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# THE DISTRIBUTION, VARIATION AND ORIGINS OF PRE-DEVENSIAN TILLS IN EASTERN ENGLAND

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In order to define quantitatively the lithological properties of the pre-Devensian tills in eastern England, calcium carbonate contents and mechanical compositions of 501 samples from 289 sites have been measured and heavy minerals counted in 102 of them. The results show that the tills may be divided into two groups: (*a*) a North Sea Drift group consisting of the Norwich Brickearth, the Cromer Tills, the Marly Drift of Cromer type and till members of the Contorted Drift, which is characterized by high sand and low opaque heavy mineral contents; and (*b*) a Lowestoft Till group including the Lowestoft Till of East Anglia, the Chalky Boulder Clay of the east Midlands, the Calcethorpe and Wragby Tills and the Lowestoft-type Marly Drift, which is characterized by low sand and high opaque values. The qualitative similarity of the mineral suites in the two groups, however, suggests a common origin in the North Sea basin.

Automated contouring (SYMAP) has been used to represent the spatial distribution of till properties. These confirm that the Lowestoft Till group can be spatially separated from the North Sea Drift group, and divided into a Calcethorpe–Marly facies high in carbonates and lying astride the Wash, and a Lowestoft–Wragby facies with moderate but variable contents of calcium carbonate and occupying the rest of the region.

Trend surface analysis has been applied to the Lowestoft Till group. At the first order level there are decreasing trends across the region, from northeast to southwest, in calcium carbonate, amphibole and epidote values and increasing trends in silt and clay. These are interpreted as showing a general movement from the North Sea of sandy and chalky material which became progressively modified by assimilation of Mesozoic clays. Higher order surfaces, particularly those of sand, garnet and amphibole values, point to the Wash as the focus of this glacial activity.

It is proposed that the most vigorous stream of ice entered eastern England at this point, levelling the Cretaceous scarps and excavating the Jurassic clays of the Wash-Fens basin, and then fanned out into most of the region to deposit the clay-rich Lowestoft–Wragby facies. The Calcethorpe–Marly facies is considered to represent chalky North Sea material carried by marginal, and weaker, ice streams directly onto the Chalk of Lincolnshire and north Norfolk.

The North Sea Drift group is believed to be the product of another ice body, penecontemporaneous with that depositing the Lowestoft group, which entered Norfolk from a more easterly part of the North Sea, incorporating sediments from this basin, but without crossing substantial outcrops of Jurassic or Lower Cretaceous formations or Tertiary clays. The Marly Drift includes a variant showing lithological affinities with both Lowestoft and Cromer Tills and which may be the product of complex interaction between the two ice sheets.

All the tills studied seem most likely to be of Anglian age.

## 1. Introduction

Although nearly one hundred years have passed since Wood (1880) established the distribution of the Chalky Clay (or Chalky Boulder Clay) and since much of the complex succession of the Cromer Tills and associated beds in the Norfolk cliffs was clarified by Reid (1882), there is still considerable uncertainty about the relation and origins of the pre-Devensian tills of eastern England. Particular confusion prevails on the stratigraphy of the Chalky Boulder Clay itself and its correlations in East Anglia and the east Midlands (West 1973; Phillips 1976; Shotton *et al.* 1977).

Some factors that have delayed agreement, and that the present study seeks to avoid, include a general neglect of the lithology of the till matrix in favour of the more easily recognizable but volumetrically far less important erratic stones (although Hill (1902), Boswell (1916) and Solomon (1932*a*, *b*) have shown the potential value of mechanical and mineralogical analyses); a conspicuous lack of quantitative data; a tendency for far-ranging conclusions to be based on very few sites; the correlation of widely separated deposits by means of a single and unquantified character, such as chalkiness, without any other lithological or age control (Cox & Nickless 1972, p. 81); and sometimes inadequate definitions of the till units being studied.

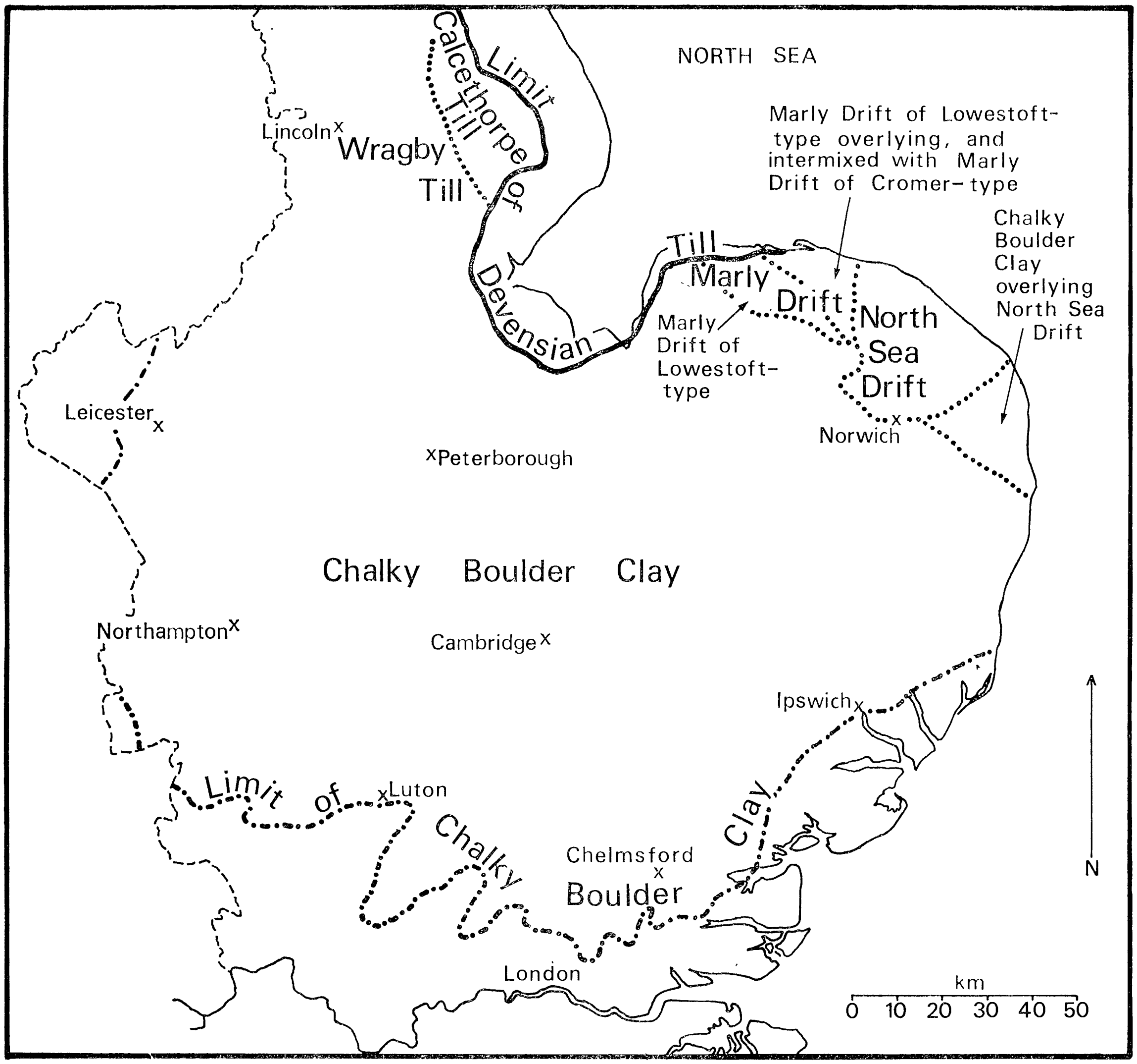


FIGURE 1. Distribution of till types in eastern England.

Definitions of the tills that will be accepted in this paper and contrasting views on their interrelations are summarized in appendix 1.

Systematic quantitative analyses of the matrix of the Chalky Boulder Clay to assess its variability as a soil parent material were started in 1957 by C. A. H. Hodge and Perrin as part of an unpublished reconnaissance survey of East Anglia for the Soil Map of Europe (F.A.O. 1965). They found that the matrix is often closely similar in particle size distribution and carbonate content at widely separated localities and that division into facies such as Chalky–Kimmeridgian or Chalky–Oxfordian (Harmer 1909), although usefully describing stone content, is less satisfactory for the main till matrix. This work suggested that pedological methods for specifying lithology, which normally concentrate on the fraction of particles smaller than 2 mm in effective spherical diameter ($-1\phi$, where $\phi = -\log_2$ of particle diameter in mm), with particular emphasis on colour, particle size distribution, sand and clay grade mineralogy and carbonate content, could usefully be applied to Quaternary sediments in the region. It was hoped that these techniques, when applied to large numbers of samples, would quantify, on a regional scale, not only their properties as soil parent materials but also their detailed geological relations.

The present paper is one of a series (Perrin *et al.* 1973, 1974; Banham *et al.* 1975) using this approach; mechanical, mineralogical and spatial analyses are here used to elucidate the relation and origins of all the pre-Devensian tills (appendix 1) that have been recognized in the region shown in figure 1. These are taken to be:

(i) the Chalky Boulder Clays of East Anglia and the east Midlands;
(ii) the Calcethorpe and Wragby Tills of Lincolnshire; and
(iii) the Marly and North Sea Drifts of north Norfolk, including till units in the Contorted Drift.

The investigation was carried out in two stages. First, samples from all the tills were analysed for carbonate content, mechanical composition of the insoluble residues and heavy mineral percentages. The results led to an initial separation of the tills into two groups and a tentative conclusion concerning their source area. Preliminary reports of this stage have been given in the papers noted in the last paragraph. Secondly, spatial analysis was used to establish regional distributions and trends of till properties, leading to a new interpretation of regional ice movements.

## 2. REGIONAL GEOLOGY AND PHYSIOGRAPHY

The region is underlain by Jurassic, Cretaceous and Tertiary rocks which dip in easterly directions, and respectively strike northwest to southeast, north to south and northeast to southwest across its northern, central and southern parts (figure 2). Thus, Jurassic clays, Lower Greensand and Gault Clay outcrop over most of the central area; Chalk occupies much of the south, most of East Anglia, eastern Lincolnshire and the adjacent North Sea; and Tertiary clays and sands cover the rest of East Anglia and most of the North Sea basin.

Relief is, in general, closely related to rock type, so that in western areas the high land is located along the outcrops of Jurassic limestones and ironstones, and extensive lowland along those of the Jurassic clays (figures 2 and 3). Further east, minor hill features are associated with the Lower Cretaceous sands (Lower Greensand in and south of the Fens, Sandringham Sands and Carstone in north Norfolk, and Carstone and Spilsby Sandstone in Lincolnshire), and low lying topography with the Gault Clay. The Chalk forms prominent scarps in the Chiltern Hills and the Lincolnshire Wolds, but a degraded scarp over much of East Anglia, particularly in the Breckland district (figure 3). However, the general correlation of topography with lithology breaks down around the Wash, where a wide basin overlies the relatively resistant Chalk and Lower Cretaceous sands.

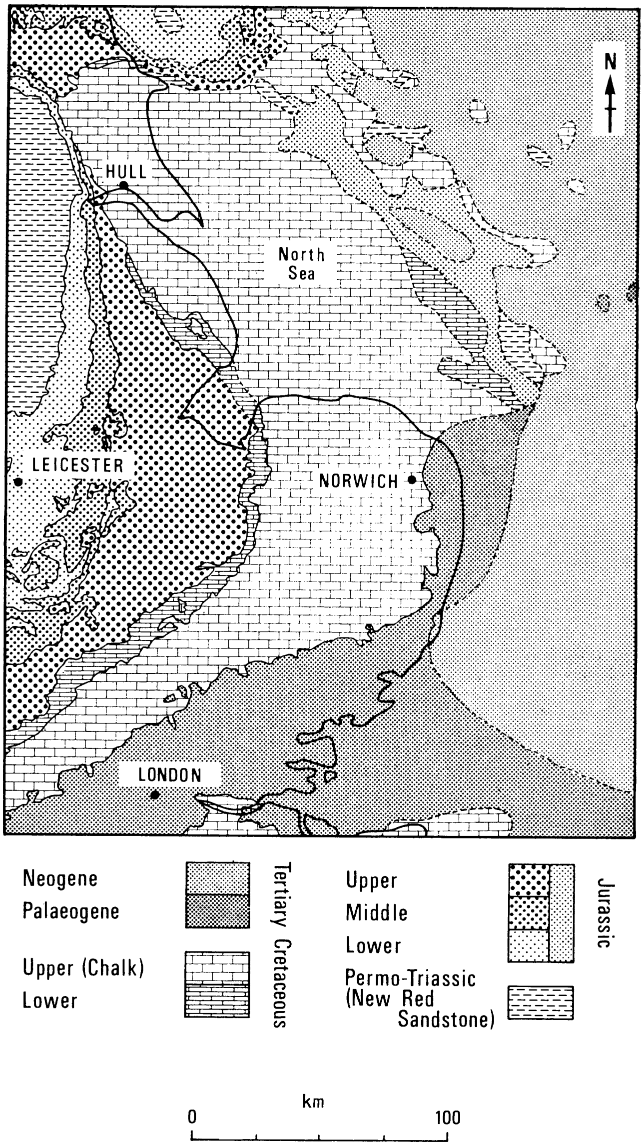


FIGURE 2. Solid geology of eastern England and the western part of the North Sea basin. (Reproduced by permission of Director of the Institute of Geological Sciences.)

The pre-Devensian tills usually rest directly on solid formations but in some areas they overlie various sands and gravels. For example, the Third Cromer Till succeeds the glacifluvial Mundesley Sands (Reid 1882; Banham 1968), while the Lowestoft Till overlies the Corton Sands at Corton (TM 5497) (Baden-Powell 1948) and the Kesgrave Sands and Gravels in southern East Anglia (Rose *et al.* 1976). In Lincolnshire, east of the Wolds they are buried under Devensian till and in the Wash-Fens basin, beneath recent alluvial and estuarine sediments.

