Clay mineralogy of the Cretaceous strata of the British Isles

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ABSTRACT: The clay mineralogy of the Cretaceous strata of the British Isles is described and discussed within its lithostratigraphical and biostratigraphical framework using published and unpublished sources as well as 1400 new clay mineral analyses. The regional clay mineral variation is described systematically for the following strata:

(1) Southern England − Purbeck Limestone Group (Berriasian/Ryazanian; Lulworth and Durlston formations), Wealden Group (Valanginian−Barremian/Aptian; Ashdown, Wadhurst Clay, Tunbridge Wells Sands, Grinstead Clay Member, Wealden Clay, Wessex and Vectis formations), Lower Greensand (Aptian−Lower Albian; Atherfield Clay, Hythe, Sandgate, Folkestone Sands, Ferruginous Sands, Woburn Sands and Faringdon Sponge Gravels formations), Selborne Group (Middle−Upper Albian; Gault Clay and Upper Greensand formations) and the Chalk Group (Cenomanian−Lower Maastrichtian).

(2) Eastern England − Cromer Knoll Group (Ryazanian−Upper Albian; Speeton Clay, Spilsby Sandstone, Sandringham Sands, Claxby Ironstone, Tealby, Roach Ironstone, Dersingham, Carstone and Red Chalk (or Hunstanton Red Limestone) formations).

(3) Scotland − Inner Hebrides Group (Cenomanian−Campanian; Morvern Greensand, Gribun Chalk, Coire Riabhach Phosphatic Hibernian Greensands formations).

(4) Northern Ireland − Hibernian Greensands (Cenomanian−Santonian) and Ulster White Limestone formations (Santonian−Lower Maastrichtian).

The stratigraphical patterns of clay mineral variation divide naturally into two types; firstly, the more complex pattern of the Lower Cretaceous strata and secondly, the simple pattern of the Upper Cretaceous. Clay mineral variations in the non-marine and marine Lower Cretaceous strata of England are best explained by the interplay of two main clay mineral assemblages between which all gradations occur. The assemblage which dominates the main clay formations consists of mica, kaolin and poorly defined mixed-layer smectite-mica-vermiculite minerals, and sometimes includes vermiculite and traces of chlorite. It is dominantly of detrital origin and detailed evidence indicates it is derived largely from the reworking of Mesozoic sediments although ultimately from weathered Palaeozoic sediments and metasediments. Although mainly of detrital origin, this assemblage contains a persistent component that formed coevally with the approximate depositional age of its host sediment. Whether this component is of soil origin or was neoformed in the sediment shortly after deposition is unclear. There is little firm evidence indicating the sources of this clay mineral detritus. However, in the strata of the Wealden Group of southern England, mineral trends suggest three sources; one of these was to the west (Cornubian Massif), another must have been the Anglo-Brabant landmass. In the Selborne Group (Middle−Upper Albian) and in the overlying Lower Chalk (Cenomanian) where this assemblage makes its last appearance in the Cretaceous of England, there is good evidence of easterly and south-easterly sources.

The second main assemblage tends to be largely monomineralic, and usually dominated by smectite with or without small amounts of mica; less frequently, kaolin, berthierine or glauconite *sensu lato* is the sole or dominant component. It is considered to be of volcanogenic origin, derived from the argillization of volcanic ash under different conditions of deposition and diagenesis. The

source of the ash in Berriasian−Aptian times seems to have been an extensive volcanic field in the southern part of the North Sea and in the Netherlands, whereas in the Albian (and extending into the Cenomanian) a westerly source dominated. The current controversy about the role of climate or pattern of volcanic activity controlling the clay mineral stratigraphy of the Lower Cretaceous is reviewed.

In the lower part of the Upper Cretaceous strata of England, Scotland and Ireland, sand-grade glauconite is particularly abundant. Much of it represents the glauconitization of pene-contemporanous volcanic ash, possibly of basaltic origin, associated with continental breakup and the opening up of the Atlantic Ocean and the earliest stages in the development of the Hebridean Tertiary Igneous Province. The Upper Cretaceous Chalk facies of England and Ireland is dominated by a smectite-rich clay assemblage containing mica, and the various hypotheses for its origin (detrital, neoformation, volcanogenic) are reviewed in the light of available mineralogical, chemical and geological data.

The Cretaceous was a period of dramatic geological change. The stratigraphical and regional variations in the clay mineralogy of its strata provide a unique insight into the changing palaeogeography, climates, detrital source areas, soil types, volcanism and depositional conditions. The British Isles were located on the western margin of the Eurasian continental plate during the time that witnessed enhanced volcanism and other major regional geological events leading up to the rapid opening of the Proto-Atlantic Ocean and the exceptionally high sea levels and possibly greatly enhanced atmospheric carbon dioxide of the Late Cretaceous. The most spectacular of the clay mineral changes occurs in the mid-Cretaceous. Here a complex, regionally controlled pattern of clay mineral assemblages that characterizes the Lower Cretaceous suddenly switches to one dominated by smectite which characterizes the Upper Cretaceous. Closely associated with this smectite-rich assemblage is the appearance of the very pure coccolithic Chalk facies. Both the Chalk and its smectite-rich clay assemblages dominate the Upper Cretaceous strata of the British Isles and much of western Europe for a period of 30 Ma. No less significant is the exceptional abundance of sand-grade glauconite and its dominance over berthierine as the main Fe-rich clay mineral.

Perrin's (1971) monograph describes the general range of clay mineral assemblages to be found in many of the Cretaceous formations although in some (e.g. Purbeck Limestone Group, Pre-Aptian strata of the Spilsby Basin) little information was available. At the time of publication very little work had been done on the regional and stratigraphical variations of clay mineralogy within particular formations. Subsequently two lines of research developed, one concerned with the origin of the detrital clay mineral assemblages, the other with the role of volcanism in the development of mono-minerallic or nearly monominerallic clay assemblages (smectite, kaolin, berthierine, glauconite). Work by Parker (1974) and Sladen (1980) on the pre-Aptian clays of England led to Sladen's (1983) climate-control hypothesis to explain the variations in the detrital clay mineral assemblages − the assemblages rich in smectite and mixed-clay minerals came from vertisols developed in lowland areas during period of warmer, drier climates, whereas those enriched in kaolin and vermiculite were characteristic of the soils of wetter, cooler climates in highland areas. This hypothesis has played an important role in the palaeoclimatic interpretation of the Early Cretaceous in western Europe (Hallam, 1984; Hallam et al., 1991; Ruffell & Batten; 1990; Ruffell & Rawson, 1994). The volcanogenic investigations proved that the pure smectite clay assemblages of the Aptian fullers' earths were argillized volcanic ash (Jeans et al., 1977) and that a considerable proportion of the sand-grade glauconite represents altered lava fragments (Jeans et al., 1982). It was also suspected, but without definite proof, that many of the clay mineral assemblages that were exceptionally enriched in smectite, kaolin and berthierine owed their origin to the argillization of volcanic ash under different physico-chemical conditions (Jeans et al., 2000). The same smectite (or mixed-layer clay)-rich assemblages were being interpreted as either indicating a drier, warmer palaeoclimate or a period of enhanced volcanicity and fallout of

volcanic ash. Definitive evidence is weak for both explanations, since no palaeovertisols have been recognized in western Europe nor is there direct evidence of the pre-argillization state of any volcanic material! Jeans *et al*. (2005) recognized specific volcanogenic horizons within the Purbeck Limestone Group, one of the main formations of contention.

This paper reviews all clay mineral data known to the author from the Cretaceous strata of the British Isles and it provides an explanation and discussion of the regional and stratigraphical variation. It is based upon published sources, unpublished PhD theses, and 1400 new clay mineral analyses (Tables 1−24 in the Appendix) that have been undertaken to fill in some of the major gaps in our knowledge.

CLAY MINERAL ANALYSIS

The clay mineral data in this account come from published and unpublished investigations. These studies range from attempts to define the precise nature of the clay minerals and their relative proportions (e.g. Weir & Catt, 1965; McCarty *et al*., 2004) to the use of the general changes in clay mineral assemblages as a tool for stratigraphic correlation (e.g. Knox, 1991) or climatic interpretation (Hallam *et al*., 1991). The methods of sample preparation and analysis used to obtain these different objectives vary considerably. They include the separation of a clay fraction defined by its particle size (usually <2 μm) and its subsequent examination by X-ray diffraction (XRD) analysis in combination with various chemical and heating tests. Certain potential sources of unpublished data have been excluded from this review because of their incompatibility in regard to their methods of sample preparation (use of strong acids; undefined particle size of clay fraction) for XRD analysis. The method used for the new clay mineral data in Tables 1−24 is based on the XRD analysis of the <2 μm clay fraction in the untreated state, then after glycerolation and heat treatments at 400ºC (440ºC prior to 1982) and 550ºC (Jeans, 1995). Less-detailed analyses (e.g. Knox, 1991) may involve just the untreated and a glycol-treated sample so as to identify the presence of expandable minerals. Some authors restrict heat treatments to a single one at ~550ºC. The temperature used by various authors for the first heat treatment may vary from 300ºC to 440ºC.

Clay mineral identification is usually at group level and does not generally provide evidence to differentiate between dioctahedral and trioctahedral sheet occupancy. Most authors assume that the kandite group and mica group minerals are dioctahedral and describe them as kaolinite (kaolin) and illite (= white mica) respectively. Smectite, smectite-illite or mixed-layer clay minerals are used to describe the more or less expandable minerals (with glycol or glycerol) which collapse to ~10 Å on heating. Knox (1991) uses the term 'mixed-layer' to describe the minerals (presumably smectite and smectite-illite) in the Speeton Clay that expand on glycerolation; his method did not involve heating. Once again, these smectite-illite minerals are assumed to be dioctahedral. Only occasionally (e.g. Weir & Catt, 1965; McCarty *et al*., 2004) is there sufficient evidence to allow a more precise identification.

The clay mineral terminology used in the text and in Tables 1−24 to describe the new data is as follows. **Mica** is used to describe what most authors refer to as illite (but see Perrin, 1971; Weir & Catt, 1965). **Kaolin** is used for the kandite mineral stable at 400ºC. **Berthierine** is used for a kandite which displays considerable loss of intensity on heating to 400ºC. There are difficulties in identifying berthierine since its XRD pattern is little different from that of kaolin because of the overlap of the 001 and 002 peaks. However, there is considerable intensity loss in the berthierine XRD pattern on heating to 400ºC. This changes the profile of the combined 7.1 Å and 3.56 Å peaks and reveals that a double peak is present in the unheated sample, where both kaolin and berthierine are present (Figs 12d, 13a).

Clay minerals with 001 peaks between 10 and ~18 Å, which collapse to ~10 Å when they are heated to 400ºC, are referred to as **collapsible minerals**. They consist of smectite and vermiculite, as well as the mixed-layer minerals consisting of mica, vermiculite and smectite. Four groups of collapsible minerals are recognized in XRD patterns of glycerolated clay samples. (1) **Smectite**, peak between 14 and 18 Å (e.g. Figs 32c, 44d); (2) **vermiculite**, peak at ~14 Å (e.g. Figs 12c, 20b, 32a); (3) **mixed-layer mineral**; peak between 10 and 14 Å (e.g. Fig. 7e; Fig. 38, samples 6422, 6451); and (4) **poorly defined minerals**, no definite peak but displaying enhanced background between 10 and 18 Å which collapses to ~10 Å on being heated to 400ºC (e.g. Figs 19a, 20a). Cretaceous

clay assemblages always contained poorly defined minerals usually mixed with some of the other types of collapsible minerals. The collapsible minerals of a particular sample may be referred to as **smectitic** or **vermiculitic**. If the smectite component is very dominant (as in clay assemblages from the Aptian fullers' earths and the Chalk Group), the collapsible minerals may just be referred to as smectite.

Mixed-layer smectite-chlorite and **vermiculite-chlorite** display variable glycerol-expandability, and on heating collapse to $10-14$ Å. **Chlorite** (in trace amounts) is identified by a ~14 Å peak in the 550ºC XRD pattern. **Glauconite** is used to describe either green grains or green clay assemblages consisting predominantly of mica and collapsible minerals; it does not indicate necessarily the presence of the mineral glauconite (*sensu stricto*).

Methods of quantifying the clay mineral assemblages vary between different investigators. The simplest are based upon peak height or peak area ratios of characteristic XRD peaks before and after various tests and their comparison either with external binary mixtures of standard minerals (Jeans, 1968) or by using standard relative intensity factors for different minerals (Tables $1-24$). More detailed analyses (Weir & Catt, 1965; Robertson, 1961; McCarty *et al.*, 2004) involve bulk or selective chemical analysis and the use of idealized structural formulae for the component minerals. All clay mineral analyses are of a more or less semi-quantitative nature unless the various components of clay mineral assemblages can be separated or individually characterized. The clay preparations used for XRD analysis typically contain many millions of crystals derived from many different sources and, therefore, even within clay mineral groups relatively little homogeneity is to be expected except under very particular circumstances.

Detailed investigations of clay mineral assemblages are restricted to the commercially important fuller's earths (Aptian) which are dominated by Ca^{2+}-montmorillonite (Robertson, 1961; Perrin, 1971), the typical Chalk assemblages which are dominated by montmorillonite with varying amounts of mixed-layering with mica (illite) and with discrete mica (Weir & Catt, 1965; Deconinck & Chamley, 1995), and the complex mixture of glauconite (*sensu stricto*), nontronite and various mixed-layer clay minerals reported from the Ferruginous Sands of the Isle of Wight (McCarty *et al.*, 2004).

SEDIMENTARY SETTING

Cretaceous sedimentary rocks crop out and form the shallow sub-crop in England, Scotland and Ireland (Fig. 1). In England the sediments range in age from Early to Late Cretaceous, whereas in Scotland and Ireland they are only of Late Cretaceous age. The palaeogeography and general stratigraphy of the Cretaceous strata are shown in Figs 2 and 3, respectively. Dominating the palaeogeography of the earliest part of the Cretaceous (Berriasian–Barremian) was the emergent London Platform − the westward extension of the Anglo-Brabant massif. This land mass separated areas of marine deposition (now preserved in the Spilsby and Cleveland Basins and also in the southern part of the North Sea Basin) from an area of non-marine deposition preserved in the Wealden, Wessex and Paris Basins. The non-marine strata of southern England consist of clays, marls, limestones and evaporites of fresh-water and marine facies (Purbeck Limestone Group) overlain by deltaic strata (Wealden Group) dominated by silts, clays and lesser sandstones of freshwater, brackish and marine facies. The marine strata (Cromer Knoll Group) consist of sandstones, silts, oolitic ironstone, oolitic siltstone and limestone in the Spilsby Basin and of clays in the Cleveland Basin. The Spilsby Basin is considered to have been separated from the Cleveland Basin by a spur of the emergent Welsh-Midland massif. There was limited connection between the marine and non-marine areas of deposition through the Bedford Strait around the west end of the London Platform.

In late Barremian or earliest Aptian times marine conditions spread over the whole of southern England with the deposition of shallow water sands (Lower Greensand Group, Aptian−Mid Albian) containing a considerable volcanoclastic component. There is no evidence that these sands extended across the London Platform, which may have persisted as an area of shallows and low islands separating the southern area of marine deposition from that of eastern England. The marine sediments of the Spilsby and Cleveland Basins, equivalent in age to the Lower Greensand Group, retain their pre-Aptian lithofacies.

