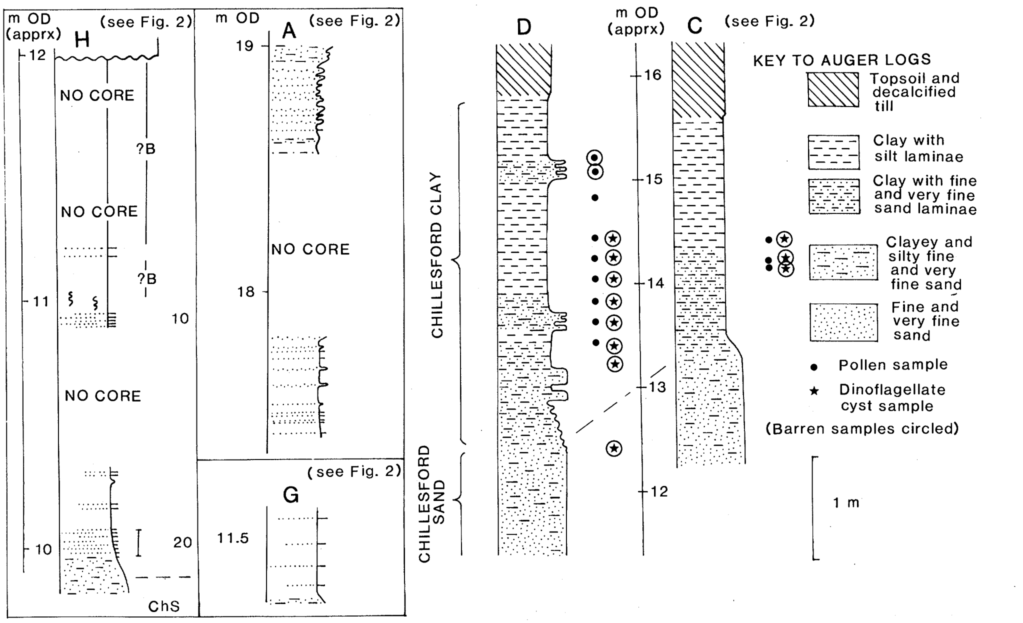

Figure 5. Diagrammatic graphic sections of the Chillesford Clay in the Poplar Farm, Staverton Park and Firs boreholes (for key see figure 4), and of the Hill Farm and Chillesford Brickyard boreholes (logs generalized), with sampled levels.

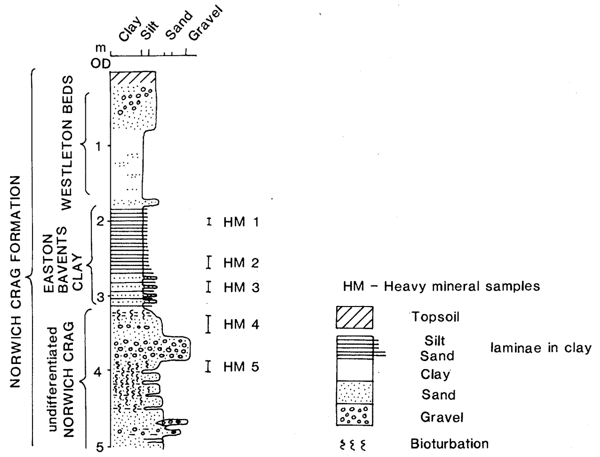

Figure 6. Diagrammatic lithological log through the cliff section at Easton Bavents (TM 517790), showing levels sampled for heavy mineral analysis. See also Funnell & West (1962).

Borehole (figure 4), are rare; Prestwich (1849) reported shell moulds and whale remains from the Chillesford Brickyard Pit.

(ii) *Easton Bavents Clay*

The Easton Bavents Clay, less than 3 m thick, lies at a lower elevation than the Chillesford Clay, its base being between +1 m and +3 m O.D. Its type locality is the cliff section at Easton Bavents in Suffolk (figure 6), and it is also exposed in the cliff section at Covehithe, 3–4 km to the north. It overlies shelly sands of the Norwich Crag (Funnell & West 1962; Long 1974), of Antian to early Baventian (Lp 4a) age, and is overlain by flint-rich marine gravels of the Westleton Beds.

Lithologically it is similar to the Chillesford Clay, with laminae and some thin beds of fine-grained sand. In the cliff section (figure 6) the clay is 1.4 m thick, its basal 0.5 m containing more sand laminae, locally with ripple cross-lamination. The base of the clay rests on a bioturbated clay – fine sand layer *ca.* 10 cm thick.

(*b*) *Interpretation*

The lithology of the Chillesford Clay is consistent with, although not diagnostic of, deposition in a high intertidal environment (cf. Evans 1965). This accords with the interpretation of the underlying Chillesford Sand as a tidal sand flat deposit (Funnell 1961; Dixon 1972; Zalasiewicz & Mathers 1985). The Easton Bavents Clay has also been interpreted as a high intertidal deposit, with evidence of intermittent desiccation at Covehithe (West *et al.* 1980).

3. HEAVY AND LIGHT MINERAL PETROGRAPHY

The heavy mineral assemblage of the Easton Bavents Clay was reported by Solomon (in Funnell & West 1962) to be distinct from those of other Crag deposits. The distinguishing feature was said to be an abundance of fresh, weatherable heavy minerals, especially alkali amphiboles. Solomon proposed that the Easton Bavents Clay consists 'in the main of outwash material of a northern (Scandinavian) ice-sheet' (p. 135 in Funnell & West (1962). This has been widely quoted (e.g. Bowen *et al.* 1986) as evidence that the Baventian had a significantly more severe climate than earlier cold stages of the Quaternary.

Fine sand (63–250 μm) fractions were separated from the following samples by sieving after ultrasonic dispersion in a weak (0.1 g l^{-1}) solution of sodium hexametaphosphate.

1. Five samples from the Easton Bavents Clay at Easton Bavents (figure 6).

2. Six samples from the Chillesford Clay of the Captain's Wood borehole (the lowermost sample is from the uppermost Chillesford Sand) (figure 4).

3. Three samples from the Chillesford Sand at Chillesford Church Pit (TM 38295231; Zalasiewicz & Mathers (1985), figure 8, B1) at levels of 11.1–11.3, 8.8–9.0 and 7.8–8.0 m O.D.

4. Four samples from the Thorpeness and Sizewell Members of the Red Crag Formation recovered from the Aldeburgh-Sizewell area (Zalasiewicz *et al.* 1988, borehole C, at −13.2, −22.2, −40.3 and −41.4 m O.D.).

Approximately 10 g of each fine sand was divided into light and heavy fractions by flotation in bromoform (density 2.9 g cm^{-3}) and analysed mineralogically by identifying more than 500 grains in each fraction using a petrological microscope. Despite the range in their stratigraphic level, all samples yielded generally similar assemblages (table 1). The main differences between the Chillesford Clay and Easton Bavents Clay are: (i) pyrite is common in the Chillesford Clay but absent from the Easton Bavents Clay; (ii) plagioclase feldspar is absent from the Chillesford Clay but occurs in small amounts in some samples of Easton Bavents Clay; (iii) flint fragments, ilmenite + magnetite, zircon, colourless garnet, pink garnet and brown rutile are slightly more abundant in the Easton Bavents Clay, whereas muscovite, green hornblende, brown amphiboles, chlorite, apatite and collophane are slightly more abundant in the Chillesford Clay.

Differences (i) and (iii) can be explained by greater weathering of the Easton Bavents Clay, as the minerals that are absent from or less abundant in this deposit are fairly easily weathered, and the minerals that are more abundant in this clay are very resistant to weathering and would have been proportionally enriched by the loss of weatherable constituents. The differences are insufficient to distinguish the likely original mineral suites of these two deposits. The minerals that Solomon (in Funnell & West 1962) believed to form the distinctive glacial assemblage of the Easton Bavents Clay are in fact more abundant in the Chillesford Clay.

The mineral composition of the Chillesford Sand samples shows some similarities with that of the Chillesford Clay (e.g. in amounts of flint fragments, garnet and collophane) and other similarities with that of the Easton Bavents Clay (e.g. in amounts of quartz, alkali feldspar, muscovite, ilmenite + magnetite, zircon, green hornblende, brown rutile, chlorite and apatite). Some of the ways in which the Chillesford Sand resembles the Easton Bavents Clay rather than the Chillesford Clay may be attributable to the greater mineral weathering to be expected in sand compared with clay, but the overall composition of the sand intermediate between the two clays serves mainly to emphasize the overall similarity of detrital sand mineral suites in the two groups of deposits.

The sand mineral composition of the Red Crag is slightly more variable than that of the other three groups of samples. For example, at some horizons it contains much larger amounts of the non-detrital constituents pyrite and glauconite. In addition, the range of amounts of many minerals is greater than in any of the other three groups and often spans the full range of their composition. The main exceptions to this are chlorite, biotite, red rutile, sillimanite, olivine, sphene and apatite, most of which occur sporadically in trace amounts in all four groups of samples. Overall the Crag is mineralogically very similar to the Chillesford Sand and Clay and Easton Bavents Clay, and it is clear that all have a common provenance. The small differences in amounts of minerals between the four groups of samples are readily explained by differences of depositional or post-depositional (weathering) environment. It would be necessary to analyse a much larger number of samples more closely spaced through the succession before these four formations could be reliably separated by sand mineralogy.

The assemblages differ markedly from those of the fluviatile Kesgrave Formation (Rose & Allen 1977), which represents early Thames deposits of pre-Anglian age. These contain fewer mineral species, and are derived mainly from Palaeogene sediments of the London Basin (Kemp 1987). Previously described Red Crag assemblages (see, for example, Double (1924); see also Burger in Gibbard *et al.* 1991) also contain a more restricted mineral suite, which may result in part from loss of certain minerals by weathering.

On this evidence, Solomon's proposal (in Funnell & West 1962) that the Easton Bavents Clay is mineralogically distinct cannot be supported. There is no petrographic objection to equating the Chillesford Clay and the Easton Bavents Clay, although their mineralogical similarity cannot be taken as proof of their equivalence.

4. PALAEOMAGNETIC POLARITY

(*a*) *Easton Bavents Clay*

The results of palaeomagnetic studies of the Easton Bavents Clay from Easton Bavents (figure 6), Covehithe (TM 530821) and Cove Bottom Brick Pit (TM 493803), in part done by J. C. Battersby, are summarized in table 2. They are consistent between the three sites and all show normal polarity.