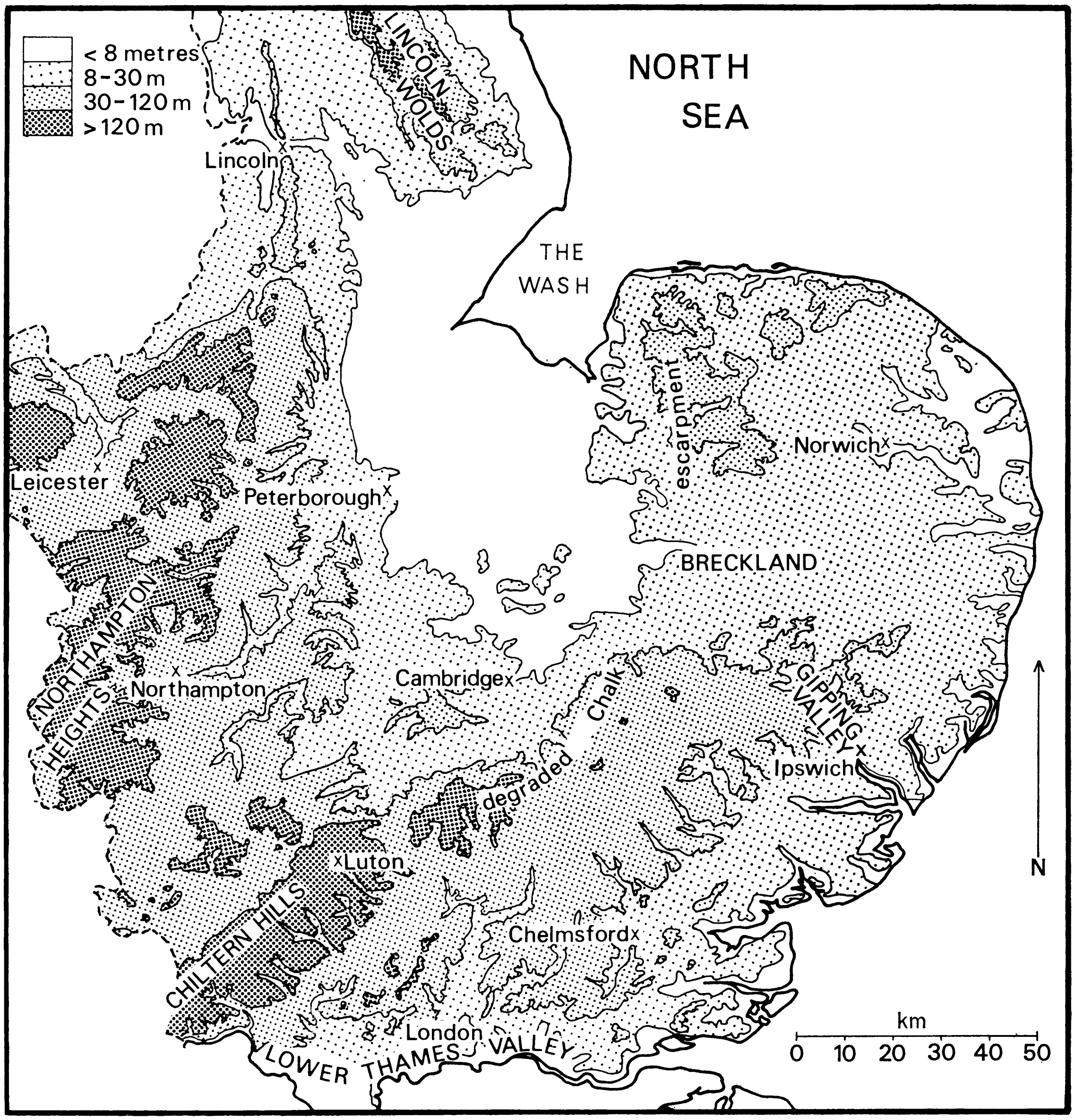


Figure 3. Generalized topography of eastern England.

## 3. Mechanical and mineralogical compositions of the tills

### (a) *Field sampling and laboratory methods*

Analytical data were derived from the sampling programme of Perrin *et al.* (1973 and unpublished data). The pattern of collecting was neither geographically regular nor deliberately randomized, but depended on the availability of suitable sections or boreholes or the possibility of excavation by hand. Wherever possible, samples were collected from depths greater than 2 m and on interfluves to avoid including re-worked materials. But, in some parts of the region, for example in the Breckland and the Gipping Valley, most till exposures occur at low altitudes and there is little choice.

A sample was allocated to a particular till only if it was found in the same general area and had the same gross lithology as described by the author whose definition was accepted (appendix 1). Wherever feasible its stratigraphic position was checked but, whereas this was relatively easy in some cases, for example the Cromer Tills in the Norfolk cliffs, it was virtually impossible for most surface tills for which allocation had to be made by lithological character alone.

Five hundred and one samples were collected from 289 sites on the tills specified on page 538.

The colour, calcium carbonate content and mechanical composition of each sample were measured, the latter being expressed on a carbonate-free (insoluble residue) basis to show up differences that could otherwise be masked by varying contents of chalk. Heavy minerals were counted in the sand fractions separated from 102 of the samples. Laboratory procedures are specified in appendix 2.

Resources did not permit the statistical counting of stones (particles with effective spherical diameter greater than 2 mm), which, to be valid, must be applied to very large volumes of till. Preliminary trials also showed that clay mineralogy was not effective in distinguishing between the tills of the region.

### (*b*) *Analytical results and interpretation*

Colour and calcium carbonate contents are summarized in table 1, typical mechanical compositions of insoluble residues in table 1 and figure 4A–E and heavy mineral counts in table 2. The following conclusions were drawn from these data.

(i) The Chalky Boulder Clay is not, as implied by Harmer (1909), a simple mixture of chalk and other erratics with Mesozoic clays but, in contrast to the latter, always contains appreciable sand, the amount of which does not vary widely (figure 4A), and a constant suite of heavy minerals. Following Bristow & Cox (1973, p. 27) and Perrin *et al.* (1973), it will be accepted that in East Anglia the Chalky Boulder Clay and the Lowestoft Till are the same unit.

In neither the sampling programme of Perrin *et al.* nor in a later one still in progress, has there been found any discontinuity in mechanical and mineralogical composition between the Lowestoft Till and the Chalky Boulder Clays of the east Midlands recognized by Hollingworth & Taylor (1946) and Horton (1970). This also applies to the mechanical composition of the local chalky till of Leicestershire, named Oadby Till by Rice (1968). Although only one mineralogical analysis of this is yet available, it shows qualitative affinity with the Lowestoft Till and clear differentiation from the adjacent red till at the same site at Huncote (SP 512982) (table 2). In view of the persistence of Lowestoft lithology, which is further supported by trend surface analysis (see §7), and with lack of any clear biostratigraphic evidence to the contrary, the Chalky Boulder Clays of the Midlands can most simply be interpreted as local forms of the Lowestoft Till.

(ii) The early distinction between the Chalky Boulder Clay and the Cromer Tills (Trimmer 1858; Wood & Harmer 1868; Wood 1880) is quantitatively confirmed by particle size distributions (figure 4B), and by the percentages of opaque heavy minerals, amphiboles and micas, although the mineral suites are qualitatively the same.

The high contents of limonite found to be characteristic of the Chalky Boulder Clay confirm the observation of Solomon (1932*a*).

(iii) The First, Second and Third Cromer Tills (Banham 1968) are closely similar in non-opaque heavy minerals that are typical of a detrital basin receiving debris from metamorphic provinces, although the Second is somewhat richer in opaques. The First and Third have virtually the same particle size distributions, but the Second contains more silt (figure 4B) and is much more calcareous.

TABLE 1. COLOURS, CALCIUM CARBONATE CONTENTS AND MECHANICAL COMPOSITIONS OF TILLS

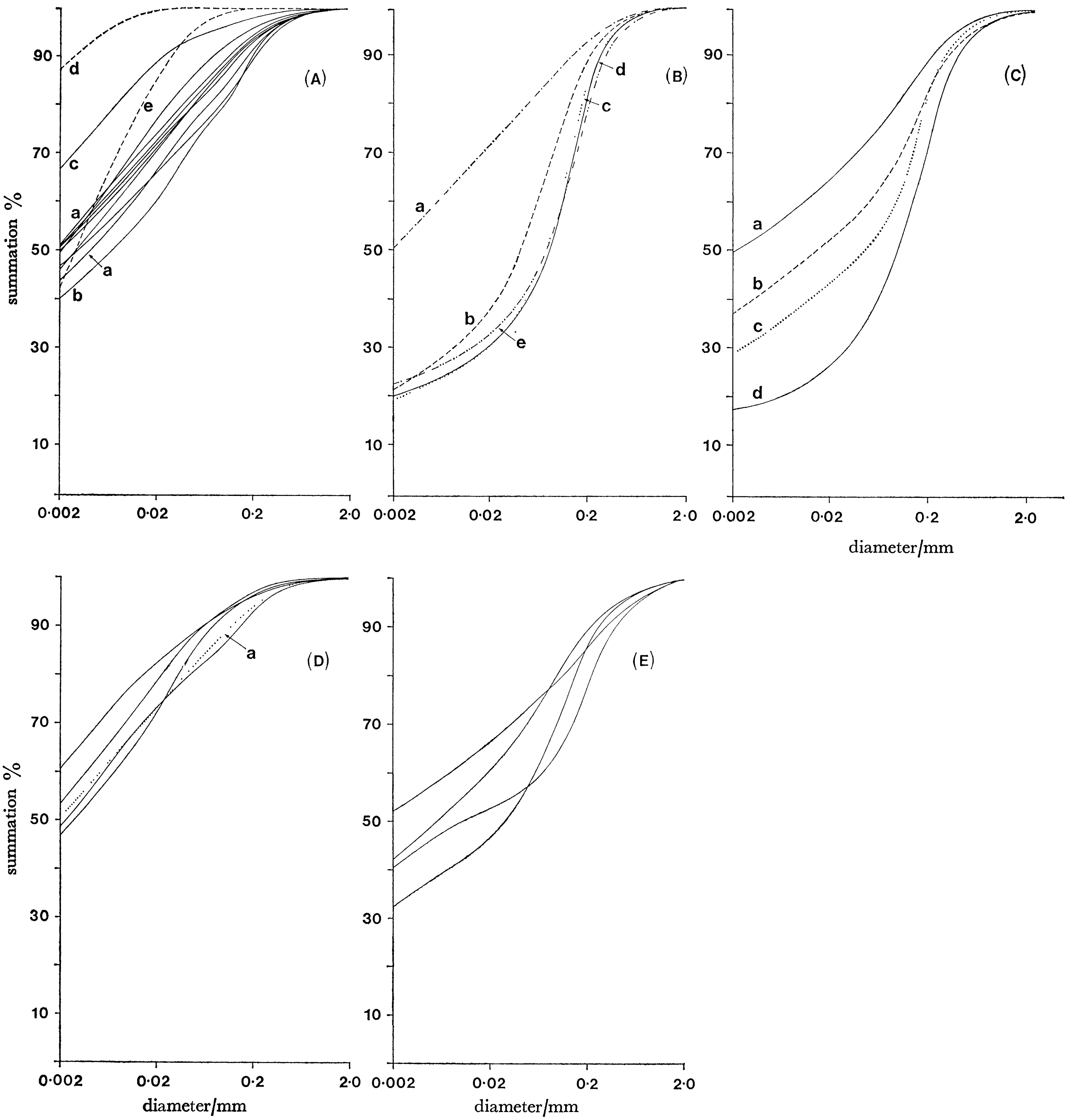
(Mean values except where otherwise stated; standard errors in parentheses. The colour range given indicates the general field appearence of each till. Although used as one criterion for allocating samples to particular tills, colour was not used in the quantitative analysis of lithology. A further 27 samples of Marly Drift were analysed and considered to be of intermediate or uncertain type.)

| | | | calcium carbonate (% bulk matrix < 2 mm diameter) | | mechanical composition (% insoluble residue < 2 mm diameter) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | mm | | | µm | | | | | |
| till | samples analysed | colour, moist (Munsell system) range | range | mean | 2–1 | 1–0.5 | 0.5–0.21 | 210–105 | 105–63 | 63–20 | 20–6 | 6–2 | < 2 |
| | | | | | | *Lowestoft Till group* | | | | | | | |
| Chalky Boulder Clay (Lowestoft Till) | 382 | 7.5 YR 5/6–<br>5 Y 6/3 | 1–70 | 40 (0.8) | 0.77 (0.05) | 1.7 (0.08) | 6.5 (0.23) | 8.6 (0.21) | 4.9 (0.11) | 13.2 (0.23) | 11.2 (0.12) | 9.1 (0.12) | 44.1 (0.50) |
| Wragby Till | 10 | 2.5 Y 7/3–<br>5 Y 4.5/1 | 10–55 | 29 (4.5) | 0.44 (0.14) | 0.95 (0.32) | 3.4 (0.81) | 5.0 (0.75) | 2.9 (0.36) | 10.3 (1.1) | 12.2 (0.81) | 12.4 (0.75) | 52.4 (2.2) |
| Calcethorpe Till | 6 | 10 YR 8/1.5–<br>2.5 Y 8/1.5 | 67–88 | 81 | 2.0 | 3.1 | 9.1 | 11.0 | 6.2 | 11.6 | 7.6 | 8.0 | 41.4 |
| Marly Drift, Lowestoft-type | 15 | 10 YR 7/6–<br>2.5 Y 8/2 | 52–92 | 72 (3.1) | 0.85 (0.21) | 2.5 (0.60) | 8.3 (1.6) | 11.2 (1.8) | 6.0 (0.73) | 12.9 (1.5) | 9.4 (1.0) | 7.0 (0.76) | 42.0 (3.9) |
| | | | | | | *North Sea Drift group* | | | | | | | |
| Marly Drift, Cromer-type | 12 | 10 YR 8/3–<br>2.5 Y 6/6 | 15–93 | 44 (7.2) | 1.2 (0.22) | 3.6 (0.30) | 17.5 (2.0) | 20.7 (0.97) | 10.5 (1.0) | 14.5 (0.96) | 6.1 (0.48) | 3.9 (0.36) | 22.1 (1.6) |
| Cromer Tills | | | | | | | | | | | | | |
| First | 8 | 10 YR 5/2–<br>2.5 Y 5/2 | 5–11 | 8 (0.74) | 0.6 (0.16) | 2.3 (0.44) | 13.0 (1.8) | 23.4 (0.79) | 15.9 (0.61) | 14.6 (0.35) | 5.7 (0.35) | 4.7 (0.32) | 19.9 (1.1) |
| Second | 9 | 2.5 Y 6.5/2–<br>5 Y 6.5/1 | 27–40 | 34 (1.6) | 0.5 (0.05) | 1.4 (0.15) | 7.8 (0.76) | 15.3 (0.89) | 13.5 (0.51) | 23.4 (0.77) | 10.4 (0.89) | 5.9 (0.33) | 21.6 (1.1) |
| Third | 4 | 10 YR 7.5/4.5–<br>2.5 Y 4/2 | 7–10 | 9 | 0.4 | 1.8 | 11.8 | 24.6 | 14.6 | 15.7 | 6.9 | 4.7 | 19.4 |
| Tills in Contorted Drift | 3 | 10 YR 6.5/2–<br>10 YR 8/4 | 8–13 | 11 | 0.5 | 1.9 | 9.8 | 23.8 | 17.0 | 17.1 | 5.8 | 4.6 | 19.8 |
| Cromer-like tills (inland) | 7 | 10 YR 5.5/6–<br>2.5 Y 7.4 | 8–60 | 34 | 1.0 | 3.4 | 17.4 | 18.5 | 11.1 | 17.6 | 6.8 | 4.2 | 19.9 |
| Norwich Brickearth | 18 | 7.5 YR 5/4–<br>2.5 Y 7/4 | 0–2 | 0.43 (0.13) | 0.78 (0.10) | 3.1 (0.32) | 14.3 (1.0) | 22.4 (1.2) | 12.3 (0.45) | 14.6 (0.56) | 5.9 (0.38) | 4.5 (0.43) | 22.1 (1.2) |
| | 474 | | | | | | | | | | | | |