The oldest strata preserved continuously over the whole of southern and eastern England, including the London Platform and the Market Weighton High, are very varied in lithofacies. In southern
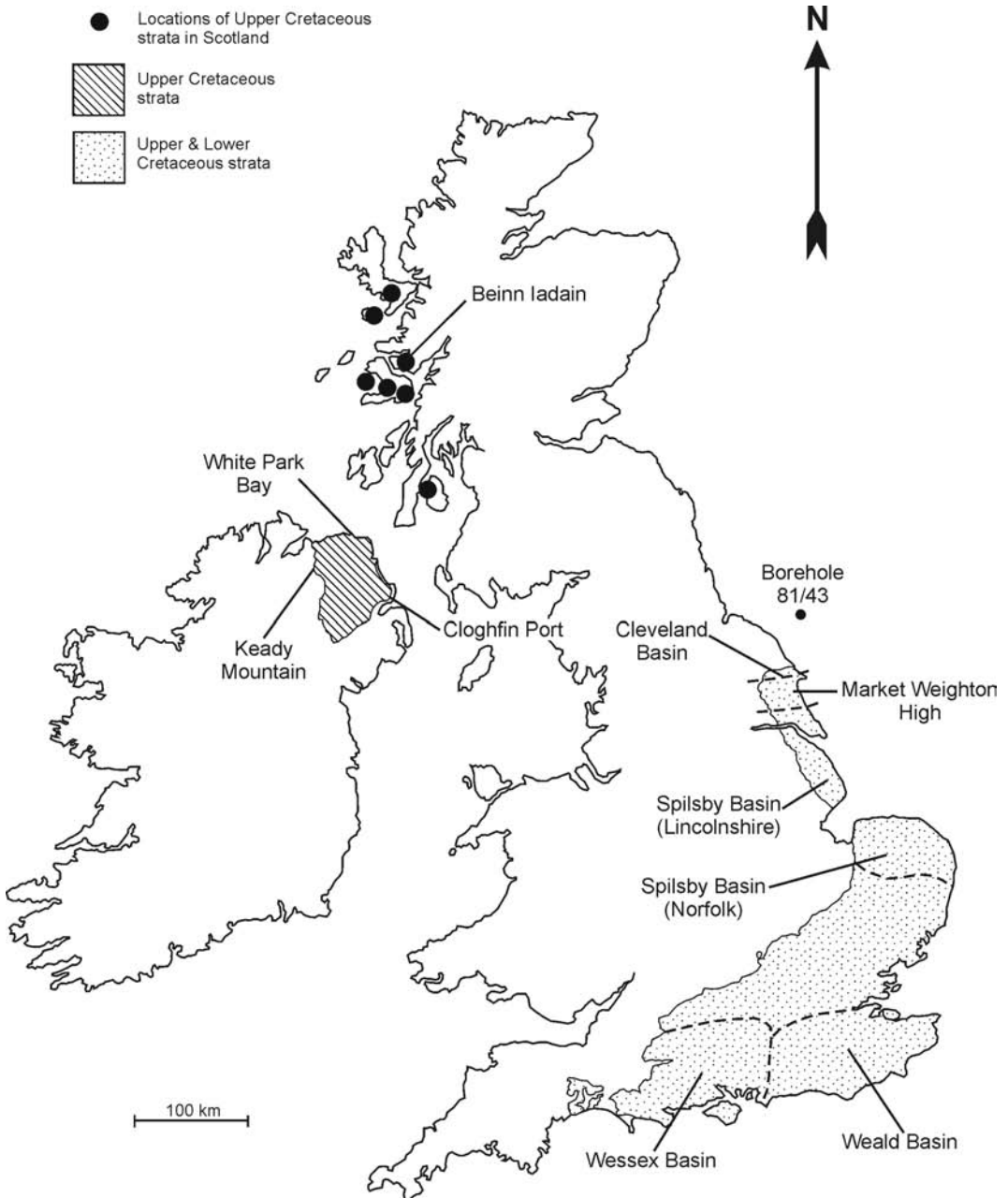
Fig. 1. On-shore distribution of Cretaceous strata in the British Isles.

England these are referred to as the Selborne Group (Middle–Upper Albian), which consists of the clay- and silt-rich Gault Formation, overlain by the sand-rich Upper Greensand Formation – both formations may contain considerable amounts of volcanogenic material. The Gault dominates in southeast England, but westwards it is increasingly replaced by the Upper Greensand. In Bedfordshire, Cambridgeshire and the southern part of Norfolk, the Selborne Group is represented only by the

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a. Mid - Hauterivian

Land area
non-marine deposition
marine deposition

Faeroe Rift
Shetland Platform
Rockall Rift
Hebrides Platform
Scottish Landmass
Rockall Rift
Cleveland Basin
Pennine Landmass
Irish Landmass
Splsby Basin
Welsh Landmass
North Celtic Sea basin
Anglo-Brabant Landmass
South Celtic Sea basin
Wessex Basin
Weald Basin
Cornubian Massif
Channel Basin
Western Approaches Trough
Amorica

b. Late Aptian

Faeroe Rift
Shetland Platform
Rockall Rift
Scottish Landmass
Rockall Rift
Cleveland Basin
Market Weighton High
Irish Landmass
Spilsby Basin
Welsh Landmass
North Celtic Sea Basin
Anglo-Brabant Landmass
South Celtic Sea Basin
Weald Basin
Cornubian Massif
Channel Basin
Western Approaches Trough
Amorica
Paris Basin

c. Early Cenomanian

d. Late Campanian

	STAGE	CLEVELAND BASIN Speeton, Borehole 81/43	SPILSBY BASIN Lincolnshire	Norfolk	WEALD BASIN Kent, Surrey, Sussex	WESSEX BASIN Isle of Wight, Dorset

FIG. 3. Stratigraphical and regional lithofacies variations in the Cretaceous strata of the British Isles.

Gault. In north Norfolk, the Gault passes into the Red Chalk or Hunstanton Red Limestone Formation (Middle−Upper Albian) which extends thro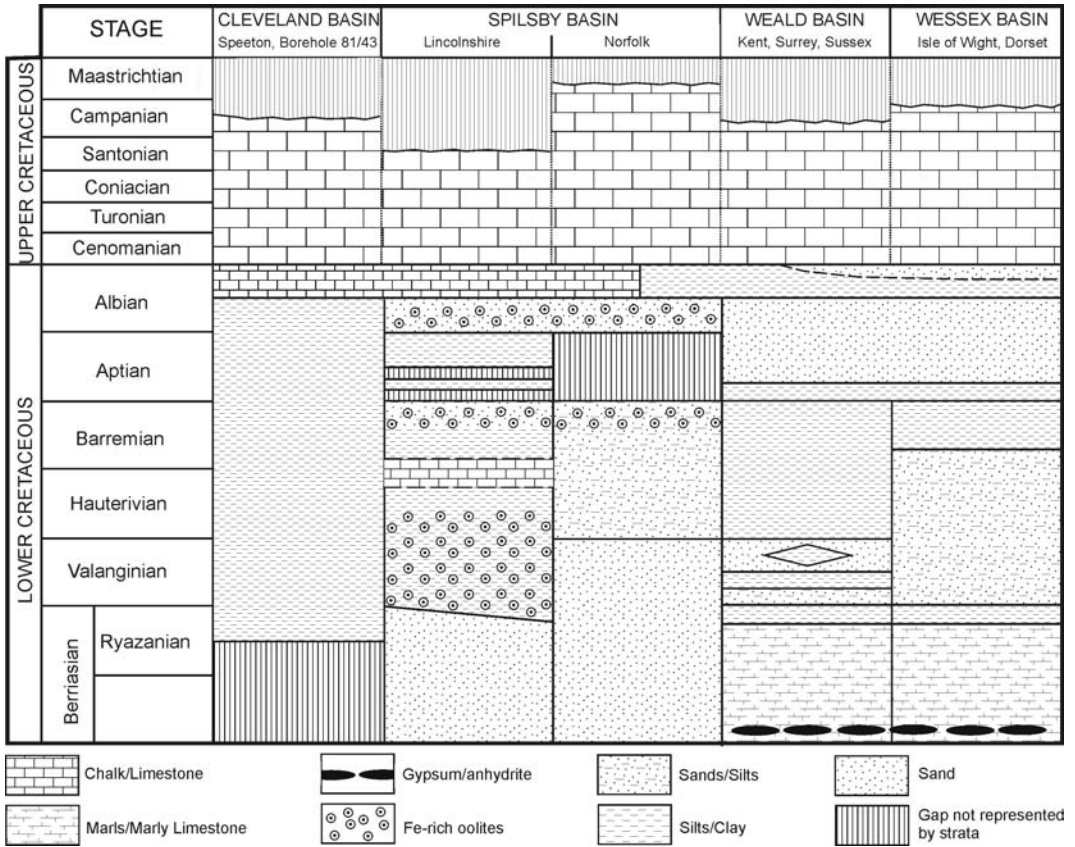ughout eastern England. Over the whole of southern and eastern England, the Selborne Group and the Red Chalk are overlain by the Upper Cretaceous Chalk Group (Cenomanian-Campanian or Lower

Maastrichtian) consisting of very pure offshore marine limestones, dominated by the remains of the Coccolithophoridae, and characterized by the absence of obvious continental silicate detritus.

In southern England, the Selborne Group is overlain by the Chalk Group (Cenomanian to low Upper Campanian); in eastern England (Norfolk)

FIG. 2 (*facing page*). Cretaceous palaeogeography of the British Isles (based on Hancock & Rawson, 1992). (a) Mid-Hauterivian. Marine and non-marine areas of deposition are separated by the Anglo-Brabant landmass (London Platform). (b) Late Aptian. The London Platform has been reduced in relief and partly submerged cutting off the main source of detrital clay to southern England. Marine deposition of sandy sediments in southern England with volcanic ash coming from volcanic centres in the southern part of the North Sea and Holland. (c) Early Cenomanian. Land areas much reduced in extent under the rising sea level. A westerly volcanic source, first evident in late Albian times, provides ash to the Lower Chalk sea. Clay detritus from the Brabant or Central European massif is carried by marine currents into south-east England. Marine sedimentation starts in the Hebridean Province where it is associated with submarine (?) volcanism. (d) Late Campanian. All local sources of clay detritus have been submerged. The small clay contents of the Chalk sediment are derived largely from trophospheric silicate dust and the occasional shower of fine-grained ash from distant volcanic centres.

the Chalk Group extends up to, and includes, part of the Lower Maastrichtian. At outcrop in Yorkshire the Chalk Group extends up to the lower part of the Lower Campanian and to an unknown higher stratigraphical level at subcrop below Holderness.

In Scotland and Ireland the earliest Cretaceous strata (Hibernian Greensand Group) are of Cenomanian and Turonian age and of sandy lithofacies. These are overlain by a thin succession of indurated chalky limestones, the Ulster White Limestone Formation (Santonian-Lower Maastrichtian) which lack appreciable amounts of continental silicate detritus.

CLAY MINERAL STRATIGRAPHY

The Cretaceous strata contain two main clay mineral assemblages (Fig. 4). One is characterized by kaolin, mica and poorly defined collapsible minerals and is referred to here as the **kaolin-mica assemblage**; the other is characterized by smectitic collapsible minerals and mica, with kaolin being absent or only present in trace amounts and is referred to as the **smectite-mica assemblage**. Other minerals may also be present either in trace amounts or locally abundant. These include chlorite, vermiculite, berthierine, glauconite, palygorskite, clintoptilolite-heulandite zeolites, opal-CT and quartz. In the main occurrence of Cretaceous strata, in southern and eastern England, the clay mineralogy is relatively well known from published and unpublished data. Here the two main clay assemblages display a strikingly close relationship to the stratigraphy. The kaolin-mica assemblage is restricted very largely to the Lower Cretaceous, whereas the smectite-mica dominates the strata of Upper Cretaceous age. Locally in the Lower Cretaceous sediments, the kaolin-mica clay assemblage is replaced by the smectite-mica. This occurs
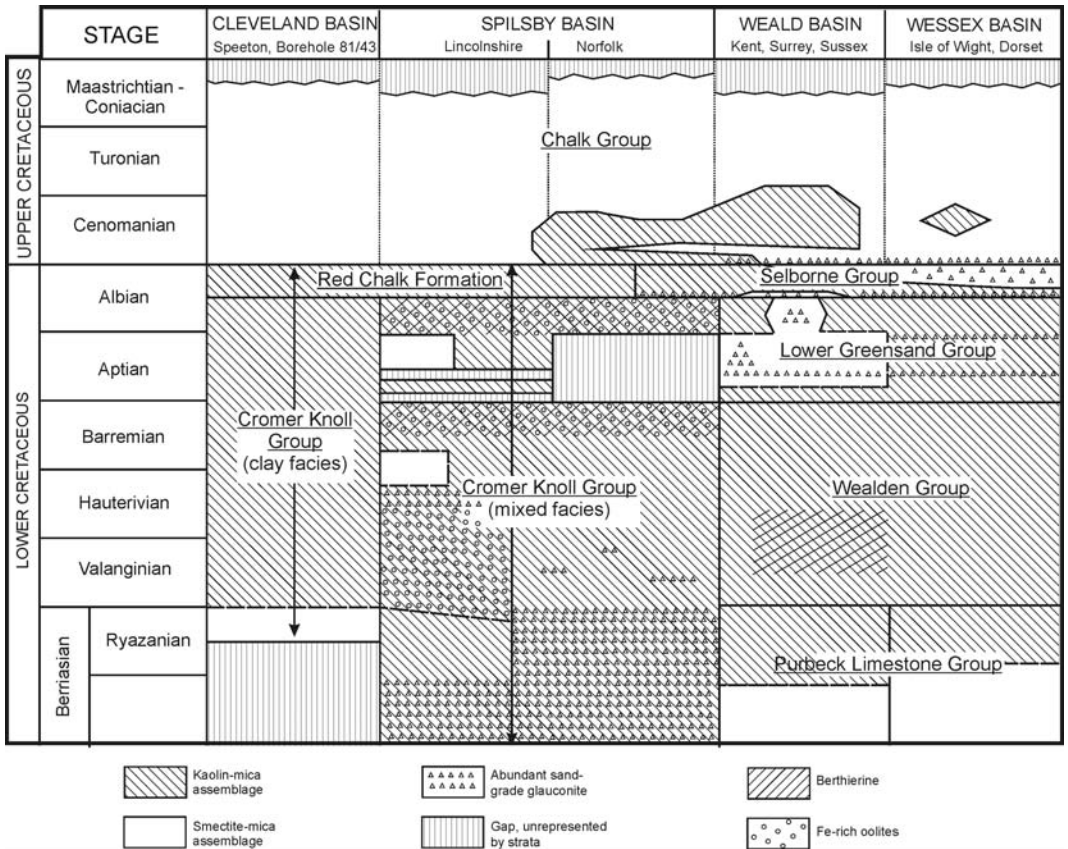

FIG. 4. Stratigraphical and regional clay mineral variations in the Cretaceous strata of the British Isles.

in the Ryazanian part of Cromer Knoll Group (Cleveland Basin), the Upper Hauterivian and Lower Barremian beds of the Cromer Knoll Group (Spilsby Basin), the lower half of the Purbeck Limestone Group, the Lower Greensand Group (Wealden and Wessex Basins) and the Selborne Group (Wealden and Wessex Basins). The transition from the predominantly kaolin-mica assemblage of the Lower Cretaceous to the smectite-mica assemblage takes place within the Cenomanian strata forming the basal part of the Upper Cretaceous. The last traces of the kaolin-mica assemblage occur in the basal Turonian of the Wealden Basin, although further to the east in the Paris Basin they extend up into the main part of the Turonian strata.