However, comparing measurements made immediately after collection and several months later showed that the magnetization of the samples changed during storage. Of particular concern was a decrease in NRM intensity accompanied by a decrease in susceptibility which showed chemical changes in the magnetic minerals; this may have been a low-temperature oxidation of magnetite to maghemite during the slight drying of the samples while in (cold) storage. This casts doubt on the normal NRM signal, which may have been acquired after deposition, perhaps in the Earth's present magnetic field.

(*b*) *Chillesford Clay*

Five samples of the clay from Chillesford Brickyard Pit were all weakly magnetized, with positive inclination, indicating normal polarity. Three of the

Table 1. *Mineralogical composition (means and ranges) of fine sand (63–250 μm) fractions from the Easton Bavents Clay (five samples), Chillesford Clay (six samples), Chillesford Sand (three samples) and Red Crag (four samples)*

	Easton Bavents Clay		Chillesford Clay		Chillesford Sand		Red Crag	
	mean	range	mean	range	mean	range	mean	range
(*a*) light fraction (%)								
quartz	88.9	86.4–91.0	86.2	82.0–89.6	90.5	88.4–93.0	88.3	80.2–95.1
alkali feldspar	7.8	5.9–9.2	8.4	8.0–9.6	6.4	5.0–7.7	6.6	3.8–9.1
plagioclase feldspar	0.1	0.0–0.2	—	—	0.2	0.0–0.3	—	—
flint fragments	1.9	1.3–2.7	0.9	0.4–1.7	1.5	0.9–2.0	1.8	0.9–2.7
muscovite	1.4	0.2–2.7	4.5	1.0–7.9	1.5	0.0–2.8	3.3	0.2–8.5
(*b*) heavy fraction (%)								
ilmenite/magnetite	28.6	20.0–33.6	12.4	8.2–14.7	38.9	32.7–46.6	20.0	7.1–34.5
leucoxene	7.9	5.5–11.7	8.1	6.7–10.0	13.0	7.3–18.1	10.1	6.0–13.7
pyrite	—	—	11.2	3.8–27.7	0.1	0.0–0.2	29.3	0.0–67.9
zircon	14.5	8.4–19.9	6.6	4.1–9.5	9.7	7.1–13.9	6.3	3.4–8.7
tourmaline	2.9	1.7–3.9	2.9	1.9–4.5	2.5	0.5–5.3	3.4	0.8–6.4
epidote	9.8	5.1–13.6	10.2	7.6–13.7	5.9	3.5–7.2	5.7	3.2–7.8
colourless garnet	14.9	8.7–20.6	7.0	4.8–7.0	5.2	1.8–7.3	3.5	1.9–5.0
pink garnet	2.6	1.3–6.4	1.1	0.7–1.4	0.7	0.2–1.1	0.6	0.1–1.2
green hornblende	8.5	7.1–11.6	15.7	12.6–22.6	6.7	4.4–9.2	7.7	4.8–12.4
brown amphiboles	0.4	0.1–0.6	0.6	0.4–0.9	0.5	0.3–0.7	0.2	0.1–0.4
tremolite/actinolite	0.8	0.2–2.1	1.3	0.9–1.7	0.7	0.4–1.1	0.5	0.3–0.6
augite	0.1	0.0–0.1	0.1	0.0–0.2	0.1	0.0–0.1	0.1	0.0–0.4
brown rutile	2.1	1.3–4.1	1.0	0.3–1.1	1.8	1.1–2.5	1.3	0.5–2.3
yellow rutile	0.7	0.3–1.0	0.5	0.2–0.9	1.0	0.9–1.2	0.3	0.1–0.5
red rutile	0.3	0.1–0.5	0.1	0.1–0.2	0.1	0.0–0.1	—	—
anatase	0.4	0.1–0.7	0.4	0.2–0.6	0.4	0.3–0.5	0.3	0.1–0.6
chlorite	2.1	0.4–5.6	10.5	7.2–22.8	5.1	4.0–6.1	1.6	1.0–2.1
biotite	0.4	0.3–1.1	2.6	0.0–7.5	2.9	1.8–3.9	0.4	0.0–0.8
glauconite	0.3	0.2–0.7	1.1	0.3–3.0	0.7	0.4–1.4	5.6	0.4–15.5
staurolite	1.2	0.6–1.7	0.8	0.3–1.6	0.8	0.6–1.1	1.2	0.3–1.9
kyanite	0.8	0.4–1.3	0.4	0.2–0.9	0.4	0.2–0.3	0.5	0.0–1.0
andalusite	0.1	0.0–0.1	0.2	0.0–0.4	0.3	0.1–0.8	0.1	0.0–0.3
sillimanite	0.1	0.0–0.3	0.2	0.0–0.3	0.1	0.0–0.3	—	—
olivine	0.1	0.0–0.1	0.1	0.0–0.4	0.1	0.0–0.1	—	—
sphene	0.1	0.0–0.1	0.2	0.0–0.4	0.4	0.3–0.5	—	—
apatite	0.5	0.0–0.2	2.1	1.4–3.6	0.9	0.4–1.6	0.4	0.2–0.8
collophane	—	—	0.2	0.0–0.5	0.8	0.7–0.9	0.9	0.0–2.8
monazite	0.1	0.0–0.1	0.1	0.0–0.2	0.1	0.0–0.2	0.1	0.0–0.1

Table 2. *A summary of palaeomagnetic results from the Easton Bavents Clay*

site location	no. of samples	dec.	inc.	α_{95}	θ_{63}	kappa	resultant
Cove Bottom Brick Pit	47	10.3	70.9	4.0	27.4	28.6	45.39129
Easton Bavents Cliff sections	105	16.0	70.7	4.5	25.3	10.3	94.8608
Covehithe Cliff section	42	16.3	69.3	7.3	25.3	10.2	37.98902

samples gave a slightly stronger NRM signal and their results were fairly consistent:

declination = 186.5,

inclination = 65.7,

$K = 18.607$,

$\alpha_{95} = 29.428$,

$R = 2.8925$.

Although these results suggest that the Chillesford Clay has the same magnetic polarity as the Easton Bavents Clay, they are subject to the same uncertainty about the origin of the signal.

5. POLLEN ANALYSIS

(*a*) *Introduction*

Sediment samples of the Chillesford Clay were prepared for pollen analysis by the standard chemical method used in the Subdepartment of Quaternary Research at Cambridge (West 1977). Pollen spectra are expressed as percentages of the pollen sum, total land pollen and Pteridophyte spores (figures 7–9). Pollen-type conventions follow Andrew (1970) with some additions from Birks (1973). Reworked pre-Neogene pollen and spores, and acid-insoluble dinoflagellate cysts were counted and are expressed as percentages of the total land pollen and spores plus each type respectively. The sequence is described for each locality individually and subsequently correlated.

The Chillesford Clay has not previously yielded pollen spectra.

(*b*) *Captain's Wood borehole*

Pollen and spore preservation in this profile was generally good, though markedly poorer in the uppermost, sandier samples. The pollen assemblages (figure 7) represent a Gramineae–Ericales–*Alnus*–*Picea*(–*Pinus*) local pollen assemblage biozone (LPAB).

The spectra are dominated by the pollen of Gramineae and Cyperaceae with low frequencies of a limited range of herbs of open or disturbed ground. Ericales pollen is abundant at all levels and includes that of *Empetrum* and to a lesser extent *Calluna*. Trees are represented by the pollen of *Alnus*, with low frequencies of *Pinus*, *Picea* and *Betula*, consistently small amounts of *Quercus* and *Corylus*, and occasional *Carpinus* and *Pterocarya*. Uniform values of Filicales spores occur throughout.

Reworked pre-Neogene and indeterminate palynomorphs are abundant, the former reaching a peak of 18% of the total at +11.55 m O.D.

The spectra are fairly uniform, although with some changes in relative proportions. For example, above +11.55 m O.D., frequencies of Gramineae pollen increase almost twofold and there is a uniform decline in tree pollen. Towards the top there is a decline in both Cyperaceae- and *Sparganium*-type pollen which is not matched in the pollen of other taxa. However, the decline of some types in the uppermost sample might result from post-depositional weathering.

(*c*) *Chillesford Brickyard*

Pollen and spores in this section were fairly well preserved. The assemblages obtained (figure 8) are assigned to a Gramineae–*Pinus*–*Picea*–*Alnus*(–Ericales) LPAB. Gramineae is the dominant pollen type in all three samples, accompanied by *Pinus* and to a lesser extent *Picea*. *Alnus* pollen is present at frequencies of *ca.* 5%, whereas other trees are represented only in very small quantities. The pollen of ericaceous shrubs is present only in the lower samples. Pollen of other taxa, mainly open or disturbed ground plants, is very restricted.

Indeterminate pollen is uniform in amount throughout, but pre-Neogene pollen and spores occur in significant quantities only in the basal level. These suggest inwash decreasing with time, as local pollen recruitment continued.

There is little upward change in the assemblage composition, except for an increase in *Pinus* at the expense of Gramineae pollen.

(*d*) *Hill Farm, Chillesford*

The samples below +13.20 m and above +14.80 m did not contain pollen and spores. Preservation of pollen and spores is good in the lower of these samples, but deteriorates upwards. The spectra obtained (figure 9) are divided into two assemblages (LPABS), the boundary being drawn at a marked decline in Ericales and rise in Gramineae pollen.

(i) *310–175 cm* (*ca.* *+13.2 m* O.D.*–ca.* *+14.55 m* O.D.)
Gramineae–Ericales–Alnus–Picea(*–Pinus*) LPAB (LPAB(*i*))

The spectra from this biozone are dominated by Gramineae and Ericales (including *Empetrum*) pollen at uniformly high frequencies, the former increasing slightly upwards. Rare *Calluna* pollen is found only in lower levels. Of the tree taxa, *Pinus* and *Alnus* are continuously present, and pollen of various other trees and shrubs, such as *Betula*, *Quercus*, *Picea*, *Carpinus* and *Corylus*, occurs in consistently small amounts. Herb pollen is mainly from plants of open heath and grassland. Undifferentiated fern spores occur at all levels.