Table 2. Heavy mineral assemblages in tills of eastern England

(Percentages by number; standard errors in parentheses. Data for Chalky Boulder Clay are based on all samples from East Anglia and the east Midlands except that from the Oadby Till at Huncote. In contrast to all other tills quoted, the red till at Huncote contains a high proportion of chlorite in the 'mica' fraction while' other minerals' are nearly all sphene. The three Cromer Tills are mineralogically very similar except in opaques, for which mean values are: First 28.8 %, Second 41.6% and Third 28.3 %.)

| | | Lowestoft Till group | | | | | North Sea Drift group | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Huncote SP 512982 | | | | | Marly Drift | | | | |
| | Red till | Oadby Till | Chalky Boulder Clay (Lowestoft Till) | Wragby Till | Calcethorpe Till | Lowestoft-type | Cromer-type | Cromer Tills (First, Second and Third) | tills in Contorted Drift | Norwich Brickearth |
| opaque heavy minerals (% total heavy minerals) | 78 | 87 | 85.0 (1.08) | 87.7 | 75.4 | 87.0 (1.91) | 46.6 (3.46) | 37.1 (4.1) | 30.3 | 44.5 (4.13) |
| non-opaque heavy minerals (% non-opaque heavy minerals) | | | | | | | | | | |
| rutile group | 3 | 1 | 2.9 (0.65) | 3.5 | 1.4 | 2.1 (0.56) | 2.3 (0.42) | 0.9 (0.28) | 2.0 | 2.9 (0.54) |
| staurolite | 0 | 0 | 3.3 (1.08) | 2.0 | 0.8 | 1.0 (0.38) | 1.0 (0.30) | 0.8 (0.24) | 1.0 | 1.6 (0.46) |
| tourmaline | 2 | 2 | 5.5 (0.84) | 4.5 | 3.2 | 2.2 (0.80) | 2.4 (0.34) | 3.3 (0.38) | 1.7 | 3.2 (0.67) |
| garnet group | 15 | 22 | 21.0 (1.40) | 21.1 | 24.6 | 21.2 (1.76) | 23.3 (1.23) | 18.6 (1.07) | 21.3 | 15.9 (2.75) |
| zircon | 15 | 6 | 9.3 (0.92) | 7.0 | 8.4 | 6.4 (1.50) | 7.8 (0.92) | 5.2 (0.58) | 7.0 | 8.1 (1.94) |
| epidote group | 3 | 19 | 19.7 (1.44) | 17.5 | 30.4 | 20.6 (0.77) | 24.1 (2.12) | 22.6 (0.97) | 26.0 | 32.7 (1.95) |
| mica group | 50 | 1 | 12.3 (2.24) | 5.0 | 2.6 | 10.8 (4.68) | 2.3 (0.62) | 4.8 (1.20) | 1.7 | 2.6 (0.80) |
| amphibole group | 4 | 49 | 23.8 (1.78) | 39.1 | 28.0 | 36.3 (3.05) | 35.1 (1.15) | 43.8 (1.80) | 38.8 | 32.5 (3.95) |
| other minerals | 8 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 |
| number of samples | 1 | 1 | 33 | 6 | 6 | 15 | 12 | 11 | 3 | 11 |



For legends to FIGURE 4A–E see facing page.

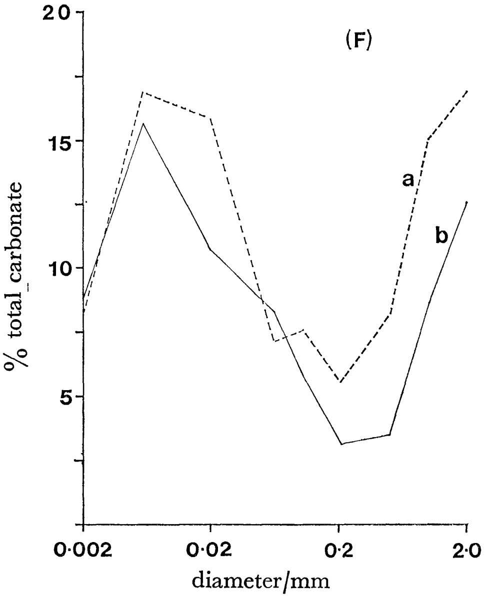


FIGURE 4. Mechanical composition curves representative of all the tills analysed, and distribution of carbonate in Lowestoft Tills. In figure 4A–E particle size distributions are expressed as cumulative percentages, by mass, of the insoluble residues.

(A) Lowestoft Tills and Mesozoic clays. (a–a) Average compositions of Lowestoft Tills by counties, after Perrin *et al.* (1973). Compositions of most of these tills fall in or close to this field. Many show a slight concentration of particles around 0.15 mm. (b, c) Extreme types of tills with Lowestoft lithology and mineralogy. Very clay-rich varieties such as (c) are uncommon; they appear to represent locally high contents of Mesozoic clays, but are distinguished from the latter by their relatively high sand contents. (d, e) Extreme types of Mesozoic clays. The composition of all 24 samples so far examined fall between these limits. The content of particles around 0.15 mm is negligible.

(B) Typical Lowestoft Till and North Sea Drifts: (a) Lowestoft Till; (b) Second Cromer Till; (c, d) First and Third Cromer Tills; (e) Norwich Brickearth. The most frequent particle diameters fall in the range 0.10–0.16 mm for the First Cromer Till, 0.06–0.15 mm for the Second, and 0.13–0.17 mm for the Third and the Norwich Brickearth.

(C) Typical examples of Marly Drift: (a) Lowestoft-type Marly Drift; (b, c) intermediate types of Marly Drift; (d) Cromer-type Marly Drift.

(D) Typical Wragby Tills compared with Lowestoft Till: (a) average Lowestoft Till.

(E) Typical Calcethorpe Tills.

(F) Carbonate distribution in two typical Lowestoft Tills: (a) Corton, Suffolk (TM 547966); (b) Great Waltham, Essex (TL 685118). (Each carbonate size fraction is expressed as a percentage, by mass, of the total carbonate in the bulk matrix of particle size less than 2 mm diameter.)

(iv) The Norwich Brickearth, apart from its lower carbonate content and generally more weathered appearance, is very like the Cromer Tills, especially the First and Third (figure 4B), confirming earlier opinions that it can be grouped with them in the North Sea Drift (Harmer 1909; Boswell 1914; West 1963).

(v) Till members in the Contorted Drift are lithologically close to the Cromer Tills (tables 1, 2; figure 4), in agreement with Reid (1882) and Banham (1968). Although only three laboratory analyses are available, neither these nor field studies confirm the presence of any Lowestoft material in the north Norfolk cliffs as claimed by Solomon (1932*a*).

(vi) The insoluble residues of the Marly Drift (figure 4C) resemble, both mechanically and mineralogically, those of the Cromer Tills, especially the Third (the 'Cromer-type' Marly Drift of Banham *et al.* 1975), or those of the Lowestoft Till ('Lowestoft-type'), or are of intermediate composition ('intermediate-type').

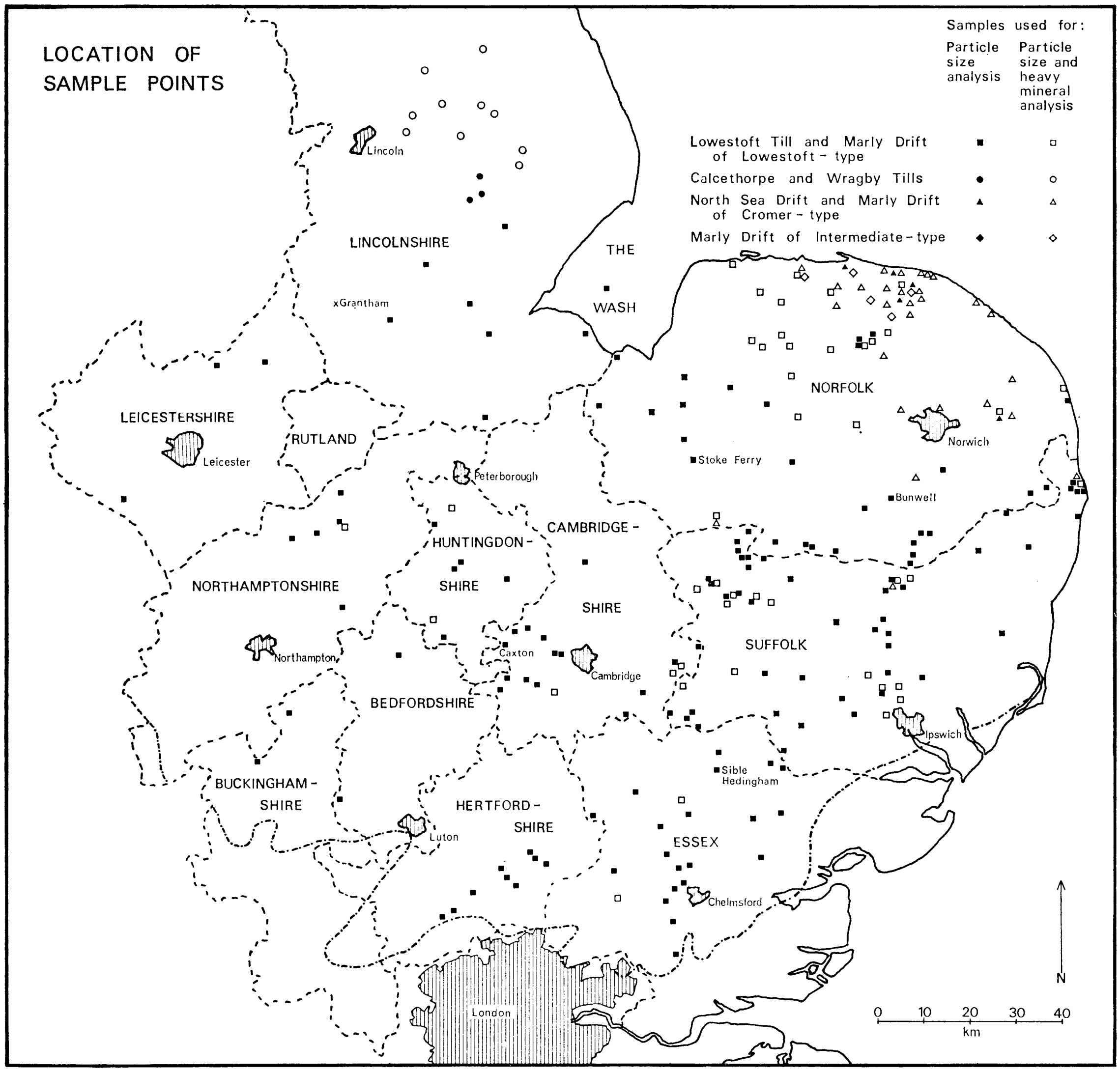


Figure 5. Location of sample points for spatial analysis and types of data collected. Some symbols represent two or more sites close together.

(vii) Inland, but outside the generally accepted areas of the Marly Drift and Norwich Brickearth, e.g. Flordon (TM 182975), Hockwold (TL 750893), there were found a few examples of variably calcareous tills mechanically and mineralogically similar to the Cromer Tills of the coastal sections. The more calcareous varieties are indistinguishable from Cromer-type Marly Drift.

These tills could represent an early advance of ice carrying Cromer-like debris with variable assimilation of chalk since, in the case of Hockwold, such material underlies a stratum of typical Lowestoft lithology. Their status will be discussed in a later paper.

(viii) Heavy mineral assemblages of both the Wragby and Calcethorpe Tills are qualitatively the same as those of the Lowestoft Till and the North Sea Drift but both resemble the Lowestoft in having high percentages of opaques. The Wragby Till is also mechanically similar to the more clay-rich examples of the Lowestoft Till (figure 4D) and carries a similar range of carbonate, These observations strengthen early opinions based on field relations and gross lithology (Wood 1880; Jukes-Brown 1885; Harmer 1909) that the Chalky Boulder Clay in Lincolnshire is continuous with that in East Anglia.

The very calcareous Calcethorpe Till has a much more variable insoluble residue content (figure 4E). This may reflect its provenance but, since it is commonly thin and occurs on sloping sites over the Chalk, it may well have been modified by periglacial processes, and caution is needed in interpreting its particle size distribution. As noted by Harmer (1909) and by Straw (1965) it forms, with the Marly Drift of Norfolk, a northerly chalk-rich province.