Outside southern and eastern England only limited clay mineral data are available. In Northern Ireland the marine Hibernian Greensands Group and the overlying Chalk Group (Ulster White Limestone Formation) contain smectite-mica assemblages. In Scotland kaolin is present in some assemblages whereas it is absent in others: there are so few analyses available that no general pattern can be discerned.

There is little doubt that the kaolin-mica assemblage dominated by mica, kaolin and poorly defined collapsible minerals is mainly of detrital origin derived from the reworking of coeval soils and older strata in the source areas. There is, however, much less certainty about the origin of the smectite-mica assemblage and the less common clay mineral assemblages which may be rich in glauconite, berthierine, smectitic minerals and kaolin. To what extent do they represent the interaction between concentrations of either volcanic ash or continental derived minerals and amorphous gels and the different physico-chemical milieux of deposition and diagenesis? Sand-grade glauconite is an abundant component of many Lower Cretaceous marine sandstones: it is often the main component of the basement beds of the Selborne Group (Upper-Middle Albian) and of the Chalk Group of southern England. Glauconite is also abundant in the Morvern and Hibernian Greensands (Cenomanian-Turonian) in Scotland and Ireland. Many of these glauconite sandgrains resulted from the glauconization of fragments of volcanic glass or volcanic rocks on the Cretaceous seafloor.

In the Lower Greensand there are seams (referred to as fullers' earths) up to 3 m thick consisting of Ca^{2+}-montmorillonite which are the argillization products of marine deposits of volcanic ash of trachytic composition. In the Cromer Knoll Group of the Cleveland Basin, in the Purbeck Limestone Group of the Wessex Basin, in the Wealden Group of the Wealden Basin and in the Chalk Group, there are thin horizons containing nearly monominerallic clay mineral assemblages which are interpreted as the argillization products of airfall volcanic ash from individual subaerial eruptions. In some instances there is collaborative evidence, in others none.

There is evidence in the sediments of the Selborne Group (Middle−Upper Albian) that volcanic ash, washed in from an adjacent landmass, was responsible for clay mineral assemblages rich in smectitic collapsible minerals that characterize the near-shore facies. The origin of the smectite-mica clay mineral assemblage of the Chalk Group is more problematic. There is little doubt that the smectitic collapsible mineral and the mica was predominantly neoformed in the Chalk sediment. However, there is little collaborative evidence to decide its pre-depositional origin. Is the Chalk's smectite-mica assemblage derived: (1) from the argillization products of fine volcanic ash and other mineral dust making up the background atmospheric fallout in a very distal marine setting out of the range of continental detritus; or (2) chemically through neoformation reactions involving minute amounts of highly weathered continental detritus that reached the depositional site of the Chalk; or (3) derived from smectite-rich soil clays developed on the continental source areas as a result of higher water tables caused by the rise in sea level in the early part of the Upper Cretaceous?

PRE-APTIAN STRATA

Lower Cretaceous strata of pre-Aptian age occur at the surface and in subsurface in southern and southeast England (Wealden and Wessex Basins), in north Norfolk and east Lincolnshire (Spilsby Basin) and in east Yorkshire (Cleveland Basin). The pre-Aptian beds of Norfolk, Lincolnshire and Yorkshire are marine, whereas those in southern and southeast England are essentially non-marine, ranging from freshwater to hypersaline. Separating the marine and non marine areas of deposition was the London-Brabant Massif. The distribution of the pre-Aptian Cretaceous strata is shown in Fig. 5. The overall stratigraphical scheme used in the description of their clay mineralogy is given in Fig. 6.
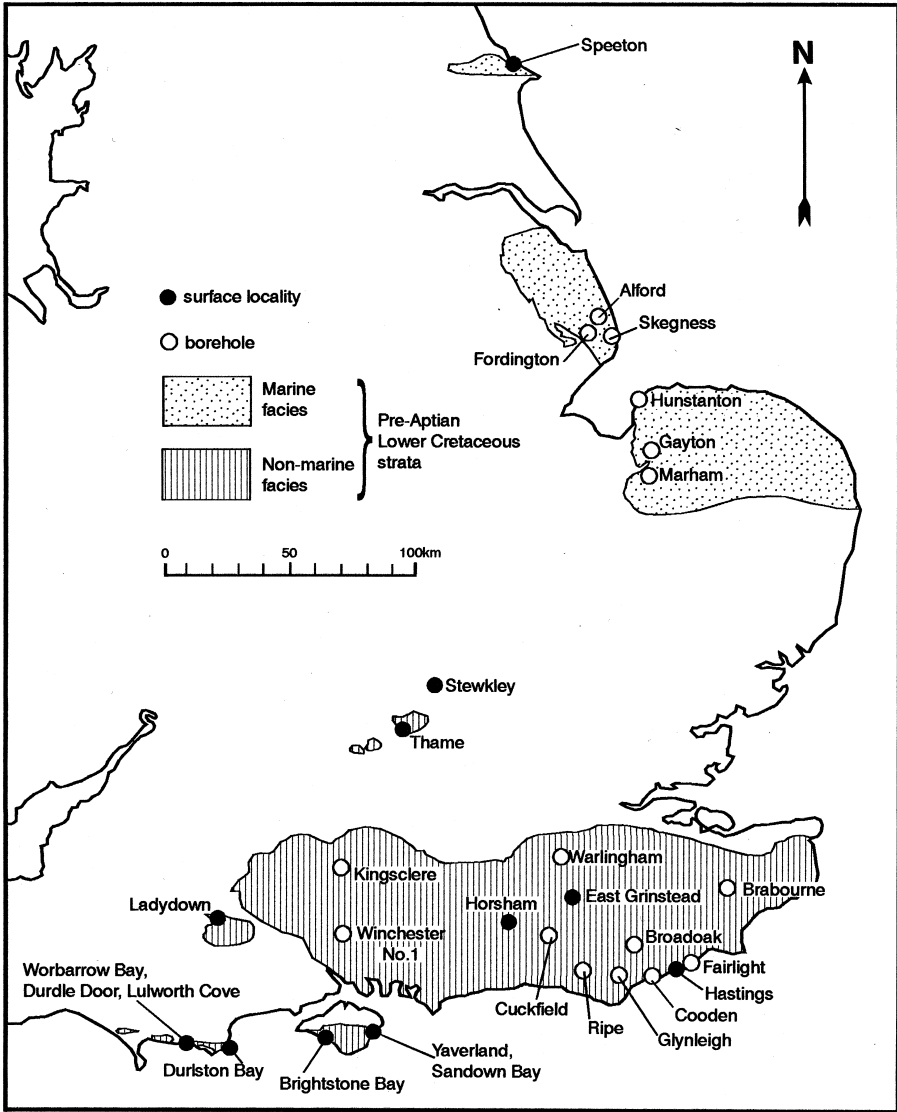
FIG. 5. Outcrop and sub-crop distribution of pre-Aptian Cretaceous strata in England (based on Whitaker, 1985). Boreholes and locations mentioned in the text are shown.

Purbeck Limestone Group

In Dorset, the Purbeck Limestone Group consists of a Lower Lulworth Formation, comprising interbedded limestones, marls, tufa and evaporites (gysum anhydrite, celestite, salt pseudomorphs) with chert nodules and dirt beds at some horizons, and an upper Durlston Formation consisting of limestones, marls and clays which grade lithologically into the overlying Wealden Group. The depositional environments ranged from freshwater to hypersaline. The base of the Cretaceous, in the sense of base of the Tethyan Berriasian Stage, has been placed on charophyte evidence at or near the base of the Cypris Freestone Beds in the lower part of the Lulworth Formation (Feist *et al.*, 1995). On the other hand, the base of the Cretaceous, in the sense of base of the Boreal Ryazanian Stage, is taken at the base of the Cinder Bed, at the base of the Durlston Formation. This presents a continuing problem. The base of the Cretaceous in any sense

STAGE		CLEVELAND BASIN		SPILSBY BASIN		WEALD BASIN		WESSEX BASIN
		Speeton, Borehole 81/43		Lincolnshire	Norfolk	Kent, Surrey, Sussex		Isle of Wight, Dorset & western Outliers

FIG. 6. Stratigraphical scheme used in the description of the clay mineralogy of the pre-Aptian (Berriasian-Barremian) strata in England.

has not yet been formally ratified and is currently under discussion. The clay mineralogy of the basal strata of the Lulworth Formation, which belong in the Jurassic and contain the soil and tufa beds, is discussed in Jeans (2006). In Oxfordshire, the non-marine Whitchurch Sand Formation (Allen & Parker, 1995), which includes the Shotover Ironsands (Taylor, 1959), is considered to equate with the Purbeck Limestone Group.

Previous studies. Perrin (1971) included a single clay mineral analysis from the Purbeck Limestone and six from the Shotover Ironsands. Subsequently, various authors have described the clay mineral stratigraphy of the Purbeck Limestone Group. Sladen (1980) included analyses from Durdle Door ($n = 4$), Lulworth Cove ($n = 6$), Durlston Bay ($n = 60$), Ladydown ($n = 11$), Warlingham Borehole ($n = 10$), Fairlight Borehole ($n = 18$), Broadoak Borehole ($n = 13$), Brabourne Borehole ($n = 8$), Kingsclere No. 1 Borehole ($n = 3$) and Stewkley ($n = 14$). Sladen's analyses demonstrated that the main part of the Purbeck Limestone Group was characterized by clay assemblages dominated by smectite and mica and lacking kaolin, and this was replaced in the upper part by assemblages containing appreciable amounts of kaolin.

Deconinck (1987) described the clay mineral stratigraphy of the Purbeck Limestone Group at Lulworth Cove and Durlston Bay on the south Dorset coast (based upon 57 analyses). He recognized the two main assemblages identified by Sladen (1980) and provided further additional details of their composition. Both assemblages were found to contain minor illite-smectite and chlorite-smectite as well as occasional chlorite. Minor palygorskite was recorded in some assemblages but this has not been confirmed with XRD analysis by more recent researchers (Wimbleon and co-workers in Allen (1998); Jeans *et al.* (2005)), although occasional fibrous crystals, possibly palygorskite, are present in transmission electron microscope (TEM) images of the clay fractions (Fig. 10b). Hallam *et al.* (1991, their fig. 3) summarized earlier work on the clay stratigraphy of the Purbeck Limestone Group and provided some additional analyses from the transitions down into the underlying Portland Limestone and up into the Wealden Group (at Mupe Bay, Dorset). Wimbledon and his co-workers (in Allen, 1998, p. 205) have provided additional clay mineral analyses from the Purbeck Limestone Group at Durlston Bay and from Mupe Bay. Allen (1998, pp. 204–208) has

discussed the possible origins of variations in clay mineral compositions described by earlier researchers. Recently the clay mineral stratigraphy of the Purbeck Limestone Group at Durlston Bay has been re-examined (Jeans *et al.*, 2005). Five beds containing suspected volcanogenic clays have been identified. 118 new analyses made for this investigation form the basis for the present account of the clay mineral stratigraphy of the Cretaceous part of the Purbeck Limestone Group. There are also new analyses of sub-crop samples from the Weald (Table 1).

Current investigation: Wessex Basin. X-ray diffraction patterns of a range of typical clay mineral assemblages are illustrated in Fig. 7. Examples of grain size-related mineralogical variation within the clay assemblages are shown in Fig. 8. The clay mineral stratigraphy of the Cretaceous part of the Purbeck Limestone Group at Durlston Bay, Dorset, is shown in Fig. 9 (see also Jeans *et al.*, 2005, Figs 3, 4). Assemblages are dominated by mica (19−91%) and collapsible clay minerals (1−80%) that display an antipathetic distribution pattern throughout the succession (Fig. 9). However, Bed 224 contains an exceptional clay mineral assemblage and is an exception to the distribution pattern (see below; also Figs 7f, 8f, 10c).

Kaolin (0−39%) is restricted to the upper part of the Purbeck Limestone Group. It is recorded first in Bed 110 (immediately below the Cinder Bed), at a few horizons in the lower part of the Intermarine Beds and then occurs throughout the upper part of these beds and the overlying succession. The nature of the collapsible mineral is quite variable. It is usually smectitic with a more or less well defined 001 peak in the glycerolated state in the range 14.7−18 Å, but most frequently between 16−17.7 Å. A few beds in the kaolin-bearing part of the sequence contain vermiculite. Poorly defined collapsible minerals are dominant in some clay mineral assemblages from the Soft Cockle Beds (47c-51b), Intermarine Beds (113, 114, 121, 132), Scallop Bed (146-151), Corbula Beds (154b, 160, 161, 165, 172, 174c, 177) and Chief Beef Beds (192). Green clays occur in Beds 239 and 241 (Viviparus Beds) (probably equivalent to the Purbeck Marble) which contain smectitic mica.

Samples 91, 98 (Cherty Freshwater Beds), 111b (Cinder Bed) and 224 (Viviparus Beds), with clay assemblages displaying particularly pronounced smectite peaks (14.7−17.3 Å) in the glycerolated

state, as well as sample 239, have been examined in more detail (Jeans *et al.*, 2005). Of these, samples 91, 98, 224 and 239 have aberrant rare earth element patterns indicating a volcanogenic origin. Samples 91 and 98 have particularly high Mg contents suggesting a saponitic composition. Dolomite is present at some horizons between beds 63 (Soft Cockle Beds) and 81 (Marly Freshwater Beds) (Dr T. Clayton, pers. comm.). No dolomite was identified by XRD in Beds 91 and 98 (Cherty Freshwater Beds), but trace amounts could be present and contribute to the Mg contents of the clays.

Sample 224 (Viviparus Beds) displays an enhanced Al, Si and Ti composition. It is exceptionally rich in kaolin (39%) which is probably of authigenic origin derived ultimately from the argillization of volcanic ash. The green glauconitic clay assemblage from Bed 239 (Viviparus Beds) in enriched in Fe and it contains an aberrant *REE* pattern; it is interpreted as volcanogenic in origin (Jeans *et al.*, 2005). The TEM examination of the <0.2 μm fraction of samples 43, 91, 224 and 239 has been carried out by Dr W.J. McHardy (Fig. 10). In samples 239 (green glauconitic clay) and 91 (Mg-rich) selected area electron diffraction (SAED) show doubling of the 060 reflections suggest the presence of both di- and tri-octahedral clay minerals.

Chlorite as a minor component has been recorded in clay assemblages from the Cypris Freestone Beds, Hard Cockle Beds and the lower half of the Soft Cockle Beds (Fig. 9); on heating to 550ºC it displays a ~14 Å peak in the XRD pattern. Irregular mixed-layer vermiculite-chlorite and/or smectite-chlorite occurs in some clay assemblages, particularly between beds 91−129a and 168−238, and was identified by incomplete collapse at 400ºC and 550ºC (Fig. 7d). Palygorskite has not been identified by XRD although Dr McHardy reported (pers. comm.) the presence of occasional fibrous clay crystals in TEM images from Bed 91 (Fig. 10b).