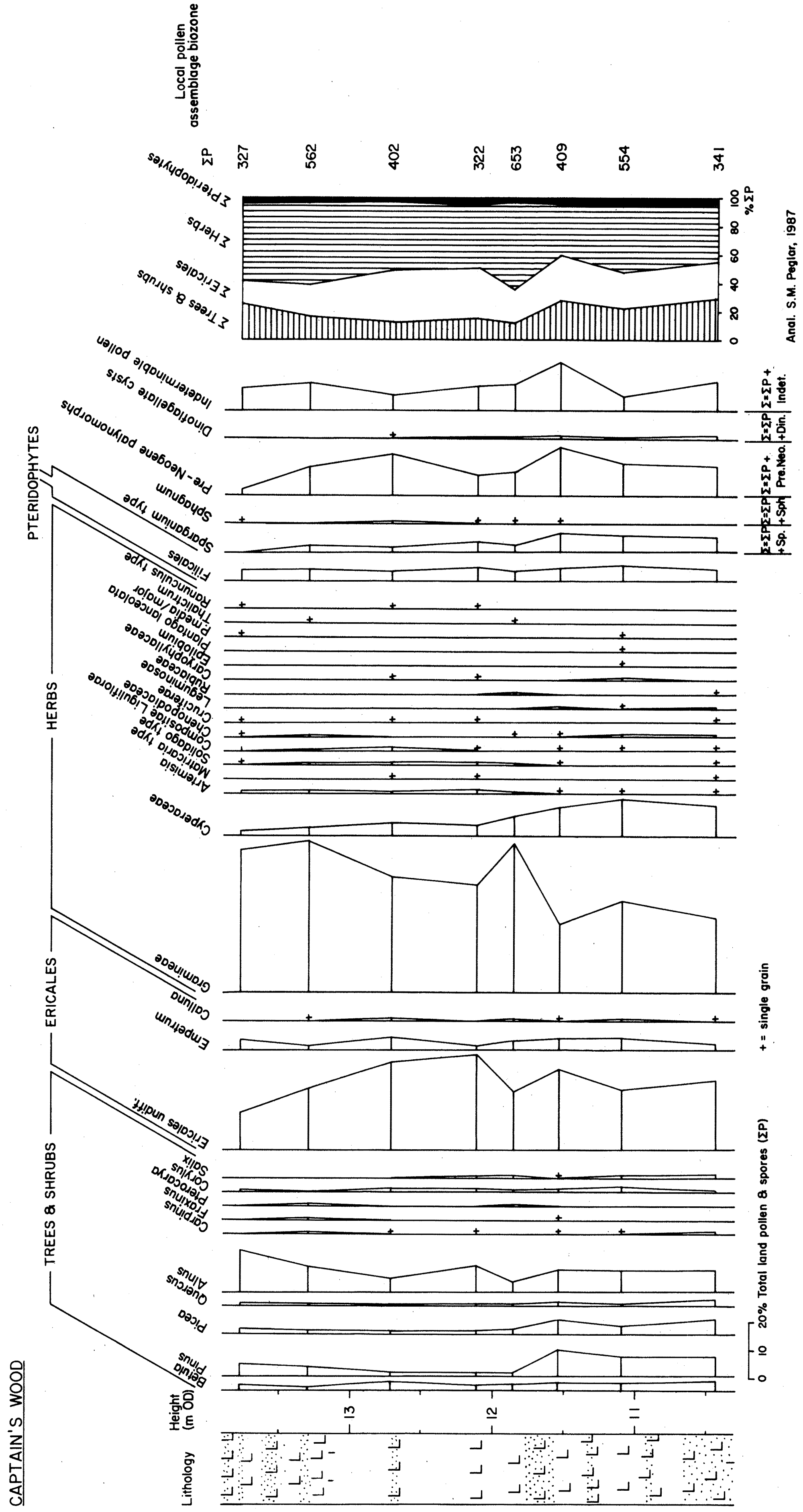

Figure 7. Pollen diagram from the Captain's Wood borehole. For explanation of the local pollen assemblage biozone (LPAB) see text.

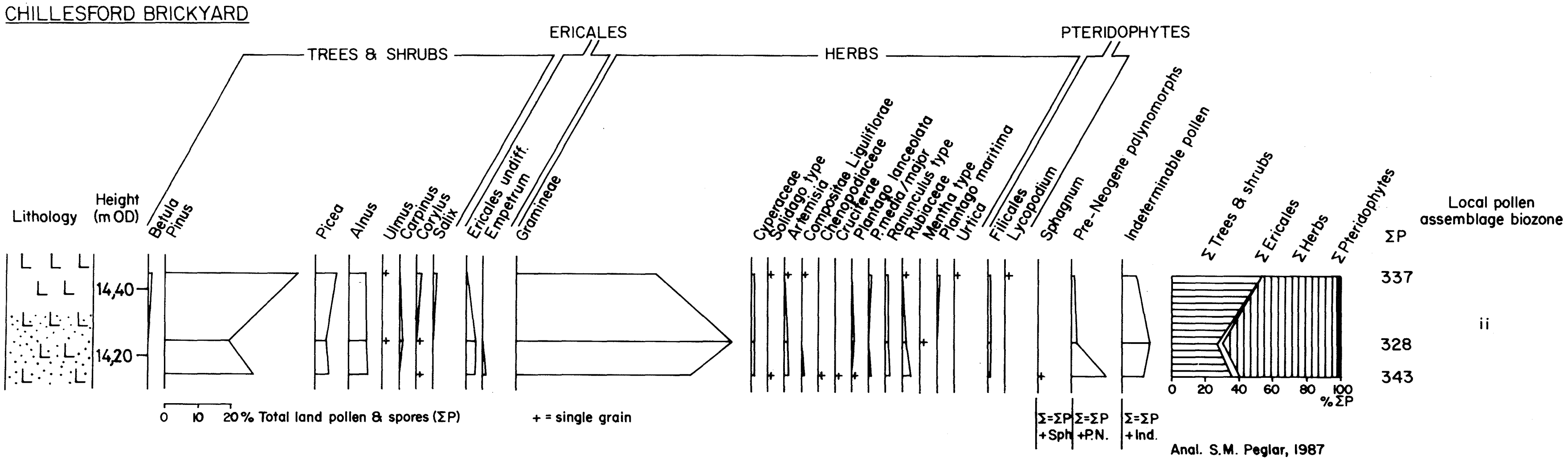

Figure 8. Pollen diagram from Chillesford Brickyard. For explanation of the local pollen assemblage biozone (LPAB) see text.

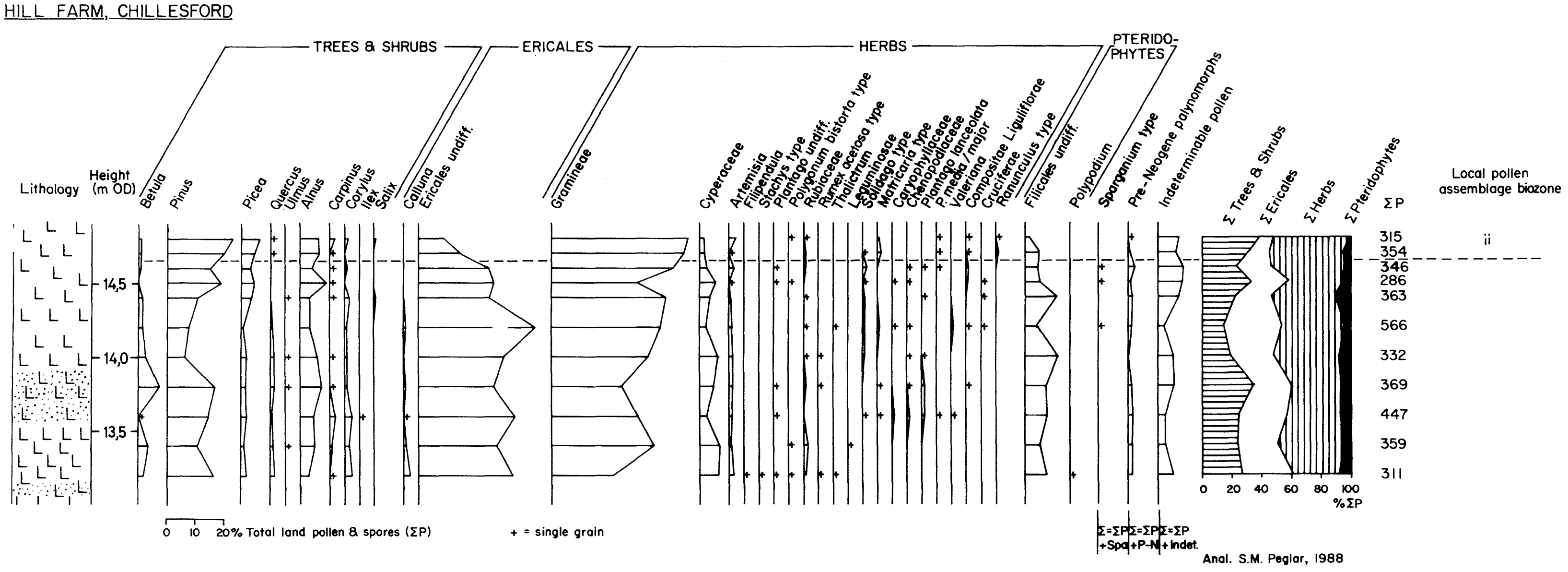

Figure 9. Pollen diagram from the Hill Farm borehole (for explanation of the local pollen assemblage biozones (LPABS) see text.

(ii) *+14.55 m* O.D. *– ca. +14.80 m* O.D.
Gramineae–Pinus–Picea–Alnus(–Ericales) LPAB *(*LPAB*(ii))*

The upper two levels of the sequence are dominated by Gramineae pollen. Compared with the lower biozone, there is also less pollen of herbs and certain tree and shrub taxa. Of these, Ericales pollen declines abruptly. In contrast, pollen of *Pinus* and to a lesser extent *Picea* increases. Except for *Alnus*, pollen of other trees is rare or absent. The increase in indeterminate pollen that began in the upper part of the previous LPAB, continues. This may indicate increasing inwash from earlier sediments or strongly weathered soils.

(*e*) *Taphonomy*

The spectra may be biased by factors known to influence pollen assemblages from marine sediments. These include the homogenization of pollen assemblages from large areas, differential transport, sorting and concentration arising from the different hydrological properties of individual pollen taxa and the proximity of the depositional site to rivers, the coast or local water currents. Such factors are superimposed on other biases such as differential pollen productivity of genera, different pollination mechanisms, etc. (see West (1980*a*) for a full discussion). Notwithstanding these potential problems, the abundance, relative proportions and diversity of taxa suggest that the locality was close to shore. This interpretation is consistent with the sedimentary evidence (see section 2(*b*) above). Thus, it is highly probable that the spectra of determinate pollen reflect the contemporary vegetation of the adjacent land.