(ix) Since all the pre-Devensian tills contain qualitatively the same heavy mineral suite as the Cromer Tills it seems very probable that the North Sea basin was the source of the sand grade in every case. A short investigation by electron probe microanalysis, to be reported elsewhere, showed that the garnets from all the tills are almandine of approximately the same chemical composition and are therefore not derived from widely different sources.

On the other hand, it is unlikely that much of the clay grade was contributed by Tertiary clays in the North Sea. The Cromer Tills, which are the nearest to these outcrops (figure 2), contain little clay, and a preliminary study by N. F. Hughes of pollen from some of the samples of Lowestoft Till, including one sample from just south of the Wash, showed that Tertiary forms were present only in trivial amounts.

It may now be suggested that the whole population of tills can be divided into two lithological groups, each of which includes members with high and low carbonate contents:

(i) a *North Sea Drift group*, characterized by high sand and low opaque values, consisting of the three Cromer Tills, till members in the Contorted Drift, some inland Cromer-like tills, the Norwich Brickearth and part of the Marly Drift ('Cromer-type' of Banham *et al.* 1975) and

(ii) a *Lowestoft Till group*, characterized by low sand and high opaque contents, comprising the Lowestoft Till (including the Chalky Boulder Clay of the east Midlands), the Wragby Till and the 'Lowestoft-type' Marly Drift. The possibly reworked Calcethorpe Till is also assigned to this group by its high opaque values, in spite of its rather variable sand content.

These groupings are based solely on quantitative lithological similarities and do not by themselves demonstrate any stratigraphic affinities. They will be justified as geologically significant if they exhibit clear spatial distributions and trends of till properties that can be rationally related to the solid geology and hence to likely regional ice flows.

## 4. Application of spatial analysis

### (*a*) *Objectives*

Spatial analysis was used for the following purposes:

(i) to prepare regional contour maps of the main till properties applicable to both pedology and Quaternary geology;

(ii) to discover whether the tills that had already been lithologically distinguished could be spatially separated even if the allocation of samples to particular units by subjective field criteria was eliminated; and

(iii) to determine whether patterns in the whole sample of pre-Devensian tills, and of the very widespread Lowestoft Till group in particular, would support the conclusions already reached (§3) and provide a regional interpretation of till origins and ice movements.

### (*b*) *Selection of samples*

Each value used in the spatial analysis was the mean of all samples collected to represent a particular lithology at that locality. Where more than one lithological unit was exposed at a site, as, for example, along the Norfolk coast, the values used were those for the uppermost till. Thus the analyses of North Sea Drift relate to the Norwich Brickearth or Third Cromer Till except where only the First Cromer Till or an undifferentiated Cromer-like till is exposed (table 1). Till members of the Contorted Drift were not included.

The distribution of samples is shown in figure 5.

### (*c*) *Preparation of data*

To facilitate analyses, the nine fractions of each insoluble residue were reduced to three: sand (particle size 2000–60 µm or $-1\phi$ to $+4\phi$), silt (63–2 µm or $4\phi$ to $9\phi$) and clay (smaller than 2 µm or greater than $9\phi$). These were expressed as percentages of the bulk material with particle diameter smaller than 2 mm in the same way as for calcium carbonate.

This mode of expression was used to generalize the information represented by the curves of insoluble residues that indicate the type and degree of sorting in the till matrix. It allows the easier recognition of the relative contributions to the matrix of rocks of differing lithologies.

Otherwise, the values used were the same as in §3(*b*) but statistical analysis of the non-opaque heavy minerals was restricted to garnet, amphiboles and epidote because they are numerically the most important (table 1).

Only the carbonate and opaque heavy mineral values are independent. The contents of clay, silt and sand in a sample depend on both the percentage of carbonate and on one another, while the garnet, amphiboles and epidote values are also dependent both on one other and on the other non-opaque heavy minerals.

### (*d*) *Tests of representativeness*

The value used for a given grid point was the mean of those for the samples from a vertical section (table 3). In order to examine the representativeness of single sample values a one way analysis of variance (Griffiths 1967) was applied to the particle size and the carbonate data from the Lowestoft Till. In all instances, the variation between the values at different grid points was significantly greater at the 99.9 % level than the variation within the samples at a single point (table 4).

TABLE 3. NUMBER OF SITES AND SAMPLE VALUES USED IN THE SPATIAL ANALYSIS

| tills | lithological properties measured | number of grid points | number of samples at a grid point | | | | | | | total number of samples |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| Lowestoft, Wragby, Calcethorpe, Third Cromer, Norwich Brickearth, Marly Drifts | calcium carbonate, sand, silt, clay | 263 | 156 | 56 | 25 | 11 | 9 | 4 | 2 | 470 |
| | opaques, garnet, amphiboles, epidote | 81 | 74 | 5 | 2 | 1 | 0 | 0 | 0 | 94 |
| Lowestoft, Wragby, Calcethorpe, Marly Drift (Lowestoft-type) | calcium carbonate, sand, silt, clay | 210 | 118 | 53 | 18 | 9 | 7 | 4 | 1 | 380 |
| | opaques, garnet, amphiboles, epidote | 54 | 49 | 4 | 1 | 0 | 0 | 0 | 0 | 60 |

TABLE 4. ONE WAY ANALYSIS OF VARIANCE TO DETERMINE THE REPRESENTATIVENESS OF SINGLE SAMPLE VALUES

| till property | source of variation | degrees of freedom | sum of squares | mean square | *F* |
|---|---|---|---|---|---|
| calcium carbonate | between grid points | 209 | 86618.12 | 414.44 | 2.90* |
| | within grid points | 166 | 23716.73 | 142.87 | |
| | total | 375 | 110334.85 | | |
| clay fraction < 2 µm | between grid points | 209 | 26199.10 | 125.25 | 6.02* |
| | within grid points | 166 | 3452.39 | 20.80 | |
| | total | 375 | 29651.49 | | |
| silt fraction 2–63 µm | between grid points | 209 | 16915.51 | 80.94 | 5.84* |
| | within grid points | 166 | 2300.10 | 13.85 | |
| | total | 375 | 19215.61 | | |
| sand fraction 63–2000 µm | between grid points | 209 | 26873.34 | 128.58 | 4.15* |
| | within grid points | 166 | 5145.14 | 30.99 | |
| | total | 375 | 32018.48 | | |

* Signifies greater than 99% level of significance.

### (*e*) *Methods of spatial analysis*

Synagraphic Mapping System or SYMAP (Robertson 1967) was used to describe the magnitude and distribution of lithological properties for the whole set of samples which had been subjectively assigned in the field to the Calcethorpe, Wragby and Lowestoft Tills, the Marly Drift, the Third Cromer Till and the Norwich Brickearth (table 3 and figure 5). This technique uses a two dimensional interpolation function designed for irregularly spaced data. The interpolation incorporates distance, direction and surface shape, and passes through all grid points, which were located to the nearest 100 m on the National Grid. Each property was mapped as five equal-interval groups between, and including, the highest and lowest values in the data distribution.

Trend surface analysis was used to generalize the spatial variations in the lithology of the Lowestoft Till group (table 3) and to determine the statistical significance of such variations (Krumbein & Graybill 1965; O'Leary *et al.* 1966). Each property was analysed by trend surfaces of orders one to six. Decisions relating to the use of particular surfaces were derived from the efficiency of the surface as indicated by the reduction in the percentage sum of squares, and the significance level indicated by the *F* value derived from an application of analysis of variance procedure (Allen & Krumbein 1962). Surfaces with an *F* value equal to, or greater than, 95% significance were considered to describe a spatial distribution that differs from random. Where a property was described at this significance level by more than one surface, the highest and lowest orders were used in the expectation that they would indicate respectively smaller and larger scale geological variation (Whitten 1963).

To identify variations from the regional patterns the residual values from each significant surface were analysed (Hill 1973) and grouped into class intervals of one standard deviation range. Areas where the original values deviate from the expected (trend surface) value by more than $1\sigma$, were located using SYMAP.

Both mapping techniques generate contours across the whole of the region, including areas where samples are few or absent.

## 5. SIGNIFICANCE OF THE TILL MATRIX COMPONENTS

The bulk constituents sand, silt, clay and carbonate represent most of the material assimilated by the glacier and their proportions should reflect the compositions of the solid, or earlier drift, formations along its path. By contrast, the heavy mineral fractions comprise only about 0.06% of the matrix (or about 0.1% of the insoluble residue) and in most parts of the region could not have been derived locally even in such small amounts. They should therefore indicate relatively distant sources and hence possible transport directions.

### (a) *Calcium carbonate*

Carbonate could be derived from any of the following formations:

(i) *Chalk*. This would be expected to be the largest source. In the Lowestoft Till most erratics other than flints are chalk stones (Perrin *et al.* 1973, figure 3) while in the matrix (particle diameter smaller than 2 mm) there are usually concentrations of particles of calcium carbonate around 6–7 μm and between 1–2 mm in size (figure 4F). The former are most likely to be coccoliths and their debris, and the latter are clearly fragments of solid chalk. An uncompleted study, by the late M. Black, of coccoliths separated from some of the Lowestoft Till samples showed that Chalk forms greatly predominate.

(ii) *Jurassic limestones*. These could be important in the west. The carbonate debris would of course differ from those from the Chalk but no detailed comparison has been made.

(iii) *Mesozoic clays*. The content of carbonate in the matrix of these clays is rather variable and, in preliminary work, was found to range from 9–36% in the Oxford Clay, from 5–6% in the Ampthill, from 5–18% in the Kimmeridge and from 27–41% in the Gault. However, in even the most calcareous of these clays the ratio of clay to carbonate is higher than in the matrix of typical Lowestoft Till so that, although the spatial pattern of carbonate may be complicated by assimilation of different Mesozoic clays, no relative enrichment of this till is likely.

### (b) *Insoluble residue*

The sand, silt and clay fractions could be derived from:

(i) clay formations (Lias, Oxford, Ampthill, Kimmeridge, Gault and Tertiary) which would provide both silt and clay in varying proportions but practically no sand (figure 4A). It was found that in 24 Mesozoic clays silt could range up to about 40% of the insoluble residue, being, in the virtual absence of a sand fraction, antipathetic to clay;

(ii) sands and sandstones (Lower Cretaceous, Tertiary and earlier Pleistocene) which would provide sand but very little silt or clay; or

(iii) the insoluble residue, which is mostly of clay grade, released from chalk and limestone debris when they are dissolved during analysis. Most Jurassic limestones and the purer Upper and Middle Chalks add very little, but much Lower Chalk in otherwise low-clay tills can significantly modify the insoluble residues.

### (c) *Heavy minerals*

The opaque heavy minerals in all the tills are mainly limonite although magnetite and pyrite are locally important. The most likely sources of the limonite are Jurassic formations, especially ironstones, Lower Cretaceous sands and sandstones (where it often consists of oxidized glauconite), the Claxby Ironstone and the Crags. It should be feasible to make some distinctions between grains from these sources but this has not yet been attempted.

Pyrite occurs sporadically in the Lowestoft Till; the most likely source would be Jurassic clays, although some could also come from the Chalk in the North Sea, where pyrite is stated to exist often in single crystals (Hancock & Scholle 1975). In the tills it has frequently been oxidized to limonite and gypsum and the latter is sometimes sufficiently abundant to partially survive solution and appear in the heavy mineral separates.

The non-opaque heavy minerals, garnet, amphiboles and epidote, are not common in the solid formations of eastern England. There are minor sources of garnet in the Lower Cretaceous sandstones and the Crags, and of amphiboles and epidote in the Crags and Tertiary clays (Rastall 1919; Solomon 1932) but no non-opaque heavy minerals in measurable amounts have been found in the 105–63 μm fraction of any of the Mesozoic clays examined. In all the tills, however, these three minerals are part of the mainly metamorphic assemblage that is believed to be derived from a common secondary source in the North Sea Basin (§3(*b*) (iv)).

## 6. Regional distributions of lithologies

Results obtained from SYMAP are recorded in figures 6 and 7.

Low contents of carbonate (figure 6A) are clearly associated with the generally accepted position of the North Sea Drift, although not confined to it, and very high values, with the positions of the Marly Drift and Calcethorpe Till. The distribution of carbonate in the Lowestoft Till area is more complex than was envisaged by Perrin *et al.* (1973).

Sand values (figure 6E) are high in the area of the North Sea Drift but do not distinguish any of the other tills. Low silt and, to a lesser extent, clay contents (figures 6D, B) are features of the Calcethorpe Till and Marly Drift, as a result of dilution with carbonate, but are not unique to them. Elsewhere silt and clay contents of the bulk matrix do not distinguish any of the tills but clay values, as percentages of the insoluble residue, confirm the separation of the North Sea Drift from the adjacent Lowestoft Till (figure 6C).

Low contents of opaques are confined to the areas of the North Sea Drift and the Cromer-type Marly Drift, these values being relatively high in all the others (figure 7). Garnet, amphiboles and epidote are unrelated to the pattern of tills observed in the field, although high epidote values are confined to the central part of the North Sea Drift.

In summary, the contour maps objectively confirm the field observations that the North Sea Drift is spatially separated from all other tills by its low carbonate and opaque values and its high content of sand. The Calcethorpe Till and Marly Drift are distinguished from all others by high carbonate values. No distinction can be made between the Lowestoft and Wragby Tills.

These conclusions do not conflict with the proposal that North Sea Drift and Lowestoft Till groups can be differentiated by sand and opaque contents.