Jeans *et al.* (2005) differentiated between the background smectite-mica assemblage (e.g. Beds 17a, 43, 44) that characterizes the Lulworth Formation and the basal part of the Durlston Formation and the particularly smectite-rich assemblages in Beds 91, 98 and 224. The background assemblage is related to the enhanced fallout of background volcanic ash (Pattern B, Jeans *et al.*, 2000) whereas the smectite-rich assemblages are linked to specific ash showers. Both assemblages
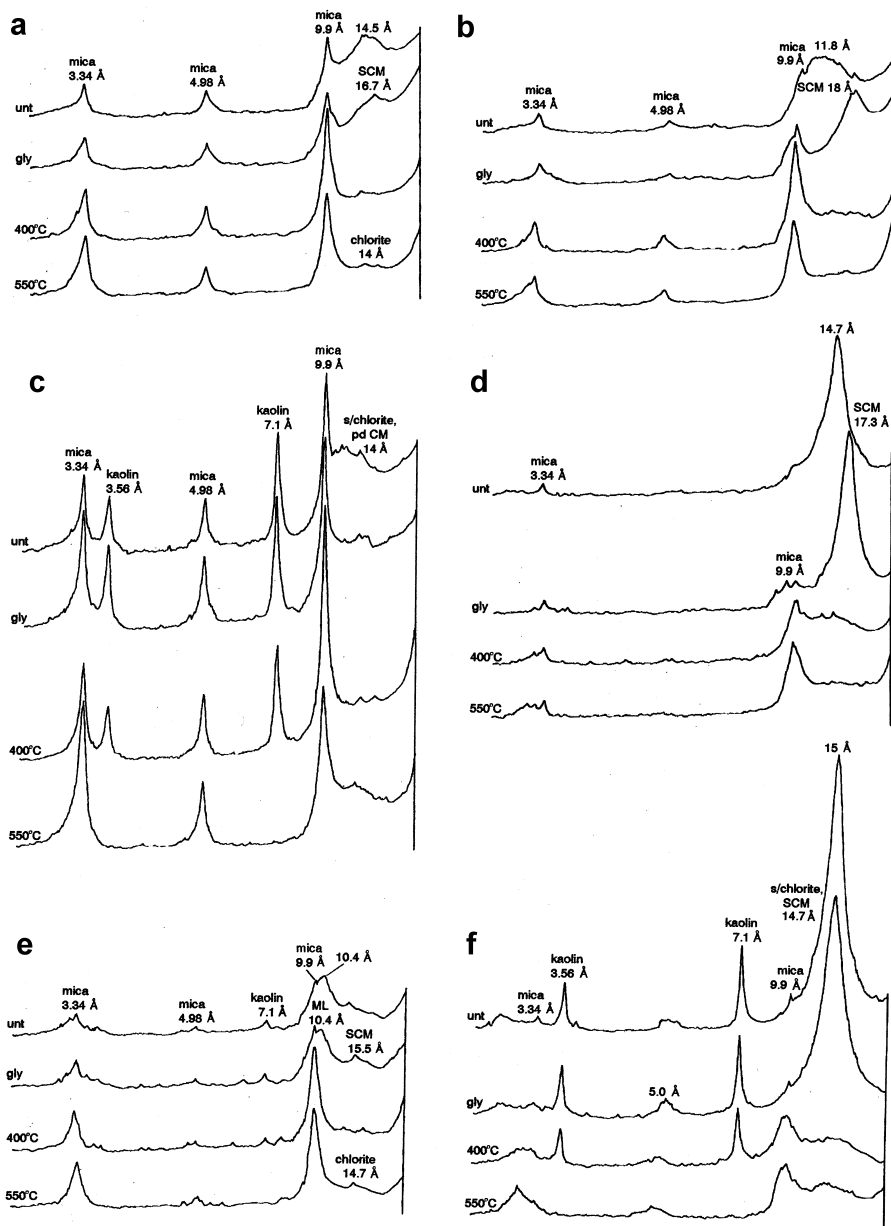
FIG. 7. XRD patterns of clay mineral assemblages (<2 μm) from the Purbeck Limestone Group, Durlston Bay, Dorset. Bed numbering is based on Clements (1993). SCM = smectitic collapsible mineral; pdCM = poorly defined collapsible minerals; s/chlorite = irregular mixed-layer smectite-chlorite; ML = mixed-layer mineral. (a) Smectite-mica assemblage, Bed 43, Soft Cockle Beds, Lulworth Fm. (b) Smectite-mica assemblage, Bed 69, Soft Cockle Beds, Lulworth Fm. Assemblages A and B are considered by Jeans *et al.* (2000) to be a background volcanogenic clay assemblage. (c) Kaolin-mica assemblage with vermiculite of detrital origin, Bed 174C, Corbula Beds, Durlston Fm. (d) Volcanogenic, saponitic smectite-dominated assemblage displaying incomplete collapse on 400°C heating, Bed 91, Cherty Freshwater Beds, Lulworth Fm. (e) Volcanogenic glauconitic assemblage, Bed 239, Viviparus Shales and Marls, Durlston Fm. (f) Volcanogenic smectite-kaolin assemblage, Bed 224, Unio Beds, Durlston Fm.
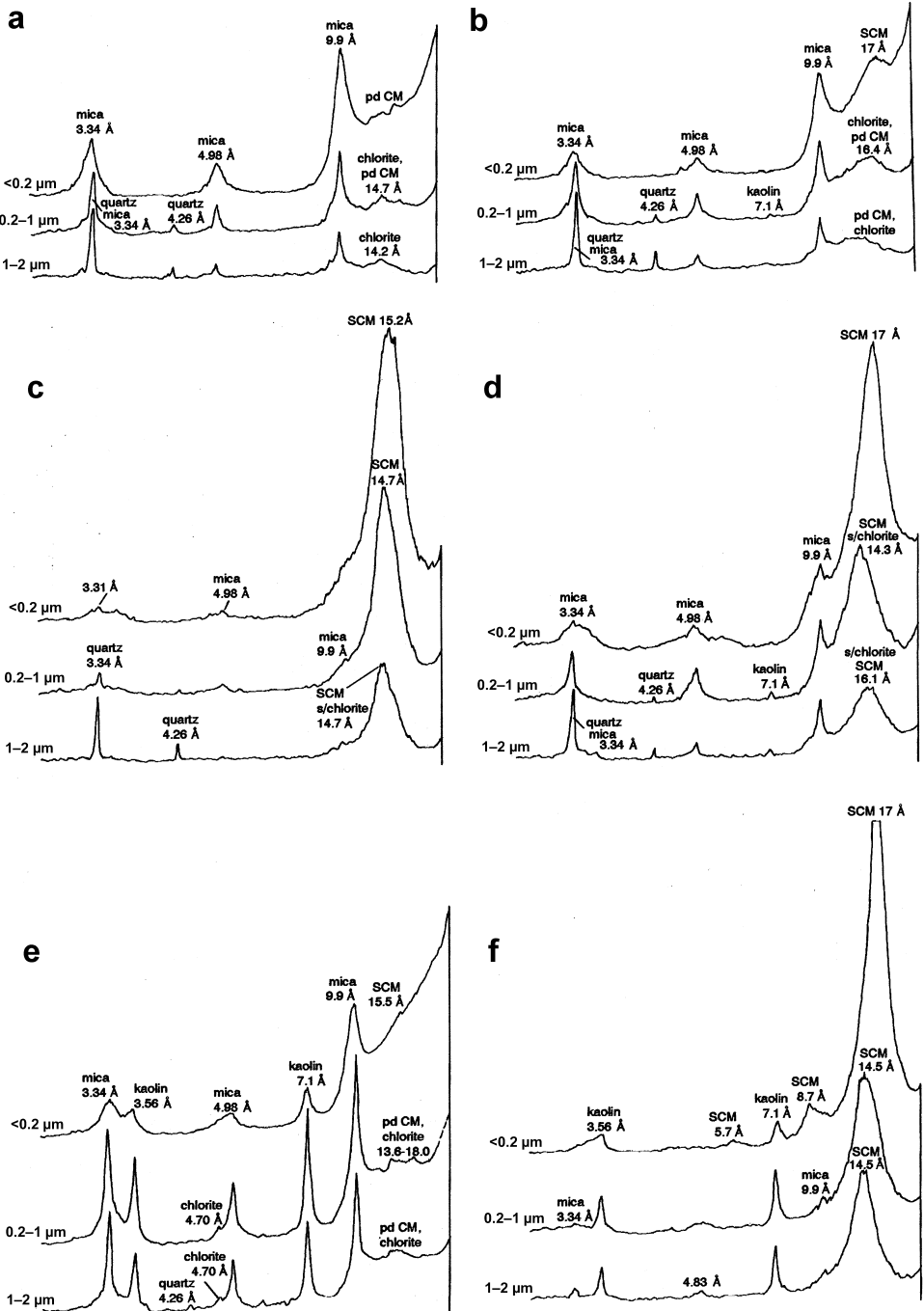
FIG. 8. XRD patterns of glycerolated clay fractions (<0.2 μm, 0.2−1 μm, 1−2 μm) showing the grain size-related mineralogical variations in the <2μm clay mineral assemblages, Purbeck Limestone Group, Durlston Bay, Dorset. Abbreviations as in Fig. 7. (a) Bed 17a, Cypris Freestone Beds, Lulworth Fm. (b) Bed 44, Soft Cockle Beds, Lulworth Fm. (c) Bed 98, Cherty Freshwater Beds, Lulworth Fm. (d) Bed 111b, Cinder Bed, Durlston Fm. (e) Bed 174C, Corbula Beds, Durlston Fm. (f) Bed 224, Unio Beds, Durlston Fm.

are considered to differ substantially from the more detrital-rich clay mineral assemblages (Beds 111b, 174c). Dr McHardy (pers. comm.) noted systematic differences between the background and specific volcanic assemblages with the latter displaying better-defined crystal morphology. K/Ar dates (Jeans *et al*., 2005, Table 5) suggest that the detrital clay assemblages (Beds 111b, 174c) contain a higher proportion of recycled old mica or K-bearing mixed-layer minerals than the background volcanic assemblage (Beds 17a, 43, 44) which, in turn, contains more recycled mica than the specific volcanic assemblages (Beds 19, 98, 224, 239).

Current investigation: Weald Basin. Knowledge of the clay mineralogy of the Purbeck Limestone Group in the Weald Basin is limited when compared to that of the Wessex Basin. Sladen (1980) included some analyses in his thesis (see above) and 53 new analyses from the Warlingham, Fairlight and Broadoak boreholes are shown in Table 1. Comparison has been made between the mica/kaolin values from the Purbeck Limestone Group of the Broadoak Borehole and of the Durlston Bay section (Jeans *et al*., 2005, their fig. 9). It is already apparent that there are significant differences in clay mineralogy between the Wessex and Weald basins. The kaolin content increases and its stratigraphical occurrence expands as the Purbeck Limestone Group is followed eastwards (Fig. 11). Clay assemblages with 50% or more smectite/collapsible minerals become less common in this direction. The proportion of poorly-defined collapsible minerals increases eastwards at the expense of smectite. Smectite-rich volcanogenic clay mineral assemblages have only been found at Durlston Bay. A very kaolin-rich clay assemblage has been recorded in the Broadoak Borehole (Weald Basin); this could be kaolinitized volcanic ash but further investigations are needed. This horizon was also recognized by Sladen (1980, sample BK 40.5).

Discussion. Sladen (1983) made the first attempt to interpret the major change in the clay mineral assemblages evident in the Purbeck Limestone Group. He suggested that his mixed-layer-illite assemblage (equivalent to the smectite-mica assemblage of this account) characteristic of the lower part of the Purbeck Limestone Group, were soil clays derived from areas of low relief where alkaline and poorly leached soils had developed under a hot semi-arid climate, whereas the kaolin-mica assemblage was derived from areas of higher relief where acid, well-leached soils developed under a warm humid temperate climate. Thus was born the 'climate-control hypothesis' which has proved popular over the past 20 y in explaining much of the variation in the Lower Cretaceous clay mineralogy of western Europe. Further support for this hypothesis was put forward by Sladen and Batten (1984) when they demonstrated that floral changes took place in parallel with the changes in clay minerals. These authors suggested that both these changes were climatically controlled, although their evidence is open to alternative explanations.

Deconinck (1987) supported the climatic hypothesis. He suggested that the smectite-mica assemblage came from two sources. The smectite, which he considered to be Al-Fe rich, was derived from smectite-bearing vertisols developed on areas of low relief under a hot seasonal climate, and was deposited in restricted basins marginal to the sea, where conditions ranged from freshwater to hypersaline. As a result of repeated wetting and drying under hypersaline conditions the smectite was more or less transformed to an Fe-rich illite. The minor amounts of palygorskite were considered by Deconinck to be the result of neoformation in hypersaline, Mg-rich conditions. The incoming of kaolin in the upper part of the Purbeck Limestone Group was considered to have been derived from kaolin-bearing soils. K/Ar dates obtained from the smectite-mica assemblage (Jeans *et al*., 2001, 2005) suggest it was formed at approximately the same time as deposition, either in coeval soils or during early diagenesis in the depositional basins. The K/Ar dates from the kaolin-mica clay assemblage (Jeans *et al*., 2001) indicate that considerable amounts of much older K-bearing clay mineral is present, derived directly from reworking of Mesozoic sediments which contained micas of Caledonian age and kaolin from the Devonian/Carboniferous.