(*f*) *Correlation of sequences*

On the basis of the three sequences obtained, two basic assemblages are represented. The first, a Gramineae–Ericales–*Alnus–Picea*(*–Pinus*) LPAB is found in the whole of the Captain's Wood profile and the lower part of the Hill Farm profile (LPAB(i)). The second assemblage is a Gramineae–*Pinus–Picea–Alnus* (–Ericales) LPAB from Chillesford Brickyard and the upper part of the Hill Farm borehole (LPAB(ii)); the assemblage from these two sites may not represent precisely the same time period; in particular, the relative abundance of Ericales pollen suggests that the deposits of this LPAB at Chillesford Brickyard may be slightly younger than those at Hill Farm.

(*g*) *Vegetational history*

The pollen assemblages from Captain's Wood and the lower part of Hill Farm (LPAB(i)) indicate a landscape with a sparse tree cover. The only tree genera represented by significant pollen frequencies, *Betula*, *Picea*, *Alnus* and *Pinus*, are all hardy and typically occur in boreal regions at present. Their lower frequencies suggest either that the trees were not growing near the locality or that there were few individuals, because in modern boreal forest regions such as Fennoscandia, modern surface pollen spectra are dominated by these taxa (Prentice 1978). Pollen of other trees is so rare that it is likely that it was probably reworked or transported a long distance from protected parts of the hinterland or beyond.

The dominance of non-tree pollen types such as Ericales and Gramineae accompanied by *Empetrum* and *Sphagnum* spores suggests oceanic grass-heath vegetation. *Empetrum* is typical of such communities in exposed coastal or montane habitats at present (cf. West *et al.* 1980), and the proportions of the taxa are closely similar to those found in modern oceanic heath communities (cf. Birks 1973). The pollen productivities of these communities is often low, and this may explain why the pollen of some tree genera is slightly more abundant than would be expected.

The upward increase of Gramineae pollen in this biozone may signify decreasing water depth, as relative frequencies of this pollen are known to be higher in nearer-shore environments (West 1980*a*; West *et al.* 1980). In addition, the absence of significant frequencies of Chenopodiaceae pollen suggests that temperate salt marsh vegetation did not exist nearby, but is consistent with Arctic or subarctic salt marsh vegetation (Chapman 1968; West *et al.* 1980). The regional vegetation represented therefore seems to be oceanic grass heath with boreal vegetation growing in protected areas. The prevailing climate indicated is of cool oceanic type.

The pollen assemblages of LPAB(ii) are more impoverished than those of LPAB(i). The lack of thermophilous tree pollen signifies a vegetation of park-tundra type, with an important herbaceous element (cf. West 1961, 1980*a*). The decrease in taxa could represent a change in taphonomy. However, it is more likely to reflect further climatic deterioration.

The extent of tree cover is difficult to determine, because of the lower pollen productivity of the herbaceous vegetation and possible long distance transport of tree pollen. The marked decline and subsequent absence of Ericales pollen late in LPAB(ii) records the retreat of heath vegetation from the area. Although this may reflect a cessation of local fluvial inwash (cf. West 1980*a*), it is more likely to be due to a disappearance of conditions favouring the growth of ericaceous plants, such as the destruction of acid soils by cryoturbation.

(*h*) *Regional correlation*

Possible correlations are summarized in table 3. The Chillesford Clay assemblages must post-date spectra of the 'Chillesford pollen assemblage' recovered by West & Norton (1974) from the underlying Chillesford Sand, which contains abundant arboreal pollen such as *Ulmus*, *Quercus*, *Alnus*, *Carpinus*, *Pinus*, *Picea* and *Betula*, and shows regional deciduous forest growing under a temperate climate. The lack of *Tsuga* pollen, which is abundant in spectra from the pre-Baventian assemblages assigned to the Antian Stage at Easton Bavents (Funnell & West 1962) and from the type Antian at Ludham (West 1961), led to the correlation of the 'Chillesford pollen assemblage' with spectra from the type Bramertonian Stage deposits at Bramerton (Funnell *et al.* 1979) and Outney Common near Bungay (West 1988).

Table 3. *Possible correlations of the Chillesford Clay pollen assemblages*

(Br. Bramerton; CC, Chillesford Clay; CS, Chillesford Sand (of Chillesford Church Pit); EB, Easton Bavents; OC, Outney Common.)

conventional stage sequence	correlation of other important sites		correlation of Chillesford Clay assemblages option 1	option 2	option 3
Pre-Pastonian	Br	Lp4c	CC LPAB (ii)	CC LPAB (ii) CC LPAB (i)	—
Bramertonian	Br OC CS	—	—	CS	—
Baventian	EB	Lp4b Lp4a	CC LPAB (i)	—	CC LPAB (ii) CC LPAB (i)
Antian	EB	Lp3	CS	—	CS

One possible correlative of the Chillesford Clay assemblages is the single *Pinus*–Ericales–Gramineae LPAB spectrum above the temperate pollen-bearing sediments at Bramerton, which was interpreted (Funnell *et al.* 1979) as reflecting a retreat of temperate forest during climatic deterioration. This LPAB was correlated with assemblages from the Lp4c Substage at Ludham (West 1961; Funnell & West 1977) and with the Pre-Pastonian *a* Substage (Pre-Pa *a*) of the coastal sequence (West 1980*a*, *b*). Although the Chillesford Clay Gramineae–Ericales–*Alnus*–*Picea*(–*Pinus*) LPAB (LPAB(i)) could record the same deterioration following the Bramertonian temperate Stage, there are some differences, notably that spectra from the Pre-Pastonian *a* Substage consistently contain higher frequencies of *Pinus* (up to 50% TLP) than those from LPAB(i). The Pre-Pastonian *a* assemblages are more similar to those of LPAB(ii) of the Chillesford Clay (although this may be because hydrodynamic sorting in the marine environment caused over-representation of *Pinus* pollen in the Norfolk localities compared to those farther south (cf. Funnell *et al.* 1979)).

The Chillesford Clay spectra from the lower part of the Hill Farm and the Captain's Wood boreholes are very similar to Baventian (Lp4b) spectra from the Suffolk coastal sites of Easton Bavents (Funnell & West 1962) and Covehithe (West *et al.* 1980). All are dominated by Ericales and Gramineae pollen with subsidiary *Pinus*, *Betula*, *Alnus* and *Picea* pollen. The only slight difference is that the Chillesford Clay assemblages include very low frequencies (less than 4% TLP) of pollen of the deciduous trees *Quercus*, *Ulmus*, *Carpinus* and *Corylus*, but this could be derived from the underlying Chillesford Sand, or could be far travelled, or could suggest a period slightly earlier in the climatic deterioration than deposits at the coastal sites.

The Baventian cold Stage was thought to *pre-date* the Bramertonian Stage (Funnell & West 1977; Funnell *et al.* 1979; West *et al.* 1980), and the main palynological evidence against correlating part of the Chillesford Clay with the Easton Bavents Clay is the pollen stratigraphy of the underlying sediments. The Antian of Easton Bavents and Ludham (Funnell & West 1962; West 1961) contains abundant *Tsuga* pollen. The Bramertonian strata that underlie the Chillesford Clay contain no *Tsuga* pollen, so it is improbable that the Antian and Bramertonian stages are exactly coeval (cf. Funnell 1987), although they could represent different parts of the same temperate episode. The possible stratigraphical relations of the Chillesford Clay are further discussed in §9(*c*).

The pollen evidence obtained during these investigations unquestionably shows a continuity between 'Baventian' type and 'Pre-Pastonian' type cold stage pollen assemblages. This change is most likely to reflect deteriorating climate conditions during deposition of the Chillesford Clay.

6. FORAMINIFERA

(*a*) *Captain's Wood borehole*

Nine samples were examined for foraminifera. The two uppermost samples at +13.77 m and +13.32 m O.D., of ochreous clay, were barren. The remainder all contained foraminifera (tables 4 and 5).

Approximately 80–140 g of each sample was prepared (table 4). Nearly all the 500–250 μm fractions and a randomized selection of the 250–125 μm fractions were picked. Estimates of the total numbers of foraminifera per gram of sediment ranged from 25 to 85 in the lowermost four samples (from +11.37 to +10.20 m O.D.), which also contain identifiable molluscs (see section 8), to 11 to 16 per gram in the upper samples at +12.71 to +11.70 m O.D.

Previous studies of the Crag foraminifera have used largely the 500–250 μm size range. Foraminifera of this size from the Captain's Wood borehole comprise only 3–17% (table 4) of the total 500–125 μm population. Percentages of the species in the 500–250 μm size range have therefore been calculated for comparison with earlier work, but table 5 also shows the percentages in the 250–125 μm size range and in the total 500–125 μm size range (in practice dominated by the 250–125 μm values).

Only three species occur consistently in the 500–250 μm size range. These are *Elphidium excavatum* forma *clavatum*, most abundant in the lowermost sample, *Ammonia beccarii*, most abundant in the next two samples, and *Elphidiella hannai*, most abundant in the top four samples. All are common in the Norwich Crag Formation, where *E. hannai* is often the most abundant species, particularly in colder episodes. At present, *A. beccarii* is typical of low intertidal muddy sand flats, and *E. excavatum clavatum* also commonly occurs in muddy

Table 4. *Captain's Wood borehole foraminifera* (*absolute abundances*)

sample no.	3	4	5	6	7	8	9
500–250µm							
no. counted	32	11	109	49	109	34	101
fraction counted	1/1	1/1	1/1	1/32	1/8	1/8	1/1
total no. estimated	32	11	109	1568	872	272	101
250–125 µm							
no. counted	40	45	56	224	147	263	74
fraction counted	1/32	1/32	1/32	1/32	1/64	1/8	1/64
total no. estimated	1280	1440	1792	7168	9408	2104	4736
ratio 250–125 µm to 500–250 µm	40	131	16	5	11	8	47
grand total estimated	1312	1451	1901	8736	10,280	2376	4837
mass of sample/g	84.78	93.22	169.40	102.34	136.45	93.71	75.02
foraminifera per g	15	16	11	85	75	25	64

Table 5. *Captain's Wood borehole foraminifera* (% *of total count*)

(a = 500–250 µm; b = 250–125 µm; c = 500–125 µm; + = less than 0.5%.)