## 7. The Lowestoft till group

### (*a*) *Constituent facies*

As neither the basic mechanical and mineralogical data for the insoluble residues nor automated contouring of bulk till properties can distinguish between the Lowestoft and Wragby

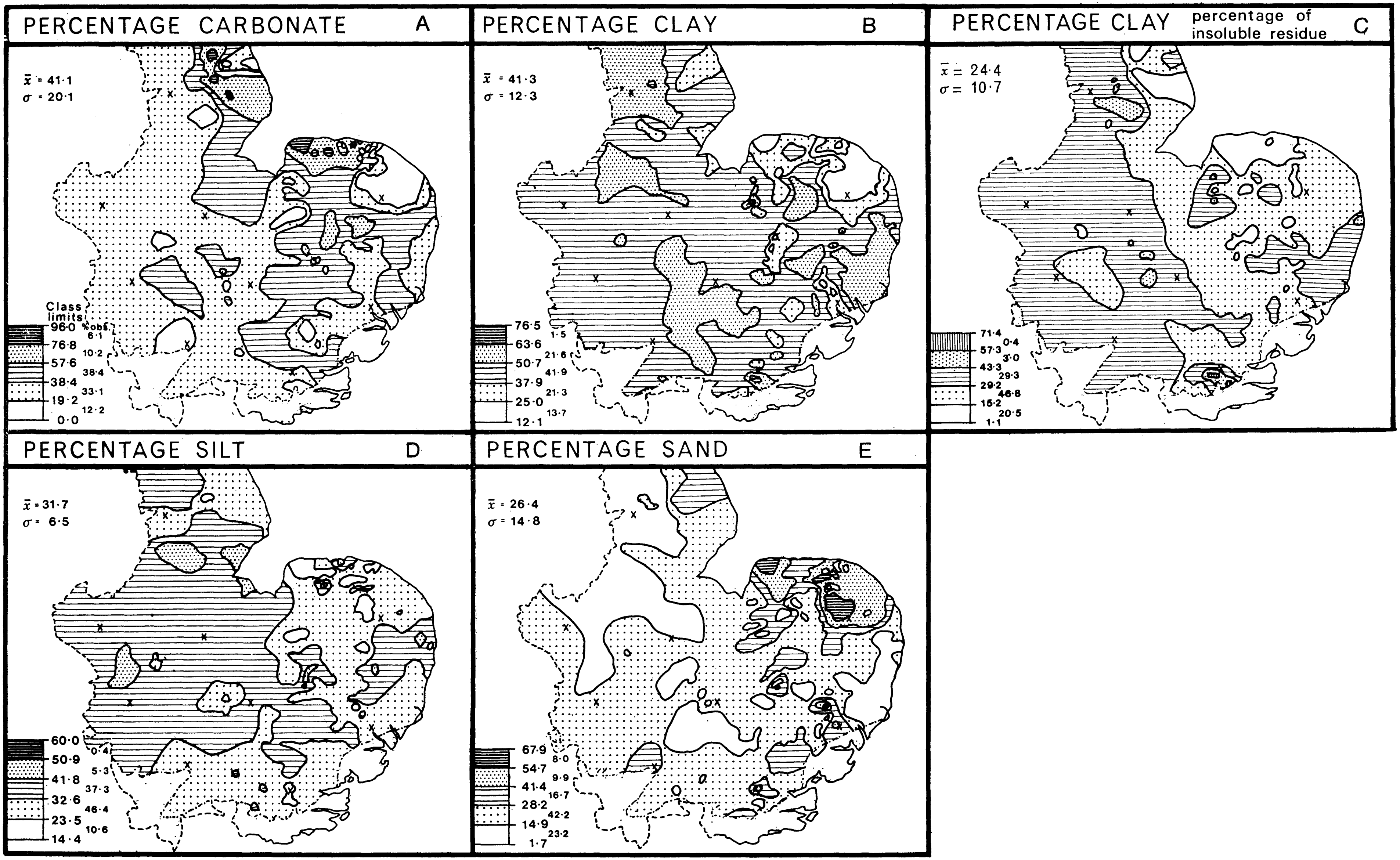


FIGURE 6. Regional distribution of carbonate, clay, silt and sand fractions from the North Sea Drift, Calcethorpe Till, Wragby Till, Marly Drift and Lowestoft Till. In all figures except (C) each fraction is expressed as a percentage by mass of the bulk matrix of particle size less than 2 mm. In (C) clay is expressed as a percentage of the insoluble residue. The distribution is indicated by equal interval contours determined by the SYMAP automated contouring technique.

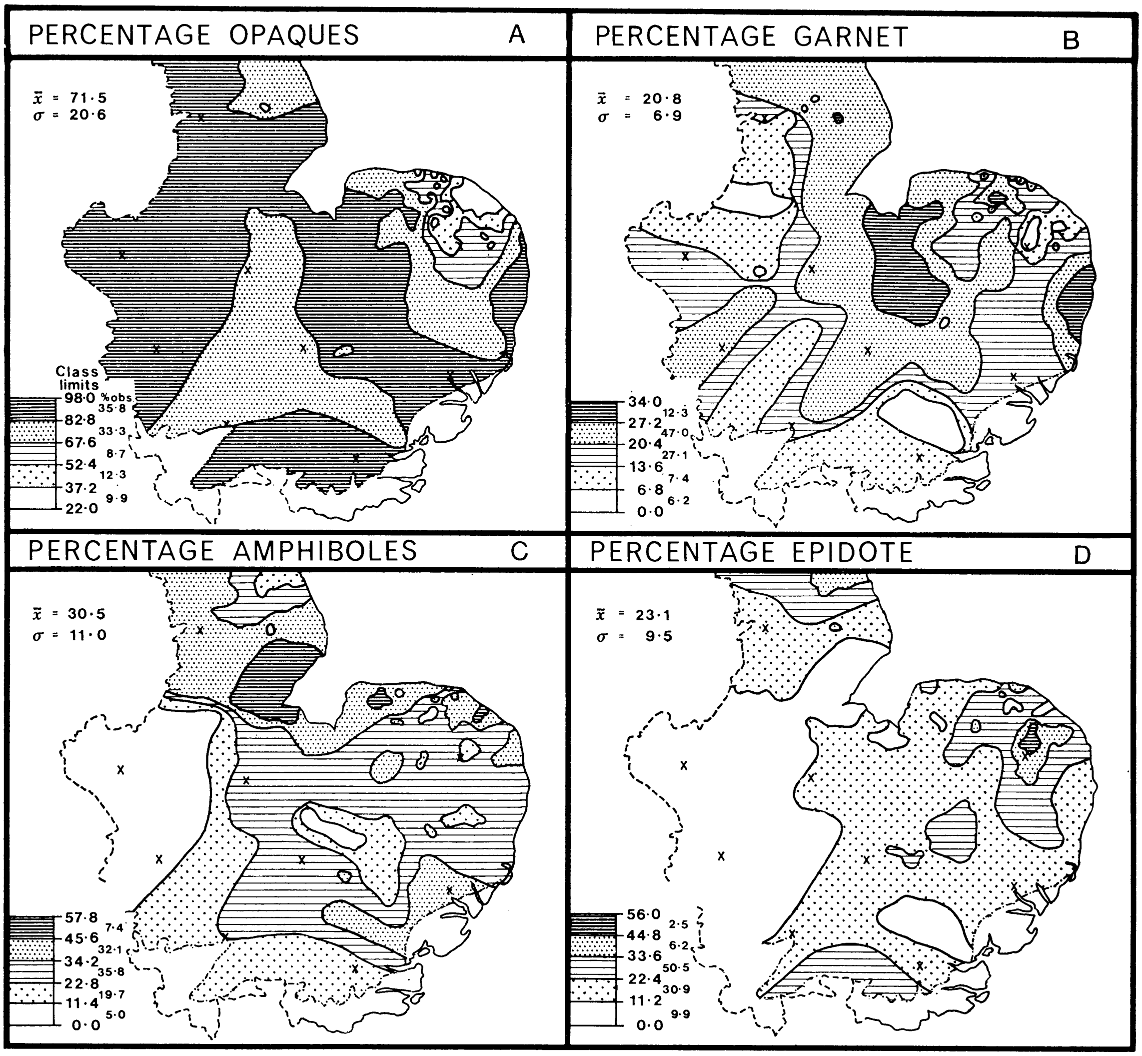


FIGURE 7. Regional distribution of selected heavy minerals from the North Sea Drift, Calcethorpe Till, Wragby Till, Marly Drift and Lowestoft Till. Opaques are expressed as a percentage by number of the total heavy minerals. Garnet, amphiboles and epidote are expressed as a percentage by number of the non-opaque fraction. The distribution is indicated by equal-interval contours determined by SYMAP.

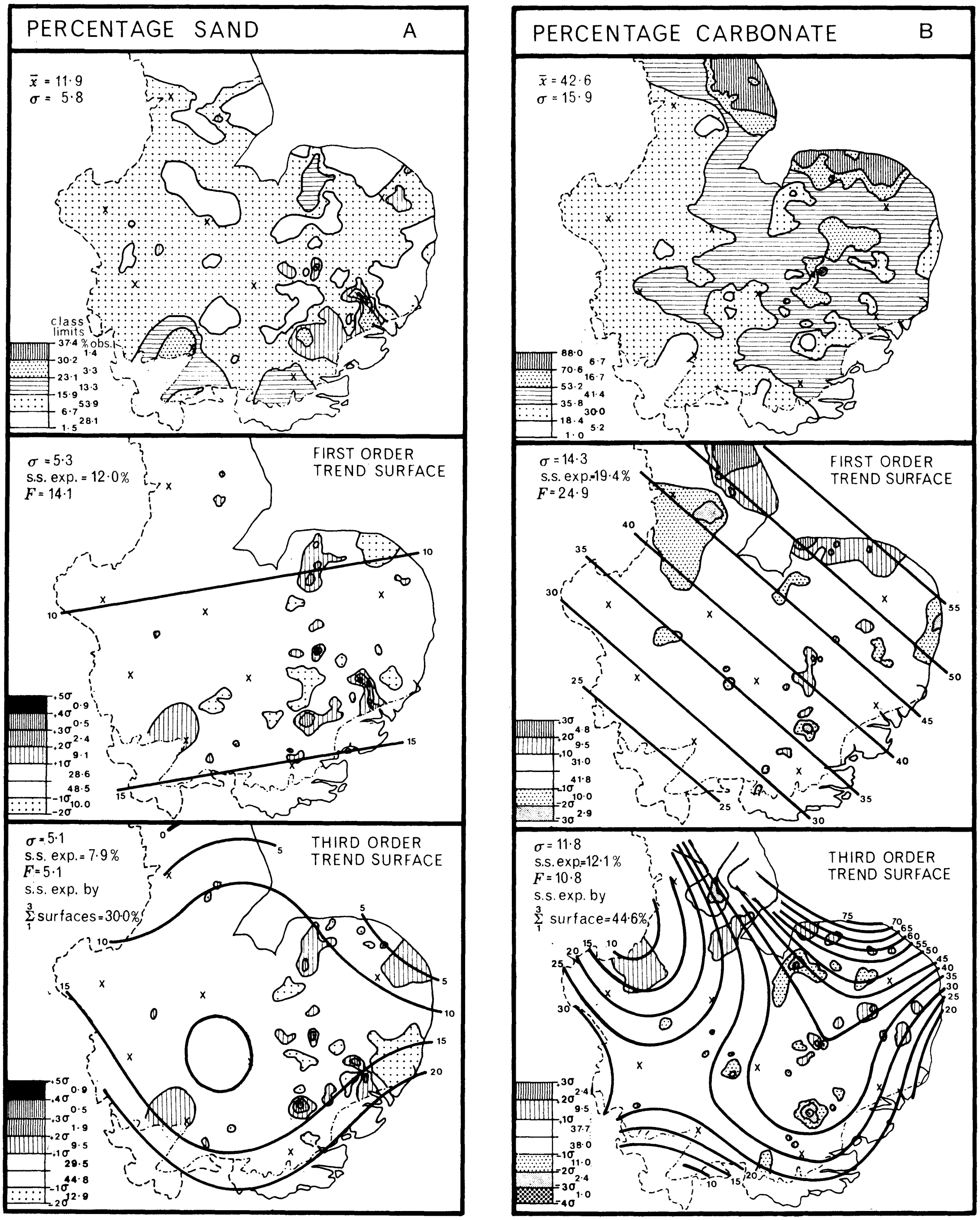
Tills, and since there is clear separation between the Calcethorpe and Wragby Tills in Lincolnshire and between the Marly Drift and Lowestoft Till in Norfolk, it may also be proposed that the Lowestoft group can be divided into two spatially distinct facies:

(i) a Calcethorpe–Marly facies, characterized by very high carbonate and low sand, silt and clay contents (expressed as percentages of the whole matrix), and located on either side of the Wash; and

(ii) a Lowestoft–Wragby facies, characterized by variable but generally moderate carbonate, low sand, and high silt and clay contents, and occupying the rest of the area of the group.

### (*b*) *Trend surface analysis*

Application of the method given in §4(*d*) showed that lithological values for the whole Lowestoft Till group form unimodal frequency distributions approaching normality for all properties except opaques. Trend surface analysis on the variables showing normal distributions



(Figure 8 continued opposite.)