Hallam *et al*. (1991) provide further discussion on the palaeoclimatic significance of the change in clay mineralogy which they suggest can be recognized in the stratigraphically equivalent marine strata in Yorkshire and in the Jura and Vocontian Trough in southeast France. The climate-control hypothesis has been reviewed by Allen (1998, pp. 204−210) who considers that the appearance of the kaolin-mica assemblage is a 'kaolinite-event' that is recognizable in England, Germany and France. However, the supposed synchronous nature of this event is not supported by the kaolin distribution pattern in the Purbeck

relative abundance of irregular mixed-layer smectite/chlorite

△ chlorite
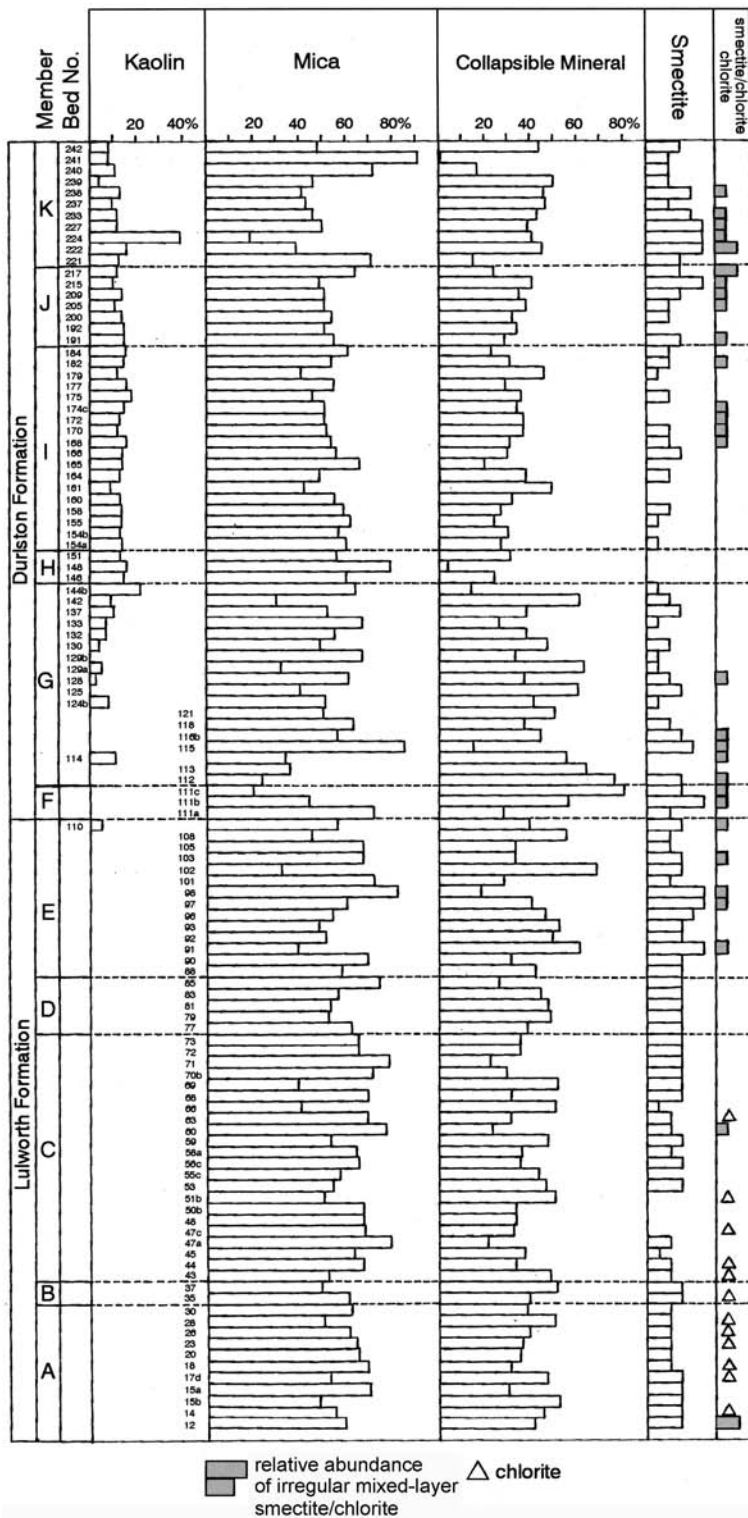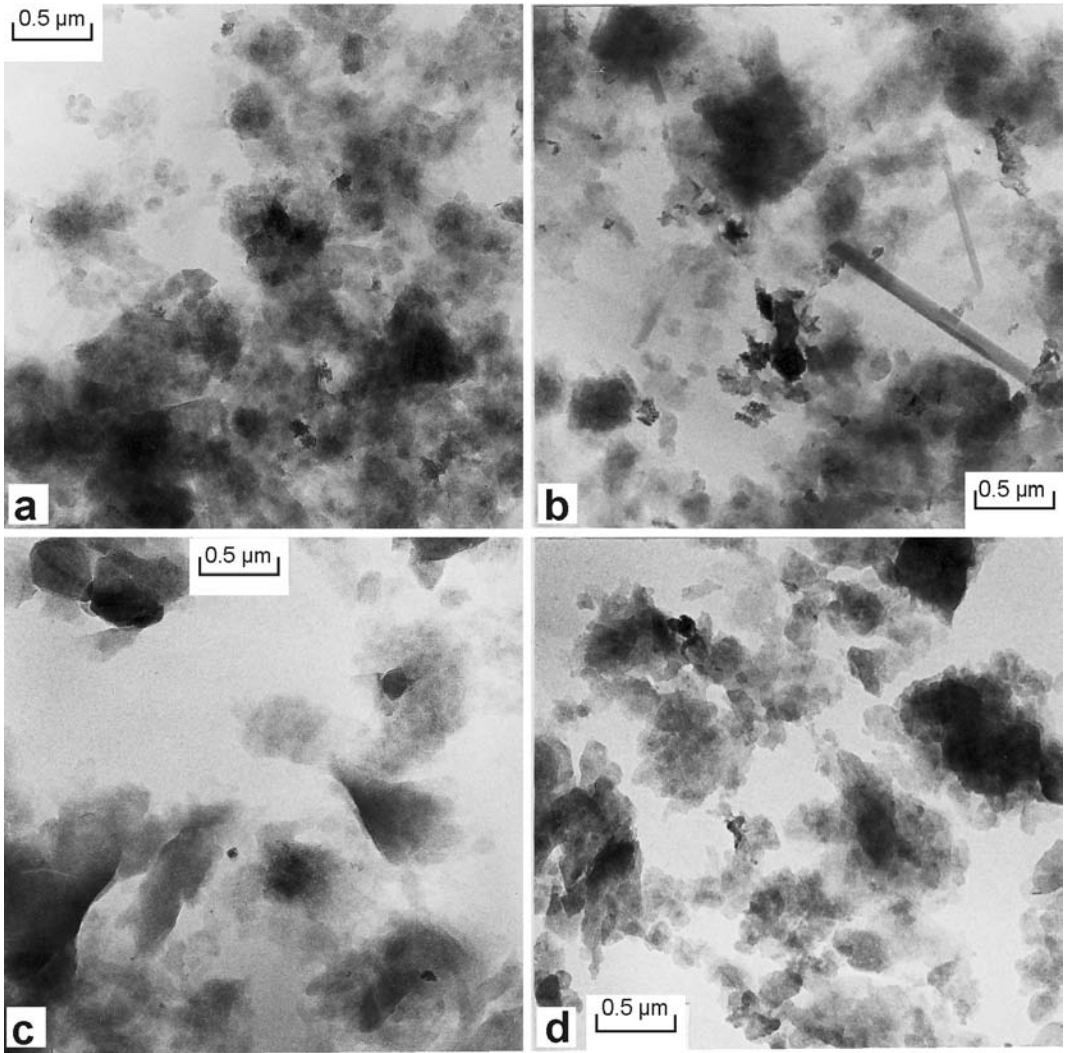
FIG. 10. TEM images of <0.2 μm clay fractions from the Purbeck Limestone Group, Durlston Bay, Dorset (taken by Dr W.J. McHardy, Macaulay Institute, Aberdeen, UK). (a) Euhedral and lath-shaped crystals with anhedral crystals and grain with and without lath-shaped overgrowths; smectite-mica assemblage, Bed 43, Soft Cockle Beds, Lulworth Fm. (b) Well-defined elongate crystals (palygorskite?) scattered among less well-defined clay particles. In places there is evidence of lath-shaped crystals and overgrowths. The electron-dense grains are probably hematite. Volcanogenic, saponitic smectite-dominated clay assemblage, Bed 91, Cherty Freshwater Beds, Lulworth Fm. (c) Poorly defined lath-shaped overgrowths are present on many of the more dense grains. There are well-defined clay crystals (probably kaolin) that show no overgrowths. Volcanogenic smectite-kaolin clay assemblage, Bed 224, Unio Beds, Durlston Fm. (d) Well defined anhedral clay crystals. Selected area electron diffraction images (not shown) indicate that both di- and tri-octahedral clay crystals are present. Volcanogenic, glauconitic clay assemblage, Bed 239, Viviparus Shales and Marls, Durlston Fm.

FIG. 9 (*facing page*). Clay mineral stratigraphy of the Purbeck Limestone Group, Durlston Bay, Dorset. Numbering of beds is from Clements (1993). A: Cypris Freestone Beds; B: Hard Cockle Beds; C: Soft Cockle Beds; D: Marly Freshwater Beds; E: Cherty Freshwater Beds; F: Cinder Bed; G: Intermarine Beds; H: Scallop Beds; I: Corbula Beds; J: Chief Beef Beds; J: Unio Beds; K: Viviparus Shales and Clays.
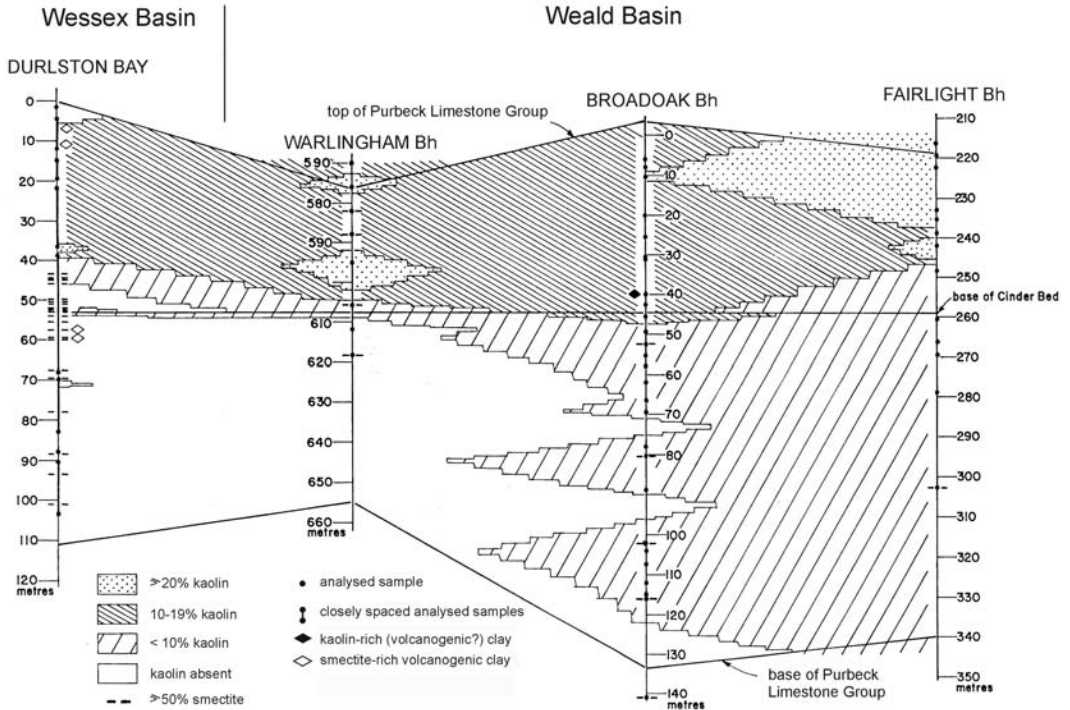
FIG. 11. Regional and stratigraphical variation in the clay mineral assemblages (<2 μm) of the Purbeck Limestone Group, southern England.

Limestone Group − at Durlston Bay it occurs ~9 m above the base of the Durlston Formation, whereas in the Broadoak Borehole in Sussex it occurs at least 22 m below the base of this formation.

In recent years the climate-control hypothesis has been critically tested. Jeans et al. (2000) suggested the smectite-mica clay assemblage associated with the uppermost Kimmeridgian-Berriasian strata of southern England is of volcanogenic origin, reflecting enhanced volcanic activity in western Europe. Five beds in the Purbeck Limestone sequence at Durlston Bay are considered to contain volcanogenic clay mineral assemblages derived from primary ash falls, of which two may match bentonites near the base of the Speeton Clay in the Cleveland Basin (Jeans et al., 2005). The K/Ar dates from these volcanogenic clays and the smectite-mica assemblage are either penecontemporaneous or younger than the date of deposition − which would be expected if the clay assemblages were derived from the argillization of volcanic ash but equally well from their neoformation in soils.

The only positive evidence for the climatic hypothesis is the linked association between floral and clay mineral changes observed by Sladen and Batten (1984). However, this could equally well be interpreted as reflecting the differential dispersion pattern of more or less buoyant pollen and fast- and slow-settling clay minerals. The more buoyant gymnosperm pollen would be concentrated with the slower settling clay minerals in more distal environments whereas the less buoyant pteridophyte pollen would be associated with the faster settling clay minerals in more proximal environments.

A further weakness of the climate-control hypothesis in the absence of any remnants of the smectitic vertisols, and in the very rare occurrence of the kaolin-bearing soils postulated by Sladen (1983) − the nearest one to southern England is ~450 km away in France (Meyer, 1976). An alternative hypothesis could include periods of low relief when local volcanic ash, both from individual ashfalls and background fallout, made a major contribution to the sediments. These periods were interrupted by episodes of tectonic uplift, which resulted in the reworking of earlier, probably Mesozoic sediments. No doubt climatic changes were involved but they have failed to leave any

obvious fingerprint of their influence on the clay mineral assemblages in the Purbeck Limestone Group.

Wealden Group

The Wealden Group consists of varied clays, silts and sandstones of freshwater, brackish to near-marine facies that occur at outcrop and in the shallow subcrop in southern England. Two inter-connected areas of deposition are recognized, the Weald Basin and the Wessex Basin, each with their own stratigraphical sequence (Fig. 6).

In the Weald Basin the sequence is divided into four formations; the Ashdown Formation is lithologically variable, with the informally-named Fairlight Clay passing laterally into the Ashdown Sands; the Wadhurst Formation is dominated by silts and clays with numerous siderite-cemented nodules; the Tunbridge Wells Sand Formation is predominantly sandy with seams of clay and silts − the Grinstead Clay is a persistent unit which divides the formation into an upper and lower division in the Central Weald; the Weald Clay Formation is predominantly of clays and silty clays with sporadic thin limestone beds of wide extent. The Small and Large Paludina horizons within the Wealden Clay enable the formation to be divided into three units.

The Wealden Group of the Wessex Basin is divided into a lower Wessex Formation, composed of sandstones and silts/clays with red/ochreous horizons of pedogenic origin, and the upper Vectis Formation is of shaly, silty clays. In the western part of the basin, the sandstones of the Wessex Formation are coarse and are represented by grits which may be conglomeratic. Stratigraphical correlation within and between the Weald and Wessex basins is very limited because of complex-ities and uncertainties about the precise depositional settings of the varied lithofacies and the endemic nature of the fossil floras and faunas.

The following correlations have been used in this account (see Fig. 6): (1) the Early/Mid-Hauterivian boundary is taken at the base of the Weald Clay Formation (Weald Basin) and correlates with an unknown horizon in the main part of the Wessex Formation (Allen & Wimbledon, 1991); (2) the Pine Raft and the correlative Quartz Grit, lithologically distinctive horizons in the Wessex Formation of the Isle of Wight and Worbarrow Bay (Wessex Basin) respectively, correlate with the British Geological Survey's Bed 3 in the Weald

Clay of the Weald Basin, which is taken to mark the Hauterivian/Barremian boundary.

Tank (1962, 1964) undertook the first investiga-tion of the clay mineral assemblages of the Wealden Group of the Weald Basin. He compared the assemblages with the clay mineralogy of the other Mesozoic and Palaeozoic strata which would have been exposed on the Anglo-Brabant Massif (London Platform) during early Cretaceous times. Tank suggested that the mica and kaolin were probably recycled from older rocks, whereas the vermiculite was a pene-contemporaenous weath-ering product.