sample no.	3			4			5			6			7			8			9		
depth in borehole/m	9.53–9.56			10.13–10.17			10.53–10.57			10.87–10.91			11.25–11.30			11.68–11.73			12.04–12.07		
height relative to O.D./m	+12.71			+12.10			+11.70			+11.37			+10.97			+10.54			+10.20		
	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
Ammonia beccarii	25	—	1	18	?	+	11	9	9	35	2	8	72	1	7	53	2	7	29	—	1
Bulimina marginata	3	2	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4	4
Buccella frigida	—	—	—	—	—	—	—	2	2	—	—	—	—	—	—	—	—	—	—	—	—
Cassidulina sp.	—	5	5	—	4	4	—	16	15	—	1	1	—	3	3	—	3	2	—	3	3
Cibicides lobatulus	3	—	+	—	—	—	2	2	2	—	—	—	—	—	—	—	—	—	1	—	+
Cibicides sp.	—	2	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	1
Elphidiella hannai	44	5	6	36	7	7	80	12	16	53	2	11	17	3	4	24	1	3	21	—	+
Elphidium excavatum clavatum	19	68	66	9	51	51	4	43	41	12	94	79	10	84	77	24	93	85	46	80	79
Elphidium frigidum	—	2	2	36	7	7	1	5	5	—	1	1	?	3	2	—	2	2	—	—	—
Elphidium incertum	—	—	—	—	2	2	1	2	2	—	—	—	—	1	1	—	—	—	—	—	—
Elphidium margaritaceum	—	—	—	—	—	—	—	4	3	—	—	—	—	—	—	—	—	—	2	3	3
Elphidium pseudolessonii	3	10	10	—	22	22	1	—	+	—	—	—	—	2	2	—	—	—	—	—	—
Elphidium sp.	3	—	—	—	—	—	—	—	—	—	+	+	—	—	—	—	—	—	—	5	5
Globulina gibba	—	—	—	—	—	—	1	—	+	—	—	—	—	—	—	—	—	—	—	—	—
Lenticulina rotulata	—	—	—	—	—	—	—	—	—	—	—	—	1	—	+	—	—	—	1	—	+
Rosalina sp.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	1
Others	—	—	—	—	—	—	—	2	2	—	—	—	—	3	3	—	—	—	1	—	+
Cretaceous species	—	5	5	—	7	7	—	4	3	—	+	+	—	—	—	—	—	—	—	3	3

sediments, including those of the intertidal zone. Currently, *Ammonia beccarii* has a limited northward range, (Funnell *et al.* 1979, p. 523) and is a post-glacial or interglacial species in the southern North Sea. The specimens from the Captain's Wood borehole are relatively heavily calcified (granulated) in the umbilical region, suggesting relatively warm seawater of normal salinity.

Overall there is little difference in the 500–250 µm size range foraminifera from the bottom to the top of the Chillesford Clay in the Captain's Wood borehole. A temperate (interglacial equivalent) climate and low intertidal or shallow subtidal marine environment are indicated. The increasing importance of *E. hannai* relative to *A. beccarii*, especially above +11.37 m O.D., may indicate some later cooling, which the appearance of *Elphidium frigidum* supports. However the continuing presence of *A. beccarii*, and the absence of *Elphidium orbiculare*, distinctly limits the degree of cooling that can be inferred.

In the 250–125 µm (or total 500–125 µm size range, *E. excavatum clavatum* is the most abundant species (41–85%) throughout. Although this is a very common species in late Devensian (deglaciation) shallow marine deposits around the North Atlantic, it is also common in muddy nearshore sediments laid down in temperate (post-glacial or interglacial) conditions. Therefore its abundance does not negate the warmer conditions indicated by other species (e.g. *A. beccarii*) that are present in the assemblages.

Reworked specimens of Cretaceous species make up to *ca.* 5% of the total foraminifera, consistently so in the top three samples. This, and the presence of *Cassidulina* sp., a typically deeper water species, may indicate shoreward transportation of contemporaneous smaller foraminifera into the intertidal environment.

(*b*) *Comparisons with other localities*

The following comparisons are based essentially on the proportions of foraminiferal species in the 500–250 µm size range.

(i) *Bramerton*

Foraminifera from the Bramertonian of Bramerton Common Pit and Blake's Pit, Bramerton (Funnell *et al.* 1979) differ from the Captain's Wood foraminifera in that *Cibicides lobatulus* and *Elphidium pseudolessoni* are consistently important species alongside the dominant *E. hannai*, and *A. beccarii* and *E. excavatum clavatum* are less important. In a sample also containing pollen referred to the Pre-Pastonian *a* Substage, *Elphidium pseudolessoni* (important in the upper part of the Bramertonian) is the second most abundant species (at 20 %) after *E. hannai*. *E. pseudolessoni* also forms 10–20 % in the top two samples of the Captain's Wood sequence.

(ii) *Chillesford Church Pit*

Foraminiferal assemblages from the upper part of the Chillesford Sand of the Chillesford Church Pit (Funnell 1961, pp. 356, 361) resemble some of those from the lower part of the Chillesford Clay in the Captain's Wood borehole in being dominated by *A. beccarii*, with subsidiary *E. hannai* and *E. excavatum clavatum* and some *E. pseudolessoni*. The 'interglacial-type climate' and a 'tidal-flat or lagoonal environment' inferred by Funnell (1961), are applicable to the lower part of the Chillesford Clay in the Captain's Wood borehole.

(iii) *Easton Bavents*

The foraminifera from pollen subzone L4a of the Baventian of Easton Bavents (Funnell & West 1962) are essentially identical to those from the Chillesford Clay of the Captain's Wood borehole, the greatest similarity being with the assemblages in the central part of the clay at +11.70 m O.D. Almost the only difference is the presence of *E. orbiculare* and some other rare species obtained from the Easton Bavents samples by carbon tetrachloride flotation.

(iv) *Covehithe*

The foraminifera obtained from the later pollen subzone L4b of the Baventian of Covehithe (West *et al.* 1980) are also very similar to those of the Chillesford Clay in the Captain's Wood borehole, but *E. orbiculare* is consistently present and *A. beccarii* absent from the uppermost Baventian sample at Covehithe, signifying cooler conditions than those implied at Captain's Wood.

7. DINOFLAGELLATE CYSTS

(*a*) *Introduction*

Dinoflagellate cyst assemblages from the Chillesford Sand Member, Chillesford Clay Member and Easton Bavents Clay Member were separated by standard palynological processing techniques and the sintered-glass funnel procedure of Neves & Dale (1963). Most samples yielded more than 150 specimens, but their proportions are shown in figure 10 only where a count of more than 50 individuals could be made.

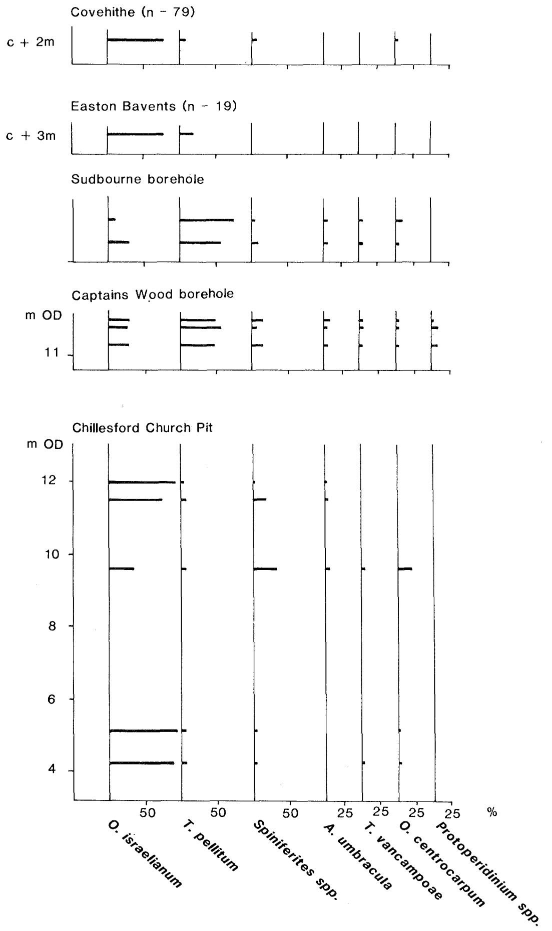

Figure 10. Dinoflagellate cyst assemblages from the Chillesford Sand of Chillesford Church Pit; from the Chillesford Clay of the Sudbourne and Captain's Wood boreholes and from the Easton Bavents Clay of Easton Bavents and Covehithe.

(*b*) *Chillesford Sand*

The assemblages from Chillesford Church Pit (figure 10) are dominated by *Operculodinium israelianum* (Rossignol) Wall, up to 83 % in some samples. Others noted include various undifferentiated *Spiniferites* species, *Tectatodinium pellitum* Wall, *Amiculosphaera umbracula* Harland, *Tuberculodinum vancampoae* (Rossignol) Wall and *Operculodinium centrocarpum* (Deflandre and Cookson) Wall. *Protoperidinium* cysts were notably absent. *Operculodinium israelianum* and *T. pellitum* were first recognized from this locality by West & Norton (1974).

(*c*) *Chillesford Clay*

(i) *Captain's Wood borehole*

Assemblages here are dominated by *T. pellitum*, with *O. israelianum* subordinate, and small proportions of *Spiniferites* spp., *A. umbracula*, *T. vancampoae* and *O. centrocarpum*. In addition, *Protoperidinium* cysts were present in all samples. Similar assemblages were recognized in the Chillesford Clay of the nearby Sudbourne borehole (TM 41425409).

(ii) *Hill Farm borehole and Chillesford Brickyard pit*

Samples from these sections were virtually barren of dinoflagellate cysts. This absence is an original feature, as pollen and spores are abundant.

(*d*) *Easton Bavents Clay*

A poor dinocyst assemblage was obtained from the clay at Easton Bavents (TM 518784) (figure 10), and a better assemblage from two samples (combined in figure 10) from a shelly clay horizon at the base of the available sequence at Covehithe (TM 527815). Both assemblages are dominated by *O. israelianum*, with subordinate *T. pellitum*, and resemble that from the Chillesford Sand. The Covehithe assemblage has, in addition, minor amounts of *Spiniferites* spp. and *O. centrocarpum*.

(*e*) *Dinoflagellate cyst assemblages*

Two types of dinoflagellate cyst assemblage are present in the sections examined.

(i) *O. israelianum-dominated assemblage*

In this *T. pellitum* is subordinate and minor amounts of *Spiniferites* spp., *A. umbracula*, *T. vancampoae* and *O. centrocarpum* are present, and *Protoperidinium* cysts are absent. This assemblage occurs in the Chillesford Sand of the Chillesford Church pit, the Easton Bavents Clay and the lower part of the Baventian clay of Covehithe.

(ii) *T. pellitum – O. israelianum-dominated assemblage*

In this, *T. pellitum* is somewhat more abundant than *O. israelianum*. The minor components are similar to those of the *O. israelianum*-dominated assemblage, but with the addition of *Protoperidinium* spp. This assemblage occurs in the Chillesford Clay of the Captain's Wood and Sudbourne boreholes.