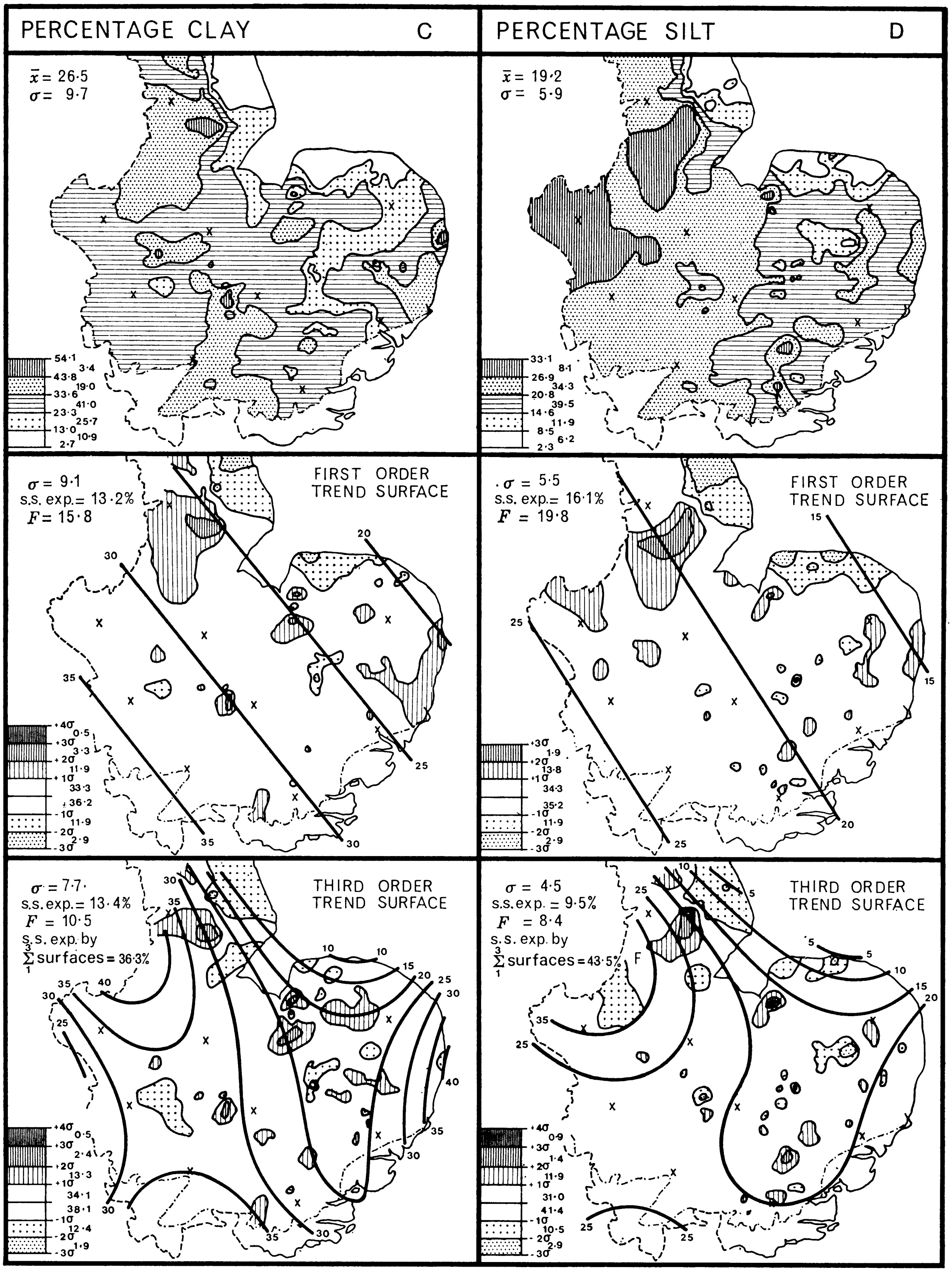


Figure 8. Regional distribution of carbonate, clay, silt and sand in the Lowestoft Till group. Each property is expressed as a percentage by mass of the till matrix of particle size less than 2 mm. The distribution is indicated by equal-interval contours determined by SYMAP, and by trend surfaces where the distribution has a statistically significant ($H_0 = 0.05$) regional trend. Residuals where $H_0$ indicates that the null hypothesis deviates from the trend surface by more than $1\sigma$ are contoured at $1\sigma$ class intervals determined by SYMAP.

Key to trend surface statistics: σ, standard deviation on trend surface; s.s. exp., sum of squares explained by the trend surface represented in the figure; *F*, *F* value computed for the trend surface, s.s. exp. by surfaces, sum of squares explained by all the trend surfaces contributing to the surface represented in the figure. The range of summation is indicated.

produced statistically significant trends at the first and third order levels in all instances except garnet content, which could only be resolved at the fifth order (figures 8 and 9).

### (*c*) *Calcium carbonate*

The first order carbonate surface (figure 8B) shows a significant decrease from northeast to southwest. The third order surface adds a ridge across the Chalk of east Lincolnshire and East Anglia, and a trough across the east Midlands with a small upward trend in the extreme west. The maximum residual values from both surfaces are at the contact zones between the Calcethorpe–Marly facies and the Lowestoft–Wragby facies, in the Breckland and at specific points such as Sible Hedingham (TL 7834).

### (*d*) *Insoluble residue*

The first order surfaces of both clay and silt significantly increase from northeast to southwest (figure 8C, D). Both third order surfaces add troughs across the Chalk of east Lincolnshire and East Anglia, and a ridge across the east Midlands. Residual values for both fractions are generally similar and again occur mainly at the contacts between the Calcethorpe–Marly facies and the Lowestoft–Wragby facies, in the Breckland and at further points such as near Sible Hedingham, Stoke Ferry (TF 7000), Bunwell (TM 1292) and Caxton (TL 2960).

By contrast, the first order sand surface (figure 8A) increases approximately from north to south. The third order surface adds a shallow dome around the Wash and a shallow basin across the central part of the region, the steepest gradients being at the northern and southern edges. Residual values for both surfaces are similar, with anomalously high values in the middle of the Marly Drift province, in the Breckland, along the Gipping Valley, and at Sible Hedingham.

### (*e*) *Heavy minerals*

The frequency distribution of opaques is unsuitable for trend surface analysis. There are high values in the west, around the Wash and in east Suffolk (figure 9A).

The fifth order garnet surface has a dome over the Wash, and troughs in Leicestershire and on the Chalk of east Lincolnshire and East Anglia (figure 9D). The only significant area o residuals is west of Norwich.

The first order surfaces of both amphiboles and epidote decrease from northeast to southwest (figure 9B, C). The third order amphibole surface is domed around the Wash with a trough over central East Anglia, while that of epidote forms a basin around the Wash and a ridge along the Chalk outcrop in East Anglia. Residuals from both surfaces show the widest deviations between observed and expected values just east of the Wash and at the eastern margin of the Marly Drift. For amphiboles only there are positive residuals in the Breckland.

### (*f*) *Regional variations*

Five out of the six first order surfaces have northwest to southeast trending isolines. Of the seven higher order surfaces, three form troughs and ridges over the Chalk and the Mesozoic clays, and three form a dome or a basin around the Wash. Both sand value surfaces, however, show east–west isolines. While some of the similarity in the trends must be due to mutual dependence of values, patterns are common to properties that are not interdependent and differences exist between properties that are. Such consistent trends are less likely to be

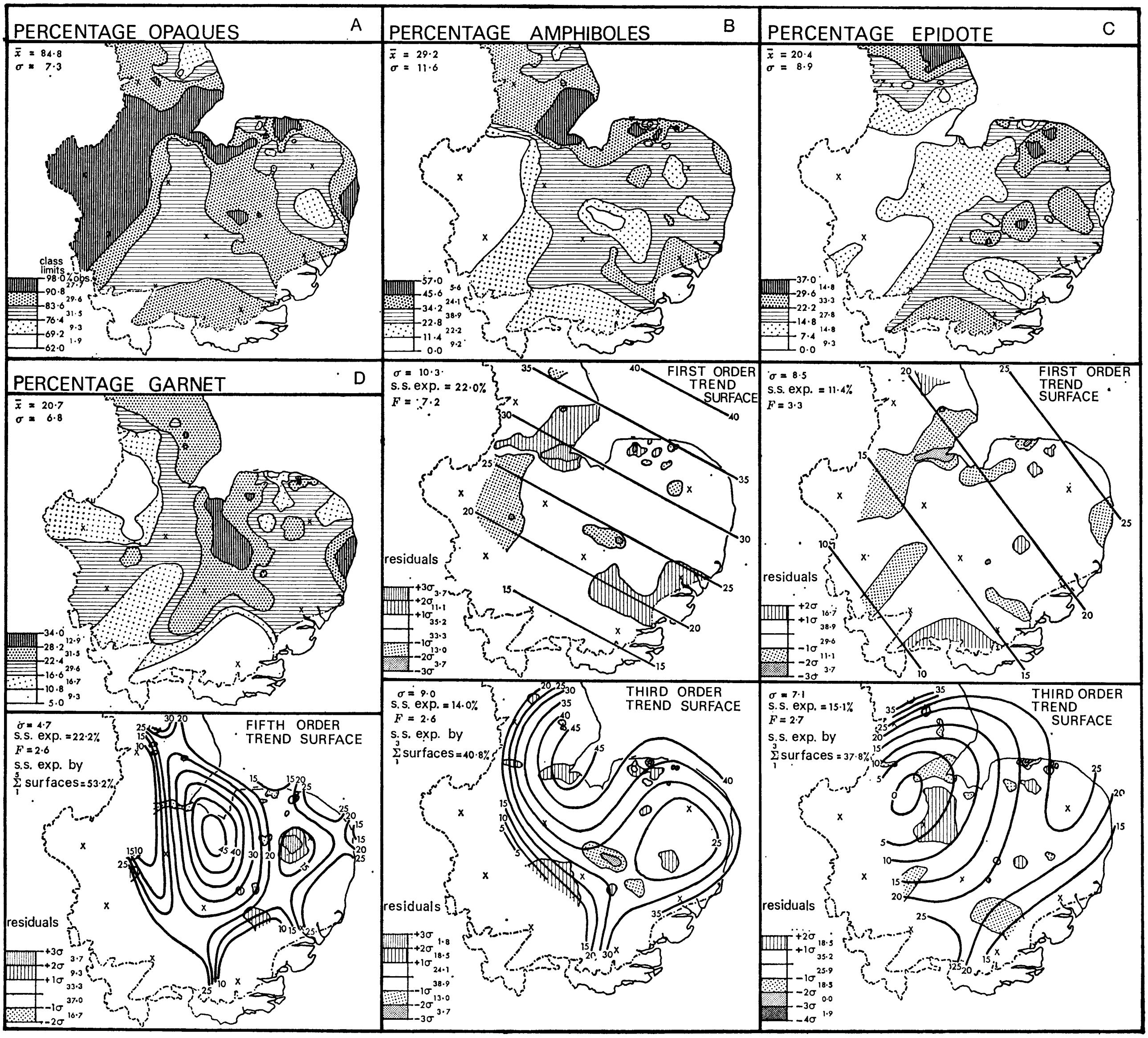


FIGURE 9. Regional distribution of selected heavy minerals in the Lowestoft Till group. Opaques are expressed as a percentage by number of the total heavy minerals. Garnet, amphiboles and epidote are expressed as a percentage by number of the non-opaque fraction. See explanation in description of figure 8.

a numerical artefact than the products of glacial processes with relatively simple constraints, and justify the recognition of the Lowestoft Till group as a geological entity.

The northeast to southwest first order trends independently suggest that, at the simplest level, the carbonate, garnet and amphiboles fractions were transported into the region from the North Sea basin. The reciprocal relation between the carbonate values and the clay and silt values is consistent with entrainment of clay and silt from Mesozoic clays in the Midlands then being mainly responsible for the relative reduction of carbonate. This is confirmed at the higher order levels where ridges of carbonate occur on the Chalk and troughs over the Jurassic clays, with domes of clay and silt over the latter. The small rise in carbonate in the extreme west could indicate assimilation of Jurassic limestones.

The domes of garnet and amphibole values over the Wash further suggest that this was a focus through which ice brought far-travelled minerals, thence spreading them out across eastern England.

The third order epidote surface is the inverse of those of garnet and amphibole and is not easy to explain. It could be a numerical artefact of relatively greater variations in the other heavy minerals but it could also reflect differences in mineral stability during glacial transport. For example, although large grains of epidote would be more susceptible to abrasion, garnet would be less stable in alkaline pore solutions (G. A. Chinner, personal communication), which, in a calcareous till matrix with low carbon dioxide contents, could have pH values greater than 9.

The relative increase of garnet, amphiboles and epidote over Tertiary and Pleistocene sediments in eastern Norfolk and Suffolk may indicate local assimilation. However, the scale of variation attributable to this is always smaller than that which can be associated with transport from the North Sea region.

The contrast between the trends of sand values and those of the other bulk constituents implies that their provenance was different. But the shallow dome on the third order sand surface is analogous to those on the higher order surfaces of garnet and amphiboles. This suggests that much of the sand may have been transported into eastern England from the North Sea across the Lower Cretaceous outcrops, carrying with it the far-travelled heavy mineral assemblage. It could then have become diluted by clay and silt and/or chalk during movement across the region, until a relatively steep increase was caused in the south by entrainment of Kesgrave Sand (Rose *et al.* 1976) or outwash.

### (g) *Local anomalies*

Residual values at two standard deviations from the trend surface reveal two general patterns. The first concerns the carbonate, clay and silt fractions, where residuals are developed on either side of the junctions between the Calcethorpe-Marly facies and the Lowestoft–Wragby facies. This shows that differences between the facies are greater here than would be expected from regional variations indicated by the trend surface and could be attributed to contrasted glacial movements. The residuals from the sand and heavy mineral trend surfaces do not differentiate the two facies, thus confirming that all members of the Lowestoft Till group probably have a common source of far-travelled material.

The second pattern concerns those isolated areas where properties deviate significantly from expected values. For example, tills in the Breckland are rich in carbonate, sand and amphiboles and deficient in clay and silt, while in the Gipping Valley there are also tills with a high sand content; in these particular cases the locally anomalous bulk properties may have contributed to the impression that a separate Gipping Till is present. While such variations cannot be explained at the scale of this study, it is hardly surprising that they should exist since they could be caused by a variety of local factors. These could include locally intense erosion of the substratum, incomplete mixing of the main till components, incorporation of earlier Pleistocene deposits (pre-existing tills, outwash, lake clays, alluvium or blown sands), and reworking, or the presence of flow-tills, particularly on valley slopes or bottoms.

Apart from these local anomalies, spatial analysis seems to confirm that it is valid to distinguish a Lowestoft Till group and to divide it into spatially discrete Calcethorpe–Marly and Lowestoft–Wragby facies.

## 8. Patterns of ice movement

### (a) *North Sea Drift group*

Since the earliest studies (e.g. Trimmer 1851; Reid 1882) there has never been any doubt that the Cromer Tills consist of sandy materials from the North Sea basin (cf. Krinsley & Funnell 1965) with chalk in amounts generally smaller than those in the Lowestoft Till (table 1). It has long been thought that the relatively low carbonate contents of the First and Third Tills result from the ice incorporating much sandy Tertiary material without cutting deeply into the subjacent Chalk, while the Second Till represents more intense erosion of the Chalk surface (Reid 1882).

In the present context, the nature of the stones (Banham 1970) and the observed high content of sand and low content of opaques (figure 2 and table 2) suggest that the ice moved over the North Sea basin, assimilating variable amounts of chalk, but without crossing substantial outcrops of either Jurassic or Lower Cretaceous formations relatively rich in limonite, or Tertiary or Mesozoic clays. A provenance lying about north or just to the east of north is thus the most likely (figures 2, 10), in agreement with Banham (1975) and Peake (1975).