Sladen (1980, 1983, 1987) increased considerably our knowledge of the regional clay mineralogy of the Wealden Group and coeval strata in northwest Europe and was impressed by the similarity in the clay mineral stratigraphy between England and successions on the continent. He concluded that the varied clay mineral assemblages in southern England were neither the result of burial diagenesis, as maximum burial depths and temperatures were low (1.1−1.5 km, 53−65C°), nor the result of segregation by differential settling, but were related to the changing soils in the Anglo-Brabant source areas. Sladen (1983) and Sladen & Batten (1984) suggested that the soils were under tectonic/climatic control and there was a link between the palynofacies and clay mineral assemblages in the Wealden Group. Assemblages rich in kaolin and Al-vermiculite were regarded as characteristic of the more sandy units of the Wealden Group − the upper part of the Ashdown Formation, Lower Tunbridge Wells Sand Formation − and were derived from soils associated with high relief and tectonic uplift that had undergone enhanced podsolization in a humid climate. The more argillaceous units − Wadhurst Clay Formation, Grinstead Clay Member of the Tunbridge Wells Sand Formation − are characterized by clay assemblages rich in mixed-layer smectite-mica and with lesser amounts of kaolin, and originated from relatively scarce podsolized soils that had devel-oped on source areas of low relief during less humid periods of tectonic quiescence.

Sladen's climate-control hypothesis formed the basis for Allen's (1998) extended discussion of the clay minerals and palaeoclimates of the Wealden Group. The pedogenic horizons in the variegated beds of the Wessex Formation display no clay mineral differentiation and are considered to be typical of wetlands with a strongly seasonal climate

(Wright *et al.*, 2000), providing further support for the overall absence of neoformed clay minerals or the modification of detrital clay minerals in the Weald and Wessex basins.

The XRD patterns of typical clay mineral assemblages of the Wealden Group are illustrated in Figs 12 and 13. There is considerable mineralogical variation within the clay assemblages related to grain size (Fig. 14). Mica, kaolin and collapsible minerals are generally the predominant components. In addition, berthierine may be present as a significant component (Figs 12d, 13a). Kaolin shows variations in 'crystallinity' (Fig. 13b,c) and in some cases shows partial resistance to breakdown on 550°C heating, particularly in the Wessex Formation, Worbarrow Bay. Infrared spectroscopic (IR) and XRD analysis by Drs A. Fraser and M.J. Wilson (pers. comm.) of kaolin from selected samples (Table 2) suggests: (1) that moderately ordered and poorly ordered kaolinite is present but discrete dickite is absent; (2) the presence of some kaolinite/dickite mixtures or intergrowths, with or without Fe substitution, in the ordered kaolinite, and possibly some 2-layer polytypic stacking in the disordered kaolinite. The collapsible mineral is usually poorly defined (Fig. 12a) consisting of various mixed-layer vermiculite, mica and smectite minerals. Vermiculite may be present either in trace amounts (Fig. 12b) or as a major component (Fig. 12c). Well-defined smectite is rare: an example from the Weald Clay is illustrated in Jeans *et al.* (1982, their fig. 2). Chlorite may be present in trace amounts (Fig. 12e). Quartz, a trace component, is concentrated in the coarser clay fractions (Fig. 14). Ruffell and Batten (1990) reported the presence of sepiolite, palygorskite and chlorite-smectite mixed-layer minerals from the variegated beds of the Wessex Formation in the Isle of Wight. These minerals were not reported by Sladen (1980) in his analysis of the same sections nor were they identified in subsequent investigations by Wright *et al.* (2000) and Jeans *et al.* (2001, p. 537).

The stratigraphical and regional analysis of the clay mineralogy of the Wealden Group is based very largely upon nearly 450 new analyses from samples collected in boreholes at Cooden, Cuckfield, Fairlight, Glynleigh, Ripe, Warlingham and Winchester as well as from cliff exposures on the Isle of Wight and Worbarrow Bay, Dorset (Fig. 5 for locations). The new analyses are listed stratigraphically − Table 3, Ashdown Formation;

Table 4, Wadhurst Clay Formation; Table 5, Tunbridge Wells Sand Formation; Table 6, Grinstead Clay Member; Table 7, Upper Tunbridge Wells Sand; Table 8, Weald Clay Formation; Table 9, Wessex Formation; Table 10, Vectis Formation.

The regional stratigraphical variation in the clay mineralogy of the Wealden Group in southern England is illustrated in Figs 15−17. Figures 15 and 16 show the schematic distribution of kaolin in the Valanginian and early Hauterivian part of the sequence and in the Hauterivian and Barremian part, respectively. In Fig. 15, particularly high values of kaolin are found in the Ashdown Beds of the Fairlight, Cooden, Glynleigh and Cuckfield boreholes and in the Tunbridge Wells Sand of the Cooden and Cuckfield boreholes. Low values of kaolin occur in the Ashdown Formation–Grinstead Clay interval in the Warlingham Borehole and more generally in the Wadhurst Clay in the Glynleigh and Cuckfield boreholes, and its suggested correlatives in the Wessex Formation at Worbarrow Bay.

Berthierine occurs throughout the Ashdown–Tunbridge Wells Sand interval of the Cuckfield Borehole, where it is commonly associated with clay minerals assemblages containing 40% or more kaolin. It also occurs sporadically in the Ashdown Formation of the Fairlight Borehole. In the upper Hauterivian-Barremian part of the Wealden Group (Fig. 16), high kaolin values are concentrated in the Wessex and Vectis formations and are lacking or poorly represented in the Ripe and Warlingham sections of the Weald Clay. Berthierine occurs throughout the basal beds of the Weald Clay penetrated in the Cuckfield Borehole and is again usually associated with assemblages containing 40% or more kaolin. Figure 17 shows the distribution of smectite, vermiculite and berthierine in the Weald Clay Formation and its correlatives in the Wessex sub-basin. The Weald Clay in the Warlingham, Cooden and Ripe boreholes is characterized by vermiculite and sporadic occurrences of smectite; berthierine is absent. The Vectis Formation at Sandown (Yaverland) in the Isle of Wight contains vermiculite only, whereas the underlying Wessex Formation contains both smectite and vermiculite. The mica/kaolin ratios of individual analyses from the various formations of the Wealden Group are plotted in Fig. 18 and display two distinctive patterns. The Ashdown Formation, the Tunbridge Wells Sand Formation and the Wessex Formation of Worbarrow Bay and
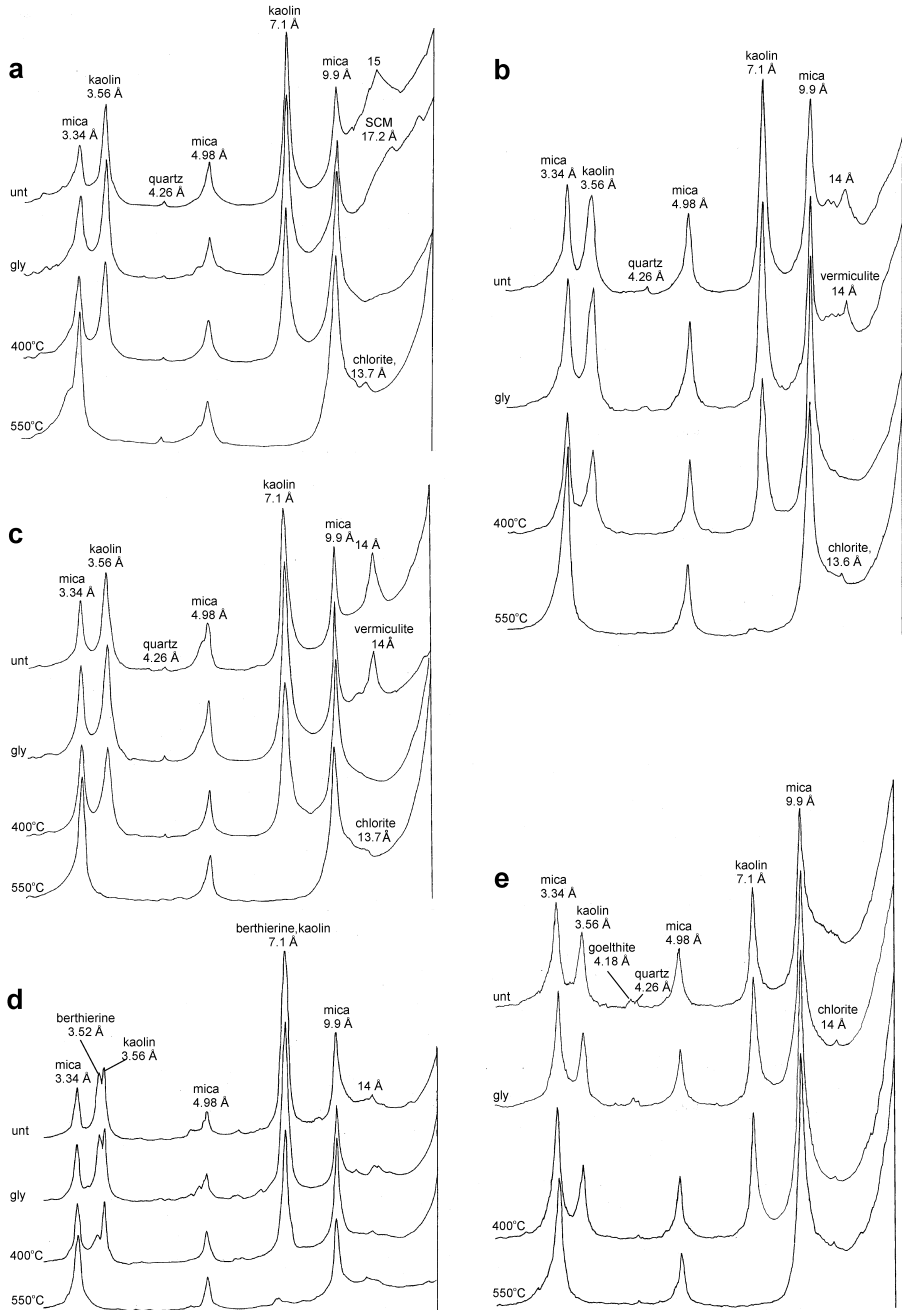
FIG. 12. XRD patterns of clay mineral assemblages (<2 μm) from the Weald Clay, southern England. Abbreviations as in Fig. 7. (a) Typical assemblage of kaolin, mica and collapsible mineral containing minor smectite. Ripe Borehole, 135.30 m. (b) Typical assemblage of kaolin, mica and collapsible minerals containing minor vermiculite. Ripe Borehole, 155.0 m. (c) Major vermiculite in clay assemblage, Ripe Borehole, 122.04 m. (d) Berthierine in a kaolin-mica-collapsible mineral assemblage. The loss of intensity of the 7 Å and 3.54 Å peak on 400°C heating is characteristic of berthierine. Cuckfield Borehole, 18.29 m. (e) Poorly defined collapsible mineral (without vermiculite and/or smectite) in association with kaolin and mica. Ripe Borehole, 98.86 m.
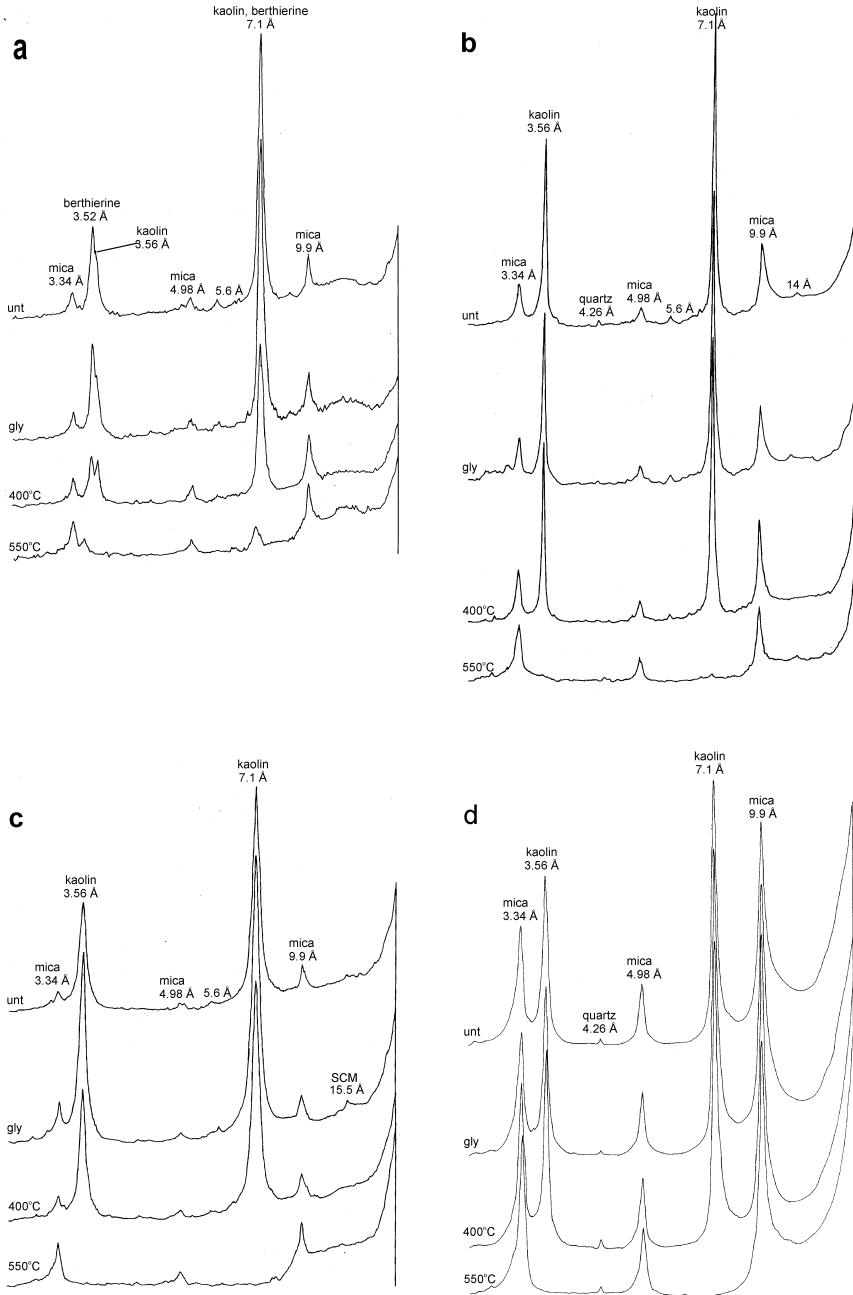
FIG. 13. XRD patterns of clay mineral assemblages (<2 μm) from the Upper Tunbridge Wells Sandstone Fm. (a,b) and the Wessex Fm. (c,d). Abbreviations as in Fig. 7. (a) Assemblage rich in kaolin and berthierine with the kaolin showing a residual 7 Å peak after 550°C heating. Cuckfield Borehole, 154.23 m. (b) Kaolin-rich clay assemblage. Cuckfield Borehole, 69.98 m. (c) Dominant poorly crystalline kaolin and minor smectite in Bed 34 (sample W104) from near the top of Wessex Formation, Worbarrow Bay, Dorset. (d) Assemblage of mica, kaolin and poorly defined collapsible mineral typical of the Wessex Formation, Worbarrow Bay. Sample W118 (Bed 12) 259.70 m from top of formation.
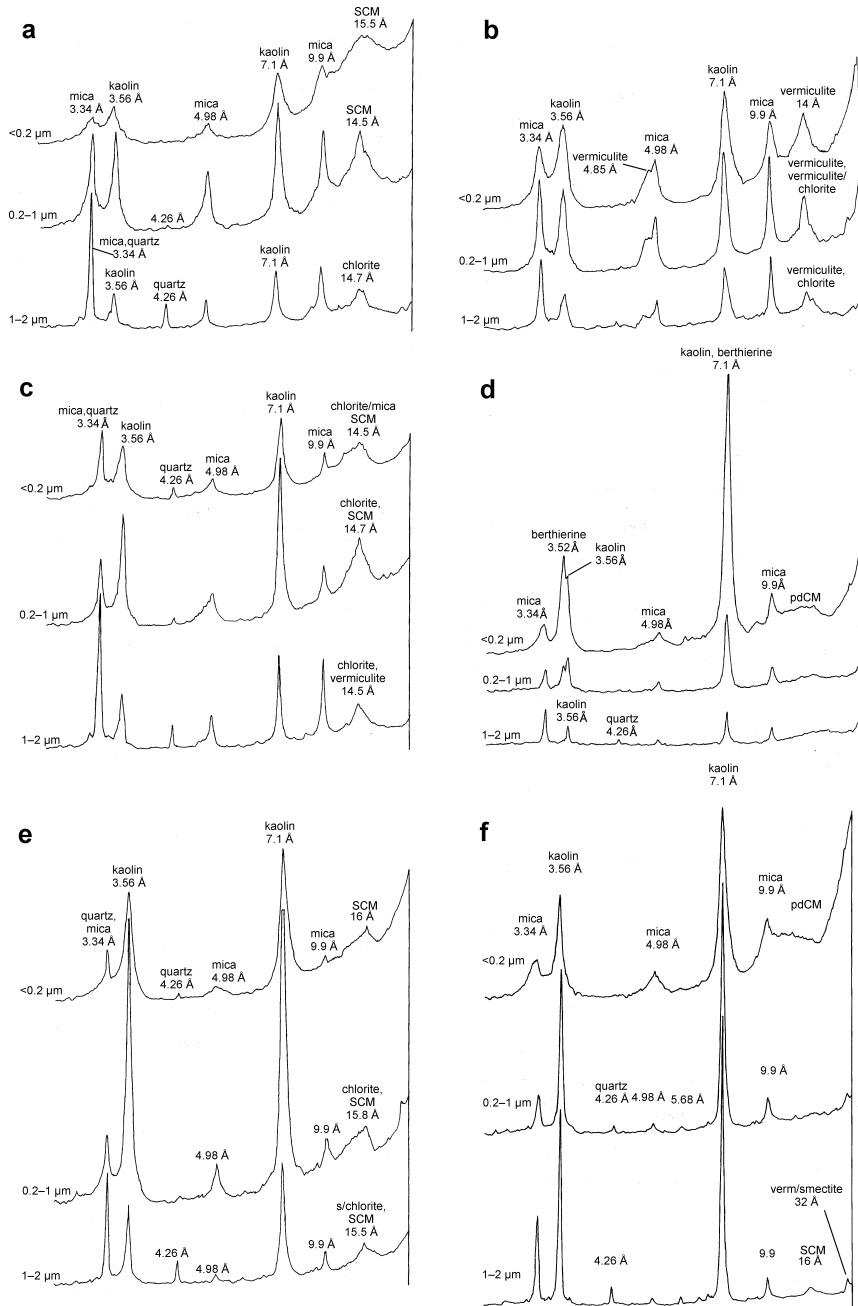
FIG. 14. XRD patterns of glycelorated clay fractions (<0.2 μm, 0.2−1 μm, 1−2 μm) showing the grain size-related mineralogical variation in <2 μm clay mineral assemblages from the Wealden Group, southern England. Abbreviations as in Fig. 7. (a) Weald Clay, Warlingham Borehole, 329.34 m. (b) Upper Tunbridge Wells Sandstone, Cooden Borehole, 60.88 m. (c) Wadhurst Clay, Cooden Borehole, 128.02 m. (d) Upper Tunbridge Wells Sands, Cooden Borehole, 163.07 m. (e) Upper Tunbridge Wells Sands, Cooden Borehole, 51.46 m. (f) Upper Tunbridge Wells Sands, Cuckfield Borehole, 124.97 m.
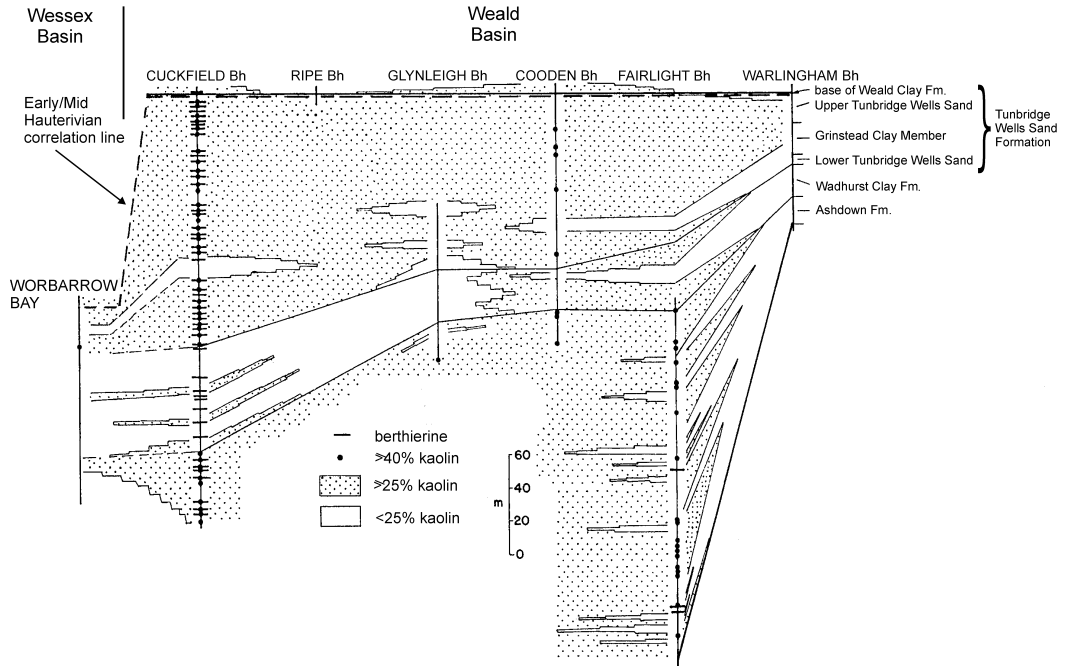
FIG. 15. Kaolin and berthierine in the <2 μm clay mineral assemblages of the lower part of the Wealden Group, southern England.