(*f*) *Palaeoenvironmental indications*

O. israelianum, from data on its distribution in bottom sediments of the Atlantic Ocean and adjacent seas and from studies of living cysts, is now known to indicate tropical and warm-temperate estuarine conditions (Wall *et al.* 1977; Dale 1983). The distribution map of Harland (1983) suggests a possible association with outflow of waters from the Mediterranean.

Modern distributions and ecological requirements (Wall *et al.* 1977) of the accompanying cysts in the *O. israelianum*-dominated assemblage, *T. pellitum* and *T. vancampoae*, support the interpretation of sea temperatures greater than today and near-shore or lagoonal environments of deposition. *Amiculosphaera umbracula* is not known from modern sediments.

The second, *T. pellitum – O. israelianum*-dominated assemblage implies similar temperatures. *Tectatodinium pellitum* is a cosmopolitan, neritic-oceanic (Wall *et al.* 1977) and neritic south-temperate to sub-tropical species (Harland 1983), and therefore indicates warmer seas than at present and a neritic setting. This assemblage may thus reflect a more offshore environment of deposition than that dominated by *O. israelianum* alone.

The absence or rarity of dinoflagellate cysts from two of the sequences examined (see above), despite the presence of pollen and spores, suggests either non-marine conditions or low temperatures during sedimentation.

(*g*) *Correlations*

The assemblages do not show any clear-cut stratigraphic order. The *O. israelianum* dominated assemblages of the Chillesford Sand predate those obtained from the Chillesford Clay (*T. pellitum – O. israelianum* dominated in part and barren in part). The Easton Bavents Clay, which cannot be related lithostratigraphically to the Chillesford Sand/Clay sequence, contains an *O. israelianum*-dominated assemblage that is similar to that of the Chillesford Sand, but is relatively impoverished.

The main reference section at a comparable level within the East Anglian Crag sequence is that in the Ludham borehole (Wall & Dale 1968). Using this, a post-Thurnian age for the Chillesford Sand and Clay is indicated from the presence of *A. umbracula* and the lack of *Impagidinium multiplexum* at Chillesford Church Pit and in the Captain's Wood borehole.

In the Ludham borehole, above the *Hystrichosphaera* (now *Spiniferites*) dominated Lp3 stage (= Antian), a *T. pellitum – O. israelianum* assemblage was recovered from stage Lp4b (= Baventian), and one dominated by *T. pellitum* from stage Lp5 (= Pastonian). The assemblages from the Captain's Wood borehole thus most closely resemble those of the Baventian from the Ludham borehole. However, correlation on this basis is premature, as assemblages from the Easton Bavents Clay at Easton Bavents, and at Covehithe (together with assemblages from the Chillesford Sand at Chillesford Church Pit) differ in being dominated by *O. israelianum*.

In general, both assemblages show an Early Pleistocene age; in detail, further work is necessary to understand the stratigraphical and environmental significance of variations in the proportions of the constituent species.

8. MOLLUSCA

(*a*) *Mollusc assemblages*

Four samples from between 10.15 m and 11.10 m O.D. in the Captain's Wood borehole (figure 4) were examined (Table 6). Molluscs are present as crushed fragile shells and casts, the best preserved being at 10.30–10.45 m O.D. Only bivalves occur, mostly as scattered isolated valves but some specimens of *Nucula* and *Yoldia* retain both valves, suggesting little transportation. The Chillesford Clay fauna is essentially an association of *Nucula* with *Yoldia*. The state of the material usually makes positive identification below genus level impossible. At the specific level only *Yoldia myalis* and a single incomplete *Macoma calcarea* were identified with any certainty; the commoner *Nucula* is probably *N. tenuis* as some better preserved fragments have a smooth inner margin.

Table 6. *Molluscs from the Captain's Wood borehole*

	sampled levels					
	+10.15– +10.25 m O.D.	+10.30– +10.45 m O.D.	+10.55– +10.65 m O.D.	+10.85– +11.10 m O.D.	borehole total (total 211)	% (borehole total)
Nucula aff. *tenuis*	—	2 P	—	—	2	0.95
Nucula sp. indet.	18 P	46 P	40 P	16 P	120	56.87
Yoldia myalis	—	9	2	1	12	5.69
Yoldia aff. *myalis*	—	—	2 P	—	2	0.95
Yoldia sp. indet.	2	10 P	6	1	19	9.00
Yoldia lanceolata	—	—	—	f	f	—
Macoma calcarea	—	1	—	—	1	0.47
Macoma sp. indet.	f	3	2	1	6	2.84
Bivalve, otherwise indet.	7	16	16	10	49	23.22
Balanus spp.	—	—	—	+	—	—

P, some specimens with valves united.
f, fragments only, no hinge remains.
+, present.

The counts in Table 6 have been combined to aid assessment of the palaeoenvironment.

(*b*) *Interpretation*

The assemblage lacks any immigrant cold indicators but is extremely impoverished compared to those listed by Norton from the Chillesford Sand at Chillesford Church Pit (figure 2) and Aldeburgh Brickyard (TM 452572) (West & Norton 1974). Both *Y. myalis* and *N. tenuis* are members of the 'old boreal fauna' (Norton 1977) and occur both in temperate and cool stages of the early Pleistocene of the North Sea basin. A similar *N. tenuis* – *Y. myalis*-dominated community has been found in fine grained muddy sand from the temperate (Antian) Smith's Knoll Formation (P. E. Long, unpublished results). This is part of a more diverse fauna including *Abra* (*A.* aff. *prismatica*) and scattered gastropods such as the extinct *Ringicula ventricosa*. *Yoldia myalis* and *N. tenuis* are also present, with *Macoma calcarea* and *Serripes groenlandicus*, in the cold Baventian fauna at Covehithe (Long 1974; West *et al.* 1980).

Selection pressures on the molluscan fauna that might account for the impoverishment include the very fine grade of sediment and falling temperatures, but it is not possible to discriminate fully between these. However, the extreme paucity of the Captain's Wood molluscan assemblage compared with even the Baventian fauna at Covehithe suggests that low temperatures were a strong selective factor and that the assemblage could show a further climatic deterioration from the high boreal *Mya* bed found in the uppermost Chillesford Sand at Chillesford Church Pit.

(*c*) *Discussion of the molluscan faunas of the underlying and associated Norwich Crag sediments*

At present the molluscan biostratigraphical context of the climatic deterioration represented at Captain's Wood is problematical. Palynologically the underlying Chillesford Sand has been correlated with the Bramertonian pollen assemblage biozone by Funnell *et al.* (1979). However, the indigenous mollusca from the Chillesford Sand at Aldeburgh Brickyard and the Chillesford Church Pit (Norton in West & Norton 1974) show some puzzling quantitative differences from Bramertonian localities at Sizewell and from elsewhere to the north.

The most noticeable discrepancy is in the morphotypes of the difficult bivalve genus *Spisula* which is common to dominant at many Red Crag and Norwich Crag localities. An elongate form of *S. subtruncata* is found at Sizewell and farther north. Norton (in West & Norton 1974) also identified the Chillesford Sand forms from Aldeburgh as *S. subtruncata* but this may require revision as over 80% of the *Spisula* from Aldeburgh are a nearly equilateral form resembling *S.* '*ovalis*' (possibly a variety of the recent *S. solida*) and another 5% are close to *S.* '*obtruncata*'; *S.* '*ovalis*' and *S.* '*obtruncata*' are characteristic Red Crag forms. Other features separating the Chillesford Sand molluscan fauna from more northern Bramertonian sites include the absence of the Wadden gastropod *Hydrobia*, despite the presence of the brackish *Scrobicularia plana*, and the absence or very rare occurrence of *Littorina* and the extinct *Potamides tricinctus* f. *icenica*.

Thus the environment and perhaps also the age of the Chillesford Sand molluscan assemblage differs from other assemblages thought to be Bramertonian. It could equally well be either a Norwich Crag fauna or an attenuated Red Crag fauna as suggested by the *Spisula* population. Whichever is true, the sparse Chillesford Clay fauna may represent the culmination of changes in the molluscan fauna caused by a gradual transition from coarse to fine sediments that accompanied a deterioration in the climate.

9. SYNTHESIS

(*a*) *Depositional environment*

The Chillesford Clay was deposited in a mud-dominated, high intertidal environment. This is indicated by its lithology, and position above the Chillesford Sand of intertidal sandflat origin (Funnell 1961; Dixon 1972; West & Norton 1974; Zalasiewicz & Mathers 1985). Strong corroborative evidence is provided by the non-detrital sand minerals and the foraminifera of the Captain's Wood borehole, which are similar to the restricted 'intertidal to lagoonal' assemblages of the upper part of the Chillesford Sand at Chillesford Church Pit (Funnell 1961). The pollen spectra also indicate a near-shore setting (see section 5 (*e*) above).

The dinoflagellate cyst assemblages of the Captain's Wood and Sudbourne boreholes suggest a more offshore environment. However, the validity of this interpretation is uncertain, because of the problems regarding the palaeoclimatic interpretation of these fossils within British marine Pliocene–Lower Pleistocene sequences (see below); it is possible that these assemblages reflect contemporaneous changes farther offshore. The virtual absence of dinoflagellate cysts from the pollen-bearing Chillesford Clay of the Chillesford Brickyard pit and the Hill Farm borehole may be due to local supratidal, brackish to non-marine conditions. But as this would suggest a fluvial rather than marine source for the clay, a temperature control on dinoflagellate cyst distribution is more likely.

(*b*) *Palaeoclimate*

The climatic evidence, although in part contradictory, suggests that the Chillesford Clay was deposited during a post-Bramertonian climatic deterioration. Changes in the molluscan assemblages at Chillesford Church Pit (West & Norton 1974) suggest that this deterioration began during deposition of the upper part of the underlying Chillesford Sand. Within the Chillesford Clay, the main evidence for climatic deterioration is provided by the pollen. The spectra are consistently NAP (non-arboreal pollen)-dominated, and consideration of the taxa shows that this is unlikely to be due to over-representation of NAP pollen from a temperate salt marsh. The spectra probably represent oceanic grass heath with limited boreal woodland, which later yielded to vegetation of park-tundra type.

Other fossils occur only in sediments that contain pollen indicating oceanic grass heath. Sediments with the later pollen assemblage indicating park-tundra conditions are devoid of calcareous micro- or macrofossils, possibly because of decalcification; in addition they are virtually devoid of dinoflagellate cysts.