The associated Cromer-type Marly Drift could consist of Cromer Till, probably the Third, enriched with chalk in the North Sea and/or Norfolk. A section in the town pit at Weybourne (TG 114431) shows Cromer-type Marly Drift in structural relations with chalk and Cromer Till implying that it was formed by their admixture (Banham *et al.* 1975). However, such mixing may well have been caused by movement of Lowestoft ice rather than of Cromer ice (Banham & Ranson 1965; Banham 1970).

### (b) *Lowestoft Till group*

For reasons given in §§3 and 5, all members of the Lowestoft Till group are likely also to have originated in the North Sea basin but in circumstances permitting the assimilation of more opaques and chalk than could be acquired by the North Sea Drift. The simplest explanation of the trend surfaces is that the ice streams of the Lowestoft group moved southwards across the western part of the basin, incorporating approximately the same kind of sandy material, with particle diameters most frequently around 0.15 mm, as that picked up by the North Sea Drift, and also chalk and oolite- and limonite-bearing Jurassic debris off the present coast of Yorkshire, and further chalk off Lincolnshire and Norfolk (figure 2).

It is suggested that the western part of this stream passed directly onto the Chalk of the Lincolnshire Wolds, depositing the Calcethorpe Till, composed of rather variable chalky debris from the North Sea basin and local chalk, but unmodified by contact with Mesozoic clays or Lower Cretaceous beds in the Wash (figures 1, 2 and 10).

The Lowestoft-type Marly Drift could be regarded as the product of the eastern part of the ice lobe which assimilated chalky material with a generally more clay-rich and less variable insoluble residue than that giving rise to the Calcethorpe Till (figures 4C, E) but also richer in clay and opaques than the adjacent Cromer Tills and Cromer-type Marly Drift. The simplest deduction from the trend surfaces is that this ice stream passed straight into north Norfolk (figure 10) and, according to Peake (1975), this is supported by the nature of the contained chalk. This interpretation does, however, assume that, although the bulk matrix of the Lowestoft-type Marly Drift is low in clay, the relatively clay-rich insoluble residue could have been acquired in the North Sea basin, and at present there is no way of suggesting a possible source.

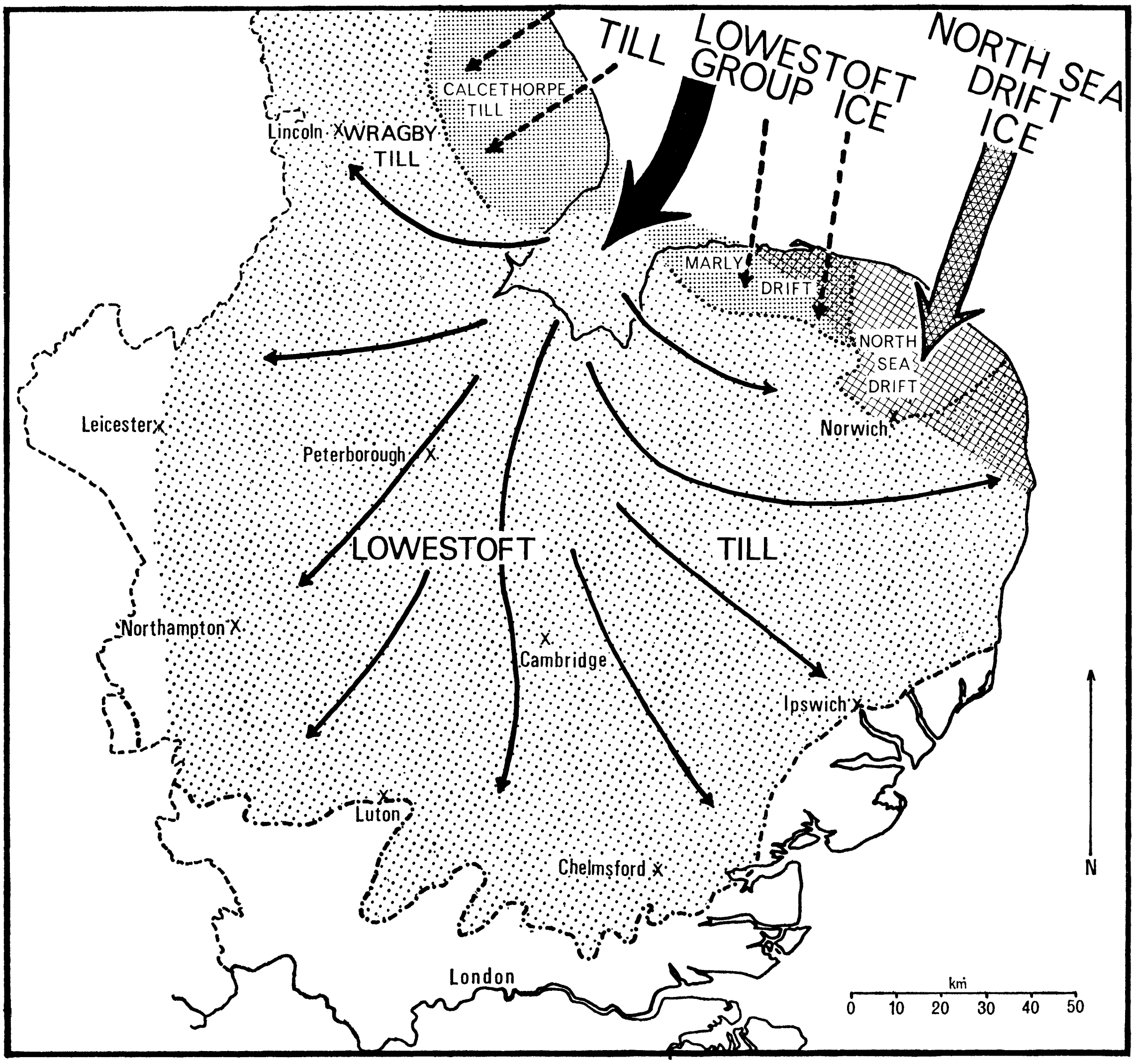


Figure 10. Suggested ice movement directions during pre-Devensian glaciation in eastern England. The thick arrows indicate a possible main source of the ice sheets. For the Lowestoft Till group the solid arrows show schematically the fan-like flow pattern of the main glacier flow track which reached eastern England through the Wash, and deposited the Wragby and Lowestoft Tills. Dashed arrows indicate minor, marginal flow tracks of ice depositing the Calcethorpe Till and the Marly Drift.

The intermediate-type Marly Drift could result from mixing of Lowestoft-type with Cromer-type, or with Cromer Till. Whatever the detailed mechanisms, it is probable that this variant of the Marly Drift represents complex interactions between the Cromer and Lowestoft ice sheets. These relations will be discussed in a further paper.

The central, and most vigorous, part of the ice stream, initially carrying sandy and chalky North Sea material, can be envisaged as passing through the present Wash over Mesozoic clays and then spreading into much of eastern England excepting those parts already occupied by the ice sheets of the Calcethorpe–Marly facies and the North Sea Drift (figure 10) (Cox & Nickless 1972, figure 3; Bristow & Cox, 1973).

The formation of the Wash–Fens basin, and the absence of scarps, which elsewhere in eastern England are associated with relatively resistant Cretaceous sediments (figures 2, 3), can be attributed to erosion by the ice that deposited the Lowestoft Till, the enormous bulk of which requires a large source of material capable of giving rise to the observed lithology.

In East Anglia, eastward movement of ice would mean that the ridge on the third order carbonate trend surface over the Chalk is caused by rapid local assimilation rather than by transport along the strike. The lithology of the till here would then be due to mixing of sandy debris and chalk from the North Sea, Mesozoic sediments from around the Wash and local chalk. The carbonate-rich tills and the subdued topography of the Chalk in the Breckland can satisfactorily be accounted for in this way.

The zones of residual values on the third order carbonate, clay and silt trend surfaces at the junctions of the Calcethorpe and the Wragby Tills, and of the Marly Drift and the Lowestoft Till, are consistent with interaction of glacial streams moving in markedly different directions (figure 10).

### (*c*) *Comparisons with earlier regional schemes*

Harmer (1904, 1909, 1928) proposed ice directions based on a great number of qualitative observations of erratics, which are summarized in his map of 1928. In his view a major ice stream (the 'Great Eastern Glacier') crossed Lincolnshire in southerly directions, being confined on the west by Pennine-derived ice, and then fanned out into the east Midlands and East Anglia. In the latter area he recognized the need for a quarry on the scale of the Fen basin to provide the great volume of Chalky Boulder Clay in Suffolk, and envisaged a very vigorous flow of the ice through the Ouse-Waveney gap in the Breckland. He supposed that the Jurassic debris found in the Fenland and East Anglia were mainly derived from outcrops in Lincolnshire. The present conclusions are very similar but differ in the following respects.

First, Harmer argued, on the basis of the frequency of hard chalk in the Chalky Boulder Clay of East Anglia, that the ice moved southeastwards over the Lincolnshire Wolds, the most obvious source of such chalk, and thence 'across' the Wash rather than southwards 'through' it, as is now proposed (figure 10). But recent work has shown that much of the North Sea chalk is similarly hard (Hancock & Scholle 1975) so it is no longer necessary to assume derivation from Lincolnshire. It would also seem that the Jurassic outcrops now known to lie off the Yorkshire coast (figure 2; and Kent 1967, p. 11) could provide limestone debris to enter the Fenland and East Anglia through the Wash, although it is difficult to estimate whether this source is sufficient to account for the amounts observed in tills. Quantitative studies of the non-chalk stones in the Calcethorpe Till could be helpful in this context, since it is very unlikely that it could have acquired Jurassic limestone debris from the east Midlands without comparable amounts of Triassic material.

Secondly, it is now suggested that the ice depositing the Wragby Till moved northeastwards from the Wash area into south Lincolnshire in contrast to traditional views that all movement was from north to south (Harmer 1909; Straw 1965, 1969). But the northward decrease in garnet and amphiboles in the Wragby Till is best explained by the assumption that these minerals were carried northwestwards and diminished by destruction in transport. Southward movement could not account for the increase in frequency towards the Wash as there are no possible sources in the area. Furthermore, there has been no apparent assimilation of reddish sand grains, or the staurolite said to be characteristic of the Bunter in Nottinghamshire (Burton 1917), to suggest passage of ice across that formation. Again, a till of typical Lowestoft–Wragby lithology has been found at Winterton (SE 958181), to the north of the region shown in figure 5 and even beyond the northern limit of the Chalky Boulder Clay as mapped by Wood (1880) and Harmer (1909, 1928). Northwesterly origins for this material are excluded by lack of Triassic or Pennine debris, and north of the Humber there are no clay-rich chalky tills or large outcrops of sediments capable of giving rise to till of Lowestoft–Wragby type.

There remain two possibilities:

(i) that this till somehow acquired the typical Wragby lithology by mixing of Jurassic and Cretaceous sediments off the Yorkshire coast and was then carried through the small gaps of the Humber or Barnetby-le-Wold (TA 0510), or

(ii) that chalky material passed through these gaps or over the north Lincolnshire Wolds, as suggested by Harmer's map of 1909, and immediately assimilated enough Jurassic clay to attain the typical composition of the Wragby Till.

Neither seems very probable and neither explains the observed trends in lithology as simply as does a northward flow of ice from the large Wash gap, the till at Winterton representing the petering out of that movement. The distribution of erratics in north Lincolnshire, as it appears on Harmer's maps (1909, 1928), can as easily be explained by northward as by southward movements of ice.

Thirdly, there is disagreement about south Lincolnshire, concerning which Harmer (1928) reiterated the observation of Jukes-Brown (1885) that a trail of Marlstone erratics stretches due south from Grantham (SK 9235). In that area the main transport would be expected to have taken place in a more westerly direction and indeed some westward movement is necessary to account for the occurrence of Harmer's 'Chalky-Jurassic Boulder Clay' north of Leicester. The north–south orientation could, of course, represent an ice direction that was only temporary in an area of complex interaction near the margin of the Pennine-derived ice, which Harmer believed to have limited the westward extension of the Chalky Boulder Clay, but the disagreement cannot yet be resolved.

There is not necessarily any conflict between the ice directions now proposed and the stone orientations measured in the southeast Midlands and East Anglia by West & Donner (1956, figure 4) as it is now generally accepted that preferred orientations of elongate particles may be produced by a multiplicity of depositional processes (Boulton 1972; Rose 1974). The present interpretation, however, accounts more satisfactorily than theirs for the observed lithologies, in particular for the very small amounts of Triassic material found in the Lowestoft Till.

### (*d*) *Stratigraphy*

As already shown, the lithological data and the spatial relations derived from them are satisfactorily and most simply attributed to a single glacial event, albeit with possible minor oscillations (Gibbard 1977). Since the North Sea Drift and Lowestoft Till in Norfolk are known to be penecontemporaneous (West 1956; Cox & Nickless 1972) and are, by definition, Anglian (Shotton & West 1969), it is difficult, in the present absence of any conflicting stratigraphic evidence, to avoid the conclusion that all the pre-Devensian tills must also be Anglian.

On the other hand, Bristow & Cox claim that all the Chalky Boulder Clay in East Anglia is Saalian (= Wolstonian), although they agree with the present authors that it is to be equated with the Lowestoft Till (Bristow & Cox 1973, p. 27). Shotton (1976) and Shotton *et al.* (1977) have discussed the status of the Midland Chalky Boulder Clays and consider them to be Wolstonian. Alabaster & Straw (1976) have proposed the same age for Calcethorpe Till at Welton-le-Wold (TF 282884). However, in none of these cases is there sufficient biostratigraphy to be fully conclusive.

Although there must be residual doubts, it therefore seems to us most reasonable to regard all these tills as Anglian until this view is refuted by a substantially larger or more detailed body of lithological information or by direct biostratigraphic evidence.

## 9. Summary of conclusions

(*a*) The pre-Devensian tills of eastern England can be spatially divided into a North Sea Drift group and a Lowestoft Till group.

(*b*) The North Sea Drift group consists of the Cromer Tills, some associated inland tills, till units in the Contorted Drift, the Cromer-type Marly Drift and the Norwich Brickearth. The group is composed of sandy material from a central part of the North Sea basin, mixed with variable amounts of chalk, and was deposited by an ice stream which probably entered Norfolk while moving in a southward direction.