the Winchester no. 1 Borehole are dominated by mica/kaolin values between 0.2 and 2.4. The Wessex Formation of the Isle of Wight, the Weald Clay Formation and the Vectis Formation are dominated by values between 1.2 and 3.1. The Wadhurst Clay Formation displays a much wider range of values (0.5−5.0).

The only recorded example of what may or may not be the debris from a clay-mineralogically differentiated palaeosol are clasts made up of sandstone fragments coated by pisolithic berthierine and goethite in a conglomerate within the top part of the Lower Tunbridge Wells Sand in the Crawley−East Grinstead area of the central Weald (J.H. Taylor, 1963; K.G. Taylor, 1990, 1992). This is interpreted as fragments from a kaolinite-goethite pisolithic laterite from somewhere within the Weald Basin which have undergone diagenesis under reducing conditions with the formation of berthierine from the reaction between goethite and kaolinite (K.G. Taylor, 1990).

Discussion. In recent years, published and unpublished evidence has indicated that Sladen's climate-control hypothesis as applied to the Wealden Group is either untenable or will have to

be modified. There is now considerable evidence that clay minerals developed diagenetically, i.e. after deposition. Lowry (1987) has reported the widespread occurrence of authigenic clay minerals including smectitic minerals and kaolin in the feldspar-poor sandstones of the Ashdown Formation, while Sladen (1980) reported authigenic kaolin from the Wessex Formation. In these sandstones the feldspars are often leached but never overgrown, and Lowry suggested that these leached grains were the source of Al and Si necessary for clay mineral authigenesis.

Berthierine is widespread in the Central Weald, occurring in all the formations (upper part of Ashdown Formation, Wadhurst Clay Formation, Tunbridge Wells Sand Formation, basal part of Weald Clay Formation) penetrated in the Cuckfield Borehole (Figs 15, 16). It is no coincidence that all previous records of berthierine are from the central Weald (fragments of rock containing pisolithic berthierine, J.H. Taylor 1963; K.G. Taylor 1990, 1992; bed of berthierine mudstone, Thurrell *et al.*, 1970). Berthierine is also found in clay mineral assemblages at a few horizons in the Ashdown Formation of the Fairlight Borehole (Fig. l5). In the
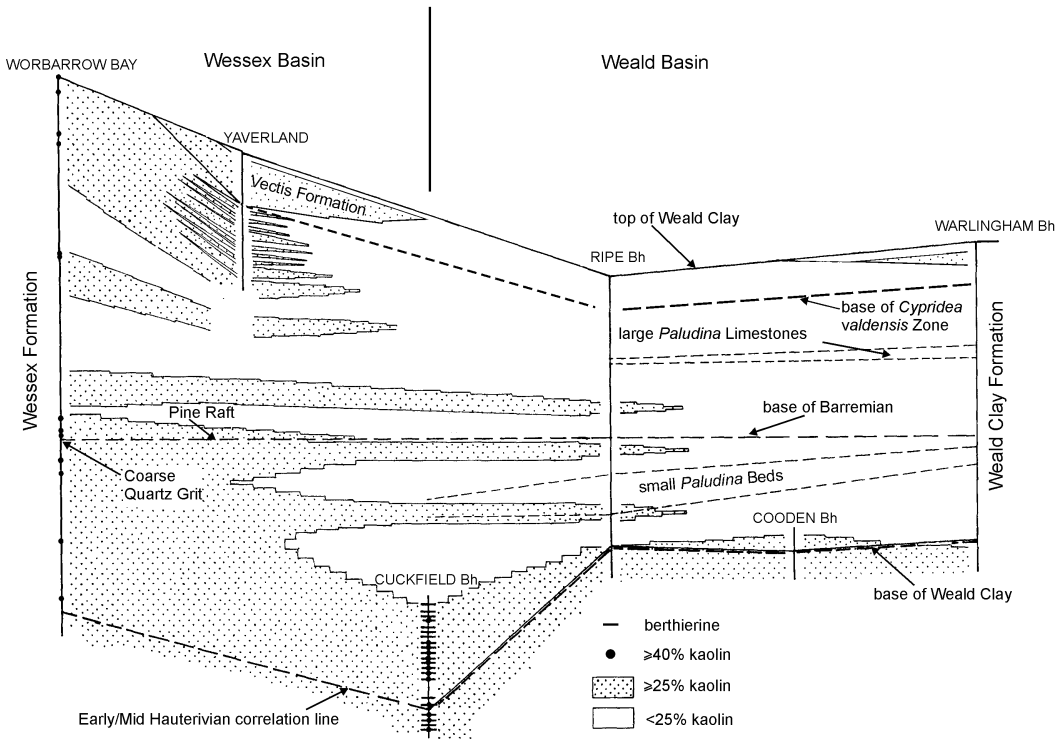
FIG. 16. Kaolin and berthierine in the <2 μm clay assemblages of the Weald Clay, southern England. Biostratigraphical correlations are from Anderson (1967; base of *Cypridea valdensis* Zone), Hughes & McDougall (1990; Hauterivian-Barremian boundary) and Allen & Wimbledon (1991; Early/Mid-Hauterivian, base of Weald Clay).

Cuckfield Borehole, the berthierine is associated with exceptionally high kaolin values (> 40%) in all the formations penetrated, except for the Wadhurst Clay. Such an association is similar to that described by J.H. Taylor (1949) from the berthierine-kaolin facies of the Northampton Sand Ironstone Formation; Jeans *et al*. (2000) has suggested that this facies may have a volcanogenic source.

Some beds in the Wealden Group that contain clay mineral assemblages with exceptionally high kaolin content are considered to be secondary volcanogenic deposits (Jeans *et al*., 2000, their fig. 9). The berthierine mudstone band in the Weald Clay (Thurrell *et al*., 1970) is regarded as the argillization product of a primary ash (Jeans *et al*., 2000).

There is evidence of considerable grain-size mineralogical variation within the <2 μm clay assemblages of the Wealden Group (Fig. 14). This indicates that differential settling of various clay minerals during transport and in the depositional environments could have been responsible for some of the variation in the clay assemblages. Sladen (1980) was aware of the grain-size mineralogical variation, but considered it to be insignificant over the short transport distances he judged to be involved. Sladen and Batten's (1984) climatic linkage between variations in palynofacies and clay mineral assemblages could equally well be explained by the combined effects of differential settling of the suspended clay mineral load and the differential dispersion of various palynomorph types. The vermiculite-rich clay assemblages, representing a proximal depositional setting, would be associated with higher proportions of locally-produced pollen, whereas the smectite-mica- rich clay assemblages, representing a more distal depositional setting, would be associated with a greater proportion of widely dispersed pollen types.

The new clay mineral analyses now available for the Wealden Group (Tables 3−10) allow Sladen's
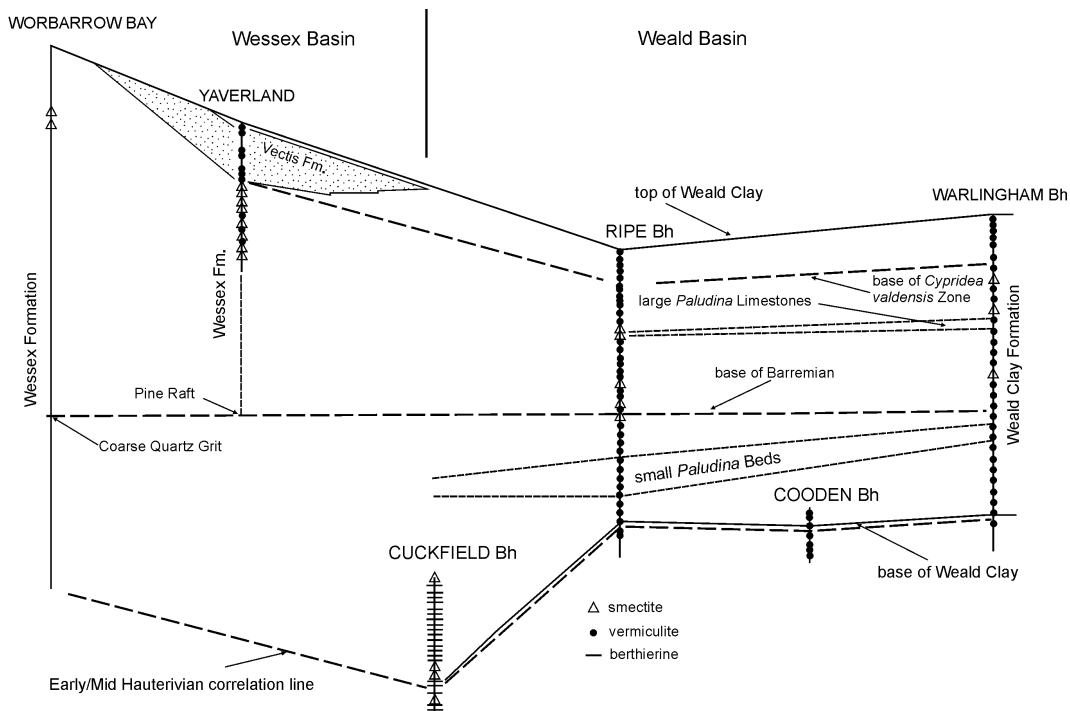
FIG. 17. Occurrence of berthierine, vermiculite and smectite in the Weald Clay, southern England. Biostratigraphical correlation lines as for Fig. 16.

generalizations on the relationship between the types of clay mineral assemblages and the lithologies of the different formations to be tested. Vermiculite is widespread as a minor component of the clay mineral assemblages throughout the Wealden Group in the Weald Basin. In the Wessex Basin it is restricted to the Vectis Formation. Appreciable proportions of vermiculite are found only in the Weald Basin, where they occur particularly in the Ashdown Formation of the Fairlight and Cooden boreholes, the Upper Tunbridge Wells Sand of the Cooden Borehole and the Weald Clay of the Warlingham Borehole. Smectite is essentially absent from the Ashdown, Wadhurst Clay and Tunbridge Wells Sand formations; it occurs sporadically in the Weald Clay of the Warlingham, Ripe, Cuckfield boreholes, and in the Wessex Formation of the Isle of Wight but not of Worbarrow Bay.