The low-diversity mollusc assemblage of the Chillesford Clay is consistent with, although not diagnostic of, a cold climate during deposition. However, the climate suggested by the foraminifera and dinoflagellate cyst assemblages contrasts with that suggested by the pollen. The foraminifera imply temperate conditions, with evidence for climatic deterioration in only the upper part of the sequence examined, and the dinoflagellate cyst assemblages, from their present-day distribution, imply warm-temperate to sub-tropical conditions (n.b. in the case of the Easton Bavents Clay, dinoflagellate cyst samples were collected independently from pollen and foraminifera material collected by West *et al.* (1980), and thus may not be from the horizons within the clay which indicate the coldest climatic conditions).

Similar conflicts of palaeoenvironmental interpretation have been reported from elsewhere in the British marine Pliocene-Lower Pleistocene sequence (see, for example, Wall & Dale (1968); Cameron *et al.* (1984); Zalasiewicz *et al.* (1988)) and have not been satisfactorily explained. The dinoflagellates in the Chillesford Clay may have been brought from the Mediterranean region by water masses flowing much farther north in the early Pleistocene than now. During the Early Pleistocene the North Sea may have responded more slowly to climatic deterioration than in the late Pleistocene when glaciers were more extensive on surrounding land areas. Another factor that could explain the conflicting palaeoenvironmental evidence is increased drought or seasonality of rainfall in the early Pleistocene; this may have reduced forest cover at times when the sea was still warm.

The mineralogical similarity of the Chillesford Sand and Clay to the Easton Bavents Clay and parts of the Red Crag throws doubt upon the concept of a strong glacial influence on North Sea sediments during only the Baventian Stage of the Lower Pleistocene. A few of the more weatherable heavy minerals (brown amphiboles, augite, olivine) were probably derived from as far away as Scotland or Scandinavia. It is possible that glacial action was partly responsible for transporting them, but they are very minor constituents of the total sediment. The other minerals could have been derived from Tertiary or older formations in the Southern North Sea basin, and the similarity of all of the Lower Pleistocene formations studied probably resulted from prolonged marine reworking and mixing of locally derived sediment with the minor glacial inputs.

(*c*) *Correlations*

The options for the correlation of the Chillesford Clay are summarized in Table 3.

If the established system of Pleistocene stages (Mitchell *et al.* 1973; modified by Funnell *et al.* (1979)) is correct in placing the Baventian below, and the Pre-Pastonian *a* above, the Bramertonian, then the Chillesford Clay cannot correlate with any part of the Easton Bavents Clay. It would thus represent a later cold climate episode. This could be the Pre-Pastonian *a*, or some other, as yet un-named, episode. However, there are several objections to such an interpretation.

First, it ignores the marked similarity of the Chillesford Clay LPAB(i) to the pollen assemblage of the type Baventian and Lp4b. LPAB(i) is unlikely to be a taphonomic or facies variant of the Pre-Pastonian *a* spectra, even allowing for the difficulty of distinguishing different cold stage pollen assemblages (R. G. West, personal communication; West 1980 *b*). Second, it contradicts the recent evidence from fossil microtine (vole) teeth which suggests that the Baventian may be later than the Bramertonian (Mayhew 1985). Third, it poses a problem within the recently established correlation of the East Anglian Pliocene–Early Pleistocene sequence with the more complete and better

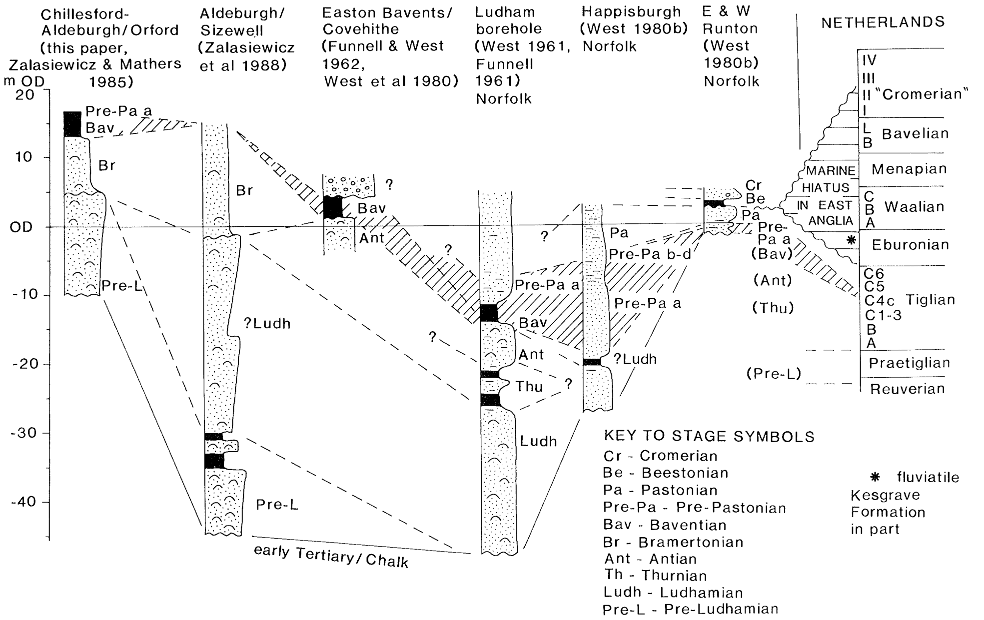

Figure 11. Schematic correlation of Red and Norwich Crag deposits in East Anglia, assuming correlation of the Chillesford Clay with the Easton Bavents Clay and with deposits of Pre-Pastonian *a* age (correlations emphasized with diagonal ornament). Correlations with The Netherlands' sequence following Gibbard *et al.* (1991) also shown. Unconformities shown in the sequence are interpreted from biostratigraphical data.

understood succession in The Netherlands (de Jong 1988). There are now strong grounds for supposing that the entire East Anglian sequence from the Ludhamian to the Pastonian is equivalent to the long, complex Tiglian Stage of the Dutch succession (Gibbard *et al.* 1991). In this only one episode of very cold climate is known from the Tiglian (the C4c Substage), whereas hitherto two (the Baventian and the Pre-Pastonian *a*) have been recognized in the corresponding time interval in East Anglia. Linking the Baventian and Pre-Pastonian *a* stages would therefore remove a major inconsistency in the proposed correlation.

We propose that the Chillesford Clay correlates in part with the Easton Bavents Clay, and in part with Pre-Pastonian *a* deposits, including those at Bramerton. It follows that the Baventian and the Pre-Pastonian *a* represent successive parts of a single cold episode, the Baventian succeeding the Bramertonian (one of the options proposed by Funnell (1987)), rather than preceding it as originally preferred (Funnell *et al.* 1979). Figure 11 shows this proposed correlation within the contexts of East Anglian Crag stratigraphy and southern North Sea basin correlation (after Gibbard *et al.* 1991).

However, it must be stressed that there are problems with this interpretation. Although it is strongly supported by the pollen, and to varying degrees by the molluscan assemblages, mineralogy and palaeomagnetic polarity, there are obstacles to correlating the Chillesford Clay with the Easton Bavents Clay. These are (i) some dissimilarity of the foraminiferal and dinoflagellate cyst assemblages; (ii) their stratigraphic position, the Easton Bavents Clay resting on Antian, *Tsuga*-rich sediments, whereas the Chillesford Clay rests on Bramertonian strata containing virtually no *Tsuga* pollen; (iii) their topographic level, the base of the Chillesford Clay occurring at +14 m to +10 m O.D., whereas the base of the Easton Bavents Clay is at *ca.* 0 to +2 m O.D.; (iv) the recognition of possible Baventian foraminifera (Funnell 1983) and pollen (West & Norton 1974) assemblages beneath undoubted Bramertonian strata at Sizewell and (v) the presence of *Macoma balthica* (Sparks in West 1980*b*) and the distinctive Group 1 vole fauna (Mayhew & Stuart 1986) in the Pre-Pastonian *a* sediments of the north Norfolk coast, but their apparent absence from Baventian or Bramertonian sediments as currently recognized.

These objections may be answered as follows: (i) the lower, foraminifera and dinoflagellate cyst-bearing part of the Chillesford Clay of the Captain's Wood borehole could represent an earlier part of the Baventian Lp4b interval than has been recognized in the type section, perhaps with affinities to Baventian Lp4a (the slightly higher frequencies of deciduous tree pollen than in the type Baventian may support such a view); (ii) the Bramertonian and Antian may be part of a single complex warm stage, a *Tsuga*-rich (Antian) phase followed by a phase lacking *Tsuga* pollen (Bramertonian); this has yet to be shown in a continuous sequence, but the thin interval of '?Baventian' at Sizewell (West & Norton 1974; Funnell *et al.* 1979) could represent a short-lived cool or cold episode separating these two warmer stages; (iii) a non-sequence may well occur between the Antian and Baventian at Easton Bavents and Covehithe (as proposed by Funnell (1987)); (iv) the lower elevation of the type Baventian results, at least partly, from post-depositional tilting; westwards from the Chillesford area the entire Crag sequence has been tilted upwards by 1 m km^{-1} (Mathers & Zalasiewicz

1988), and the tilt on the base of the Chillesford Clay is similar (see section 2(*a*) above); continuing this degree of tilt from Chillesford to Easton Bavents would account for much of the height difference observed; in addition, some pre-Baventian strata may have been removed by erosion at Easton Bavents, the clay forming as a drape during marine regression; (v) the differences in the distribution of *Macoma balthica* and the Group 1 vole faunas may be due to differences in facies or taphonomy; if not, then it has to be assumed that their incoming coincided with the environmental change from the Baventian to the Pre-Pastonian *a*.

The correlation of the Chillesford Clay with the Easton Bavents Clay, and with the Pre-Pastonian *a* deposits, suggests that the present concept of the Baventian and the Pre-Pastonian *a* as separate stages/substages is not justified. Rather, it would be more appropriate to regard them as substages of a single cold stage which possesses a well-defined vegetational succession reflecting progressive climatic deterioration. The Baventian (Funnell & West 1962) has priority over the Pre-Pastonian *a* (Funnell & West 1977; West 1980*b*) and its definition could simply be extended. It is unclear at present whether a redefined Baventian would represent the whole of the presently recognized Pre-Pastonian (including substages b–d) or only Substage *a*; consideration of this is beyond the scope of this paper.

However, it must be stressed that, given the stratigraphic implications of correlating the Chillesford and Easton Bavents clays, further work is needed to address the problem of the relation between the Antian and the Bramertonian; to establish the nature of the '?Baventian' identified beneath the Bramertonian strata at Sizewell (West & Norton 1974; Funnell 1983); to estimate the reliability of palaeomagnetic signals preserved within these sediments; and to resolve the conflicting palaeoenvironmental and biostratigraphical evidence given by different faunal groups within the same sequence of sediments. These questions reflect present uncertainties in the detailed correlation of sequences in the marine Pliocene–early Pleistocene of eastern England.