(*c*) The Lowestoft Till group consists of the Lowestoft Till (the Chalky Boulder Clays of East Anglia and the east Midlands), the Wragby and Calcethorpe Tills and the Lowestoft-type Marly Drift.

(*d*) The Lowestoft–Wragby facies represents sandy and chalky debris, with Jurassic erratics, which were brought into the region from a westerly part of the North Sea basin by a vigorous ice stream. This passed through the Wash, levelling the Cretaceous escarpments and excavating the Wash–Fens basin, and then fanned out into those parts of eastern England not already occupied by ice from the Pennines or by streams depositing the Calcethorpe Till and the Marly and North Sea Drifts. Where it crossed Mesozoic clays it picked up clay and silt which diluted the sand and chalk from the North Sea; where it passed over the Chalk or Jurassic limestones, it assimilated further carbonate.

(*e*) The Calcethorpe–Marly facies represents chalky North Sea material initially similar to that from which the Lowestoft–Wragby facies was derived, but which was carried by marginal ice streams directly on to the Chalk of Lincolnshire and north Norfolk without assimilating appreciable amounts of Mesozoic clays.

(*f*) The Cromer-type Marly Drift may result from the action of Cromer or Lowestoft ice; the intermediate-type probably represents complex interplay between the two ice streams.

(*g*) All the pre-Devensian tills seem most likely to be Anglian.

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## Appendix 1. Definitions of tills referred to in the text

The purpose of this appendix is to specify the sense in which each till name is used in the present paper and to summarize some previous correlations relevant to the discussion. It is not intended to give a full history of the use of any term.

The reference at the head of each section is to the author(s) whose definition is accepted and does not necessarily refer to the originator of the name.

Each till is described in the order: general lithology, area of occurrence, and nomenclature and correlations. Carbonate contents and field colours of those tills which were analysed are given in table 1.

### *Calcethorpe Till* (Straw 1966, 1969)

Chalk-rich, very pale-coloured tills sometimes evidently re-worked; Lincolnshire Wolds (figure 1).

The Calcethorpe Till as defined by Straw appears to correspond exactly with the very chalk-rich tills of the Wolds recognized by Harmer (1909). Because Harmer used the term 'Chalky Boulder Clay' for the whole spread of till in eastern England as well as this particular facies, the name Calcethorpe Till is adopted as being less ambiguous. Alabaster & Straw (1976) considered it to be Wolstonian.

### *Chalky Boulder Clay* (Wood 1880; Harmer 1902)

Usually clay-rich, more or less chalky tills ranging from dark grey to pale brown, often with mottling in the weathering zone; east and southeast Midlands and East Anglia (figure 1).

Trimmer (1858) first separated an upper Jurassic-rich boulder clay from the lower till at Corton (TM 5497). Wood & Harmer (1868) placed this 'true' or 'great Boulder-clay' of eastern England in their Upper Glacial and distinguished it from the Lower Glacial represented by the Cromer Till and Contorted Drift of north Norfolk and the lower Corton till. Wood (1880) mapped the same formation as the 'Chalky Clay' over eastern England including the whole area of figure 1; it was later termed the Chalky Boulder Clay and studied in detail by Harmer (1902, 1904, 1909, 1928) who distinguished facies by the relative amounts of chalk and Jurassic debris.

From Wood's and Harmer's maps it is clear that their definition of Chalky Boulder Clay included the similar tills in the Midlands described by Deeley (1886), Hollingworth & Taylor (1946), Horton (1970) and others, and the Oadby Till of Leicestershire (Rice 1968). They both evidently believed the Chalky Boulder Clay to be the product of a single glaciation but Boswell (1931) thought it contained tills from two, an older 'Chalky-Jurassic' and a younger 'Upper Chalky Boulder Clay'. Baden-Powell (1948, 1950) and West & Donner (1956) distinguished these as the Lowestoft and Gipping Tills separated by the Hoxnian Interglacial. Bristow & Cox (1973) and Perrin *et al.* (1973) maintained that there is no lithologically or stratigraphically distinct Gipping Till and that deposits previously allocated to it are only local or reworked forms of the Lowestoft.

There is no agreement on the correlation of the Chalky Boulder Clay with the Continental, or even the British, succession. West & Donner (1956) equated the Lowestoft Till with the Elsterian (= Anglian) (West 1956; Shotton & West 1969) and the Gipping with the Saalian (= Wolstonian). Bristow & Cox (1973) put the whole of the Chalky Boulder Clay into the Wolstonian and the same correlation has been made for the examples in the Midlands (Shotton *et al.* 1977). Woodland (1970) regarded it as Weichselian (= Devensian) but most authors consider that all Devensian tills lie north of the line shown in figure 1 (Suggate & West 1959).

### *Contorted Drift* (Banham 1968)

Sequences of tills of variable chalk content, and associated glacifluvial beds, with major and complex deformation; north Norfolk cliff sections, particularly between Trimingham (TG 2739) and Weybourne (TG 1043).

This drift was first described by Taylor (1824) as 'contortions in the Diluvial Formations'. Wood & Harmer (1868) used the term Contorted Drift not only for the actually contorted coastal tills but also as a stratigraphic division of their Lower Glacial series. They included in the definition deposits now known as the Norwich Brickearth and Marly Drift (see below) and the lower till at Corton, although they placed it above the 'Cromer Till' (presumably the Second Cromer Till of Reid (1882) and Banham (1968)) in the Norfolk cliffs, thus creating a stratigraphic paradox.

Reid maintained that the name Contorted Drift should properly be restricted to the 'Boulder Clay or Stony Loam' but included other lithologies in descriptions of sections. He believed the deformations to have been produced by the Chalky Boulder Clay ice, while Solomon (1932*a*) claimed that the Chalky Boulder Clay was actually present in the Contorted Drift. Banham (1968) confirmed Reid's suggestion that the normal succession of tills and glacifluvial beds might be traced into the Contorted Drift and proposed that this name should be limited to intensely deformed sequences northwest of Trimingham, regardless of lithology. This definition is accepted for present purposes, till components of the Contorted Drift being explicitly referred to as such.

### *Cromer Tills* (Reid 1882; Banham 1968, 1970)

Sandy tills with generally low but sometimes moderate contents of soft chalk; grey or brown in colour; cliff sections in north and east Norfolk and northeast Suffolk.

Reid (1882) recognized a less calcareous First Till and a more chalky Second Till and grouped them, together with the intervening Intermediate Beds, as the Cromer Till. A higher, and again less calcareous, till separated from the Second Till by sands was termed the 'Boulder Clay or Stony Loam' and assigned to the Contorted Drift. Harmer (1909) grouped the Cromer Tills with the Norwich Brickearth, which was thought to be their inland equivalent, in the North Sea Drift. Baden-Powell (1948) used the term Cromer Till for the lower till at Corton. West & Donner (1956) considered the Cromer Tills and the Norwich Brickearth to have been deposited in the earlier southwestwards, or Cromer, Advance of the Lowestoft Glaciation which was later renamed Anglian by Shotton & West (1969). Banham (1968) used the terms First and Second Till in the same sense as Reid but renamed the 'Boulder Clay' the Third Till. He considered that only the First Till should be equated with the lower till at Corton (Banham 1970). His nomenclature is accepted for present purposes.

### *Gipping Till* (Baden-Powell 1948)

More or less calcareous tills of chalky or chalky-Jurassic character, generally described as more chalky than the Lowestoft Till; east Midlands and East Anglia.

These tills were recognized by Baden-Powell in the Gipping valley, and thence widely in eastern England, by him and by West & Donner (1956), as an upper division of the Chalky Boulder Clay (see above).

### *Lowestoft Till* (Baden-Powell 1948)

Clay-rich more or less chalky tills ranging from dark grey to pale brown often with mottling in the weathering zone; east and southeast Midlands and East Anglia (figure 1).

The Lowestoft Till was defined by Baden-Powell as the upper till at the type-site at Corton where it overlies the Corton Sands. It was equated with the till immediately underlying the inter-glacial beds at Hoxne (TM 1877) by Baden-Powell, by West & Donner (1956) and by Perrin *et al.* (1973), and referred to the Anglian Glaciation by Shotton & West (1969). For its relations with the Gipping Till and the Chalky Boulder Clay see under the latter heading.

### *Marly Drift* (Banham *et al.* 1975)

Extremely chalky pale or almost white tills; north Norfolk (figure 1)

Wood & Harmer (1868) noted that parts of the Contorted Drift (see above) in the Norfolk cliffs were very chalky and that southwestwards it tended to become 'exclusively marly'. Reid (1882) made the same observation but thought that the marly Contorted Drift passed laterally into the Chalky Boulder Clay. Woodward (1884, 1885) described as the 'marly variant of the Drift' the very calcareous inland tills that appeared to him to merge into both the Chalky Boulder Clay and the Cromer Till. Boswell (1914, 1916) first used the term Marly Drift for these chalky deposits, which he considered to be part of the North Sea Drift. Harmer (1928) agreed but believed it to have been chalk-enriched by the action of the Chalky Boulder Clay ice. West & Donner (1956), pp. 72, 81), on the other hand, interpreted highly calcareous till typical of the Marly Drift at Corpusty (TG 120288) as exceptionally chalky Lowestoft Till. Straw (1965) equated it with the Calcethorpe Till of Lincolnshire and with chalky tills in the Breckland, and thought it was of Gipping age. Banham *et al.* (1975) considered the Marly Drift to consist of Cromer and/or Lowestoft matrices highly enriched with chalk.

### *North Sea Drift* (Harmer 1909)

This term was introduced by Harmer to include the Cromer Tills and the Norwich Brickearth (figure 1). It has been used by many later authors in this sense but sometimes to refer only to the Cromer Tills, with or without the associated glacifluval deposits. In the present instance only till members are considered.

### *Norwich Brickearth* (Harmer 1902)

Sandy, non-calcareous or feebly calcareous, brown tills; north and east Norfolk.

Woodward (1881) referred to the 'Norwich brickearth' as a local variant of the 'Stony Loam or Brickearth (Contorted Drift)', a division of the Lower Glacial (Wood & Harmer 1968). Harmer (1902) used the modern form Norwich Brickearth for the inland brown loams in north-east Norfolk that he considered to pass laterally into the Contorted Drift of the north Norfolk coast and the lower till at Corton. Boswell (1931) believed that the Norwich Brickearth and the Lowestoft Till represented successive glaciations but Cox & Nickless (1972) have shown them to be penecontemporaneous in the Norwich area.

### *Wragby Till* (Straw 1966, 1969)

Clay-rich usually dark-coloured calcareous tills similar in appearance to the Chalky Boulder Clay (Lowestoft Till) of East Anglia; Lincolnshire between the Wolds and the River Witham and thence northwards to Brigg (TA 0007) (figure 1).

The Wragby Till as defined by Straw seems to correspond exactly with the Chalky Boulder Clay of the same area recognized by Wood (1880) and Jukes-Brown (1885). Harmer (1909, 1928) termed it 'Chalky-Kimmeridgian' to distinguish it from the 'Chalky' Boulder Clay of the Wolds, the Calcethorpe Till of Straw, but believed both tills to be contemporaneous. The name Wragby Till is preferred since it avoids ambiguity.

## Appendix 2. Methods of mechanical and mineralogical analysis

### (*a*) *Calcium carbonate*

Carbonate in the fraction containing particles less than 2 mm in diameter was measured on duplicate finely ground samples by Collins' calcimeter and expressed as calcium carbonate since there was no evidence for the presence of appreciable amounts of other carbonates.

Carbonate was also measured in individual size fractions separated from the bulk matrix by wet sieving and sedimentation (figure 4F).

### (*b*) *Mechanical analysis*

After removal of most of the stones by hand picking, the air-dry till matrix was mechanically disaggregated with a wood pestle, with the minimum of force, and the fraction containing particles smaller than 2 mm in diameter was separated by hand sieving. Although such a separation is arbitrary, if carefully performed it is adequately reproducible and appears to have little influence on the particle size distribution of the sieved material.

A sample consisting of 30 g of the above fraction (particles smaller than 2 mm) was treated with excess molar acetic acid, buffered at pH 3 with sodium acetate, to remove carbonate. After being washed free of acid and salts it was dispersed by mechanical shaking in 0.1 % Calgon buffered at pH 8 with sodium carbonate. The fractions containing particles 20–6, 6–2 and smaller than 2 μm in diameter were estimated by gravity settling (Stoke's Law) and pipette sampling. All material consisting of particles smaller than 20 μm was removed by repeated decantation, the residue was dried and the fractions 2000–1000, 1000–500, 500–210, 210–105, 105–63 and 63–20 μm were measured by mechanical sieving. Size fractions were expressed as percentages of their own total (i.e. the insoluble residue) and plotted as cumulative composition curves as exemplified by figure 4.

In contrast to standard pedological practice, samples were not treated with hydrogen peroxide to remove organic matter as this was not present in significant amounts. Preliminary trials showed that measured mechanical compositions were the same whether peroxide was used or not.

Small amounts of iron oxides, and sometimes gypsum, are dissolved during analysis and thus not accounted for, but the quantities are considered to be negligible for present purposes.

### (*c*) *Heavy minerals*

Heavy minerals in the fraction containing particles 105–63 μm in diameter were separated by centrifuging in bromoform, and up to 500 grains were identified and counted by standard petrographic methods. Coarser fractions were found to be insufficiently diagnostic, and finer to require too much time for counting in view of the large number of samples.

Opaque minerals were expressed as percentages by number of the total heavy mineral assemblage, and non-opaques as percentages of their own total.

Although it has been claimed (Solomon 1932*a*, *b*) that certain varieties of the main heavy minerals, such as pink garnet or blue amphibole, are characteristic of particular tills in eastern England, this is not borne out when detailed quantitative studies are made of specified size fractions. Such varieties are normally present in numbers too small to be used statistically and the abundance of pink garnet seems to depend on particle size. In some cases, therefore, counts were made of groups of heavy minerals likely to have had similar parageneses rather than of individual species, for example, all garnets were counted together, zoisite and clinozoisite were included in the epidote group, and chlorite in the mica group (table 2).