Table 11 summarizes the clay mineral assemblages of the Wealden Group. The average values for the Ashdown, the Lower and Upper Tunbridge Wells Sand and the Grinstead Clay Member form one group; and the Wadhurst Clay and the Weald Clay formations form another group, with less kaolin, more mica and collapsible minerals. This does not confirm the pattern of clay mineral variation observed by Sladen & Batten (1984, their fig. 5) in their data in which the Upper Ashdown Beds and Lower Tunbridge Wells Sands are linked because of their enhanced kaolinite and vermiculite contents, and the Wadhurst Clay and Grinstead Clay were linked because of their enhanced mixed-layer minerals and reduced kaolinite contents.

Interpretation of the mica/kaolin ratios of the Wealden Group formations (Fig. 18) suggests that the pattern of variation can be explained by three detrital clay sources. The predominant source provided a clay mineral assemblage with mica/kaolin ratios of ~1.8−2.2 associated with relatively high proportions of collapsible minerals. The second source, probably located to the west of the Weald and Wessex basins, contributed a clay assemblage with mica/kaolin ratios of 0.1−1.2. In Valanginian and early Hauterivian times, distribu-
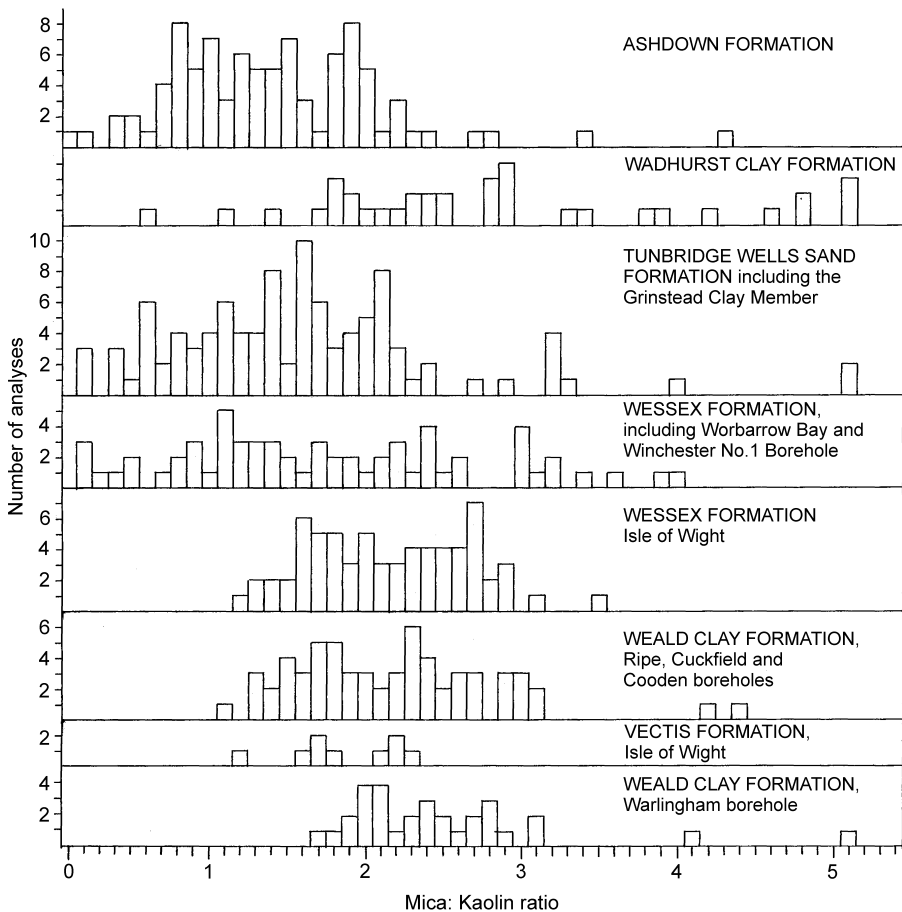
FIG. 18. Histograms showing the patterns of mica/kaolin ratios (M/K; based on analyses in Tables 2–10) for the various formations of the Wealden Group.

tion of this assemblage extended throughout the Weald sub-basin and probably also the Wessex Basin. In mid-late Hauterivian and Barremian times, during deposition of the Weald Clay, distribution from this source was reduced, so its detrital clays were largely confined to the Wessex Basin, occasionally extending into the Weald Basin. A third minor source, active during the deposition of the Wadhurst Clay, provided detritus with high mica/kaolin ratios (>2.2) and enriched in collapsible minerals.

In terms of a detrital origin of berthierine, the exceptional high kaolin values, vermiculite and smectite are problematic. With the exception of kaolin, Fig. 17 shows that the regional and stratigraphic distribution of these minerals is mutually exclusive, and therefore cannot have a common source of detrital origin. Moreover, since berthierine is very prone to oxidation if reworked, it is likely to be of authigenic origin, including some of the abundant kaolin with which it is often associated. Does this imply that vermiculite and smectite are also of authigenic origin? Is there a common parent material, perhaps volcanic ash acting as a source for Al and Si necessary for the mineral reactions in different environmental settings? At the moment there is no evidence for this origin. However, the possibility that vermiculite and smectite were sourced from soils on the Anglo-Brabant massif during different climatic and tectonic regimes is also questionable. The extent to which Sladen's climate-control model has to be modified is not clear. New clay mineral data and the alternative interpretation of new and previous

data suggest that a volcanic contribution from direct and reworked ashfalls, differential settling of detrital clay assemblages, as well as alternation between variations in detrital sources all played important roles. These alternatives question the evidence for climate switching and hence weaken the climate-control model.

Pre-Aptian strata of the Cromer Knoll Group

The stratigraphical scheme used for the Ryazanian-Barremian strata of the Cromer Knoll Group is shown in Fig. 6. The strata are of marine facies and were deposited to the north of the Anglo-Brabant Massif (London Platform). They are now preserved in two basins in eastern England, the Cleveland Basin of Yorkshire and the Spilsby Basin of Lincolnshire and Norfolk. Separating the basins is the Market Weighton High, an asymmetrical, partially fault-bounded high over which no pre-Aptian beds are preserved.

The lithologies of the pre-Aptian Lower Cretaceous strata in the two basins are quite different. The Cleveland Basin is characterized by the Speeton Clay (a ~100 m Upper Ryazanian-Barremian sequence at Speeton), consisting of clays and silty clay with horizons of phosphatic pebbles/nodules and cementstones. The equivalent strata in the Spilsby Basin are a vertically and laterally variable series (up to 70 m thick) of pebbly sands, sands, sandy and pebbly clays, oolitic ironstones and argillaceous limestone. In the central part of the Spilsby Basin (southern Lincolnshire) the sequence consists of the Spilsby Sandstone Formation (Upper Tithonian–Upper Ryazanian; up to 25 m), the Claxby Ironstone Formation (Valanginian–Lower Hauterivian; up to 5 m), the Tealby Formation (Upper Hauterivian–Upper Barremian; up to 30 m) and the Roach Ironstone Formation (Upper Barremian; up to 20 m). The Jurassic/Cretaceous boundary is placed at the mid-Spilsby nodule bed, near the base of the Spilsby Sandstone Formation. When the sequence of the central part of the basin is traced southwards into Norfolk it is represented by beds of rather different lithologies (Figs 3, 4, 6). The Spilsby Sandstone Formation consists of fine/medium glauconitic sands: its lower division, which is particularly glauconitic, passes laterally into the sandy and often very glauconitic Roxham and Runcton Beds (Sandringham Sands Formation), whereas its upper division passes into the clayey sands of the Mintlyn Beds (Sandringham Sands

Formation). The Jurassic/Cretaceous boundary is placed at the base of the Runcton Beds. The Claxby Ironstone Formation of silts and clays with limonitic ooliths and impure ironstone (Claxby Ironstone) passes laterally into the cross-bedded quartz sands of the Leziate Beds (Sandringham Sands Formation), which contain silt and clay bands, and into the lower part of the overlying Dersingham Formation. The Tealby Formation consists of a lower clay unit, commonly very glauconitic (Lower Tealby Clay), a middle argillaceous limestone unit (Tealby Limestone), and an upper greenish clay unit (Upper Tealby Clay). This formation passes southwards into the main part of the sands, silts, clays and oolitic clays that make up the Dersingham Formation of Norfolk. The Roach Ironstone Formation consists predominantly of oolitic (limonite, berthierine) clays with some pebbly horizons, clays (including reddish-coloured varieties) and some sandy horizons.

Cleveland Basin: Speeton Clay Formation. The clay mineralogy of the pre-Aptian Speeton Clay is known from the much-slipped and disturbed cliff sections at Speeton on the Yorkshire coast and from an undisturbed succession, similar to and closely correlatable with the coastal section, revealed in the off-shore well BGS 81/43, which is located 60 km to the north east of Speeton (Fig. 1). Perrin (1971) included one representative clay mineral analysis (mica 85%, smectite 15%) selected from numerous analysed samples from the Yorkshire coast.

The first considerable work on the clay mineralogy of the Speeton Clay on the Yorkshire coast was carried out by Parker (1974). Eighteen samples (Ryazanian-Barremian) were analysed for their clay mineralogy and their trace element composition. Parker noted two stratigraphical trends in the clay mineral assemblages which were dominated by kaolin, illite and a randomly interstratified illite-smectite. The kaolinite/mica ratio decreased upwards, in parallel with a change in composition of the interstratified illite-smectite from a more smectitic to a more illitic composition. Four thin bentonites (<15 cm thick argillized volcanic ash beds) were described by Knox & Fletcher (1978) from the Ryazanian D Beds at Speeton. Three of these bentonites had a smectite-dominated clay mineral assemblage, whereas one (Beds D6C, Knox, 1991, his fig. 2; not Bed D6E as reported by Knox & Fletcher, 1978) was dominated by kaolinite. Twenty three clay mineral analyses of the Speeton Clay from the Yorkshire coast are

included in Sladen's thesis (1980, p. 161), and were summarized (Sladen, 1983, his fig. 4) as showing a trend from kaolinite-dominated assemblages with lesser amounts of illite and mixed-layer minerals in the lower part (Ryazanian–Valanginian) of the succession to assemblages increasingly dominated by illite and mixed-layer minerals at the expense of the kaolin in the upper part (Hauterivian–Barremian). The clay mineral stratigraphy of the lower Speeton Clay (Beds D2−D8) and the underlying Kimmeridge Clay at Speeton, based on 29 samples, has been illustrated by Hallam *et al*. (1991, their fig. 2). Smectite, mixed-layer minerals, illite, kaolinite and chlorite are reported in the assemblages and their relative abundances display considerable stratigraphical variation. Smectite is particularly abundant (up to 70%) in the Upper Ryazanian (Beds D5-D8), whereas kaolinite is abundant (up to 50%) in the Lower Valanginian (Beds D2 and D3).

Knox (1991) has described 12 clay mineral zones (based on the <4 µm fraction without heat treatment) in the Speeton Clay sequence (Upper Ryazanian−Barremian) cored in the offshore borehole BGS 81/43. The lowest part of the sequence (Beds D5-D8, Upper Ryazanian) is dominated by smectite, and this is followed by kaolinite-dominated beds of Lower Valanginian and Lower Hauterivian age − these two clay mineral zones appear to be equivalent to the smectite- and kaolinite-rich zones described by Hallam *et al*. (1991) from Speeton. The overlying strata (Hauterivian–Lower Barremian) are characterized by clay mineral assemblages of relatively constant composition dominated by smectite with lesser amounts of illite. In the top 15 m of the succession there is a marked decrease in smectite with a corresponding increase in kaolinite and illite. Seven bentonites are recognized in the Speeton Clay of the offshore borehole 81/43, of which six can be correlated with those known from the coastal section at Speeton (Lott *et al*., 1986; Knox, 1991). Bentonites D7D and D6J have been correlated, respectively, with volcanogenic clays reported from Beds 224 and 239 in the Durlston Formation, Dorset (Jeans *et al*., 2005). Table 12 contains ten new clay mineral analyses from various horizons in the Speeton Clay of Yorkshire.

Detailed studies on the clay fractions from the bentonites in Beds D7D, D6J and D6C from the Speeton Clay are included in the following papers: Jeans *et al*. (2000): *REE* patterns; Jeans *et al*.

(2001): K/Ar signatures; Jeans *et al*. (2005): chemistry and K/Ar dates). Figure 19 shows the XRD patterns of four new clay mineral analyses from the Speeton Clay which reveal the presence of poorly-defined collapsible minerals, with vermiculite and minor smectite (peaks at ~17 Å). Sladen (1980) provided similar XRD patterns for his Speeton Clay samples. It appears that Knox (1991) used smectite to include all the collapsible minerals, whereas Sladen (1980, 1983) used the term mixed-layer mineral to refer to the collapsible minerals. Hallam *et al*. (1991) attempted a differentiation into mixed-layer mineral and smectite, there was no mention of vermiculite, but these authors recorded up to ~12% chlorite in some samples from the Upper Ryazanian and Lower Valanginian Beds which had not been identified by Sladen (1980, 1983) or Knox (1991).

Parker (1974) considered various possible origins (diagenetic, neoformational, detrital) for the pattern of clay minerals he recognized in the Speeton Clay of the Yorkshire coast. He favoured a detrital origin in which the up-sequence decrease in kaolinite/illite ratios associated with a decreasing smectite content of the interstratified illite-smectite mineral indicated: (1) a systematic change in source area composition; (2) the existence of two or more separate source areas, each with a different and, in time, changing clay mineral composition; (3) a progressive change in deposition conditions, resulting in systematic changes in the clay mineral assemblages as the result of differential settling; or (4) changes in the style and degree of weathering at the source areas. Parker argued that the weathering of the source material was the most likely controlling factor, and suggested that the stratigraphical changes in clay mineralogy represented either the deposition, in reverse order, of a deeply weathered Jurassic source material, or systematic changes in the weathering processes at source producing different clay mineral assemblages with time. Subsequent studies (Sladen, 1983; Hallam *et al*., 1991; Knox, 1991) have incorporated Parker's (1974) detrital hypothesis into palaeogeographic scenarios involving climatic change, tectonic rejuvenation of various areas (e.g. Anglo−Brabant Massif) and widespread changes in sea level, in attempts to link the varying clay mineral assemblages of the Speeton Clay with those of the Wealden Group and the Purbeck Limestone Group in southern England, as well as with coeval sediments in western continental Europe (Hallam