10. CONCLUSIONS

1. The Chillesford Clay was deposited in a high intertidal (possibly locally non-marine) environment during a post-Bramertonian cold climatic episode. Two successive pollen biozones indicate that there was a progressive deterioration in climate.
2. Earlier reports of mineralogical and palaeontological differences between the Chillesford Clay and the Easton Bavents Clay are shown to be invalid.
3. It is proposed that the Chillesford Clay correlates in part with the Baventian and in part with the Pre-Pastonian *a*.
4. This correlation implies that the Baventian Stage succeeds the Bramertonian Stage, rather than preceding it, and represents an early part of a cold episode which culminated in the Pre-Pastonian *a*. This cold episode probably correlates with the Tiglian C4c Substage of The Netherlands succession.
5. Problems remain with this proposed correlation; notably, the relationship between the Antian and the Bramertonian stages is unclear, and palaeoenvironmental evidence from the different fossil groups examined is in part contradictory.
6. However, if the interpretation proposed is correct, the Baventian and Pre-Pastonian *a* should no longer be regarded as (parts of) separate stages, but should be linked, probably as the lowermost two substages of a modified Baventian Stage.

We thank Professor R. G. West and Dr P. M. Allen, R. S. Arthurton, Dr M. F. Howells, Dr R. G. Thurrell, Dr G. Warrington and Dr R. Webster for critical reading of the manuscript. This paper is published with the permission of the Director of the British Geological Survey (NERC) and the Institute of Arable Crops Research (AFRC).

REFERENCES

Allen, P. 1984 *Field guide to the Gipping and Waveney valleys, Suffolk, May, 1982.* (115 pages) Cambridge: Quaternary Research Association.

Andrew, R. 1970 The Cambridge pollen reference collection. In *Studies in the vegetational history of the British Isles* (ed. D. Walker & R. G. West), pp. 225–232. Cambridge University Press.

Birks, H. J. B. 1973 *Past and present vegetation of the Isle of Skye – a palaeoecological study.* Cambridge University Press.

Bowen, D. Q., Rose, J., McCabe, A. M. & Sutherland, D. G. 1986 Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales. *Quat. Sci. Rev.* **5**, 299–340.

Cameron, T. D. J., Bonny, A. P., Gregory, D. M. & Harland, R. 1984 Lower Pleistocene dinoflagellate cyst, foraminiferal and pollen assemblages in four boreholes in the Southern North Sea. *Geol. Mag.* **121**, 85–97.

Chapman, V. J. 1968 *Salt marshes and salt deserts of the world.* London: Leonard Hill.

Dale, B. 1983 Dinoflagellate resting cysts: 'benthic plankton'. In *Survival strategies of the algae* (ed. G. A. Fryxell), pp. 69–136. Cambridge University Press.

Dixon, R. G. 1972 A review of the Chillesford Beds. *Bull. Ipswich Geol. Group* **11**, 2–9.

Double, I. S. 1924 The petrography of the later Tertiary deposits of the east of England. *Proc. Geol. Ass.* **35**, 332–358.

Evans, G. 1965 Intertidal flat sediments and their environment of deposition in the Wash. *J. geol Soc. Lond.* **121**, 209–241.

Funnell, B. M. 1961 The Palaeogene and Early Pleistocene of Norfolk. *Trans. Norfolk Norwich Nat. Soc.* **19**, 340–364.

Funnell, B. M. 1983 Preliminary note on the foraminifera and stratigraphy of C.E.G.B. Sizewell boreholes L & S. *Bull. geol. Soc. Norfolk* **33**, 54–62.

Funnell, B. M. 1987 Late Pliocene and Early Pleistocene stages of East Anglia and the adjacent North Sea. *Quat. Newsl.* **52**, 1–11.

Funnell, B. M. & West, R. G. 1962 The early Pleistocene of Easton Bavents, Suffolk. *Q. Jl geol. Soc. Lond.* **117**, 125–141.

Funnell, B. M. & West, R. G. 1977 Preglacial Pleistocene deposits of East Anglia. In *British Quaternary studies: recent advances* (ed. F. W. Shotton), p. 247–265. Oxford University Press.

Funnell, B. M., Norton, P. E. P. & West, R. G. 1979 The Crag at Bramerton, near Norwich, Norfolk. *Phil. Trans. R. Soc. Lond.* B **287**, 489–534.

Gibbard, P. L., West, R. G., Zagwijn, W. H., Balson, P. S., Burger, A. W., Funnell, B. M., Jeffery, D. H., de Jong, J., van Kolfschoten, T., Lister, A. M., Meijer, T., Norton,

P. E. P., Preece, R. C., Rose, J., Stuart, A. J., Whiteman, C. A. & Zalasiewicz, J. A. 1991 Early and Early Middle Pleistocene correlations in the southern North Sea basin. *Quat. Sci. Rev.* **10**, 23–52.

Harland, R. 1983 Distribution maps of Recent dinoflagellate cysts in bottom sediments from the North Atlantic Ocean and adjacent areas. *Palaeontology* **26**, 321–387.

de Jong, J. 1988 Climatic variability during the past three million years, as indicated by vegetational evolution in northwest Europe, and with emphasis on data from The Netherlands. *Phil. Trans. R. Soc. Lond.* B **318**, 603–617.

Kemp, R. A. 1987 The interpretation and environmental significance of a buried soil near Ipswich Airport, Suffolk, England. *Phil. Trans. R. Soc. Lond.* B **317**, 365–391.

Long, P. E. 1974 Norwich Crag at Covehithe, Suffolk. *Trans. Suffolk Nat. Soc.* **16**, 199–208.

Mathers, S. J. & Zalasiewicz, J. A. 1988 The Red Crag and Norwich Crag formations of southern East Anglia. *Proc. Geol. Ass.* **99**, 261–278.

Mayhew, D. F. 1985 Preliminary report of research project on small mammal remains from British Lower Pleistocene sediments. *Quat. Newsl.* **47**, 1–4.

Mayhew, D. F. & Stuart, A. J. 1986 Stratigraphic and taxonomic revision of the fossil vole remains (Rodentia, Microtinae) from the Lower Pleistocene deposits of eastern England. *Phil. Trans. R. Soc. Lond.* B **312**, 431–485.

Mitchell, G. F., Penny, L. F., Shotton, F. W. & West, R. G. 1973 *A correlation of Quaternary deposits in the British Isles.* (99 pages). Geological Society of London Special Report No. 4.

Neves, R. & Dales, B. 1963 A modified filtration system for palynological preparation. *Nature, Lond.* **187**, 775–776.

Norton, P. E. P. 1977 Marine Mollusca in the East Anglian pre-glacial Pleistocene. In *British Quaternary Studies: recent advances* (ed. F. W. Shotton), pp. 45–53. Oxford University Press.

Prentice, I. C. 1978 Modern pollen spectra from lake sediments in Finland and Finnmark, north Norway. *Boreas* **7**, 131–153.

Prestwich, J. 1849 On some fossiliferous beds overlying the Red Crag at Chillesford near Orford, Suffolk. *Q. Jl geol. Soc. Lond.* **5**, 343–353.

Prestwich, J. 1871*a* On the structure of the Crag-beds of Suffolk with some observations on their organic remains. Part II. The Red Crag of Essex and Suffolk. *Q. Jl geol. Soc. Lond.* **27**, 325–56.

Prestwich, J. 1871*b* On the structure of the Crag-beds of Suffolk and Norfolk, with some observations on their organic remains. Part III. The Norwich Crag and Westleton Beds. *Q. Jl geol. Soc. Lond.* **27**, 425–496.

Reid, C. 1890 The Pliocene Deposits of Britain. *Mem. geol. Surv. U.K.* (326 pages.)

Reineck, H.-E. 1963 Sedimentgefuge im Bereich der sudlichen Nordsee. *Abh. senckenbergische naturforsch. Ges.* **505**, 138 pages.

Rose, J. & Allen, P. 1977 Middle Pleistocene stratigraphy in south-east Suffolk. *J. geol. Soc. Lond*, **133**, 85–102.

Wall, D. & Dale, B. 1968 Early Pleistocene dinoflagellates from the Royal Society borehole at Ludham, Norfolk. *New Phytol.* **67**, 315–326.

Wall, D., Dale, B., Lohmann, G. D. & Smith, W. K. 1977 The environmental and climatic distribution of dinoflagellate cysts in modern marine sediments from regions in the North and South Atlantic Oceans and adjacent seas. *Mar. Micropalaeontol.* **2**, 121–200.

West, R. G. 1961 Vegetational history of the Early Pleistocene of the Royal Society borehole at Ludham, Norfolk. *Proc. R. Soc. Lond.* B **155**, 437–453.

West, R. G. 1977 *Pleistocene geology and biology*, 2nd edn. London: Longmans.

West, R. G. 1980*a* Pleistocene forest history in East Anglia. *New Phytol.* **85**, 571–622.

West, R. G. 1980*b* *The pre-glacial Pleistocene of the Norfolk and Suffolk coasts.* Cambridge University Press.

West, R. G. 1988 A pollen diagram from Norwich Crag at Outney Common, Bungay, Suffolk. *New Phytol.* **110**, 603–606.

West, R. G., Funnell, B. M. & Norton, P. E. P. 1980 An Early Pleistocene cold marine episode in the North Sea: pollen and faunal assemblages at Covehithe, Suffolk, England. *Boreas* **9**, 1–10.

West, R. G. & Norton, P. E. P. 1974 The Icenian Crag of southeast Suffolk. *Phil. Trans. R. Soc. Lond.* B **268**, 1–28.

Zalasiewicz, J. A. & Mathers, S. J. 1985 Lithostratigraphy of the Red and Norwich Crags of the Aldeburgh-Orford area, south-east Suffolk. *Geol. Mag.* **122**, 287–296.

Zalasiewicz, J. A., Mathers, S. J., Hughes, M. J., Gibbard, P. L., Peglar, S. M., Harland, R., Boulton, G. S., Nicholson, R. A., Cambridge, P. & Wealthall, G. P. 1988 Stratigraphy and palaeoenvironments of the Red Crag and Norwich Crag formations between Aldeburgh and Sizewell, Suffolk, England. *Phil. Trans. R. Soc. Lond.* B **322**, 221–272.

Received 21 January 1991; accepted 8 March 1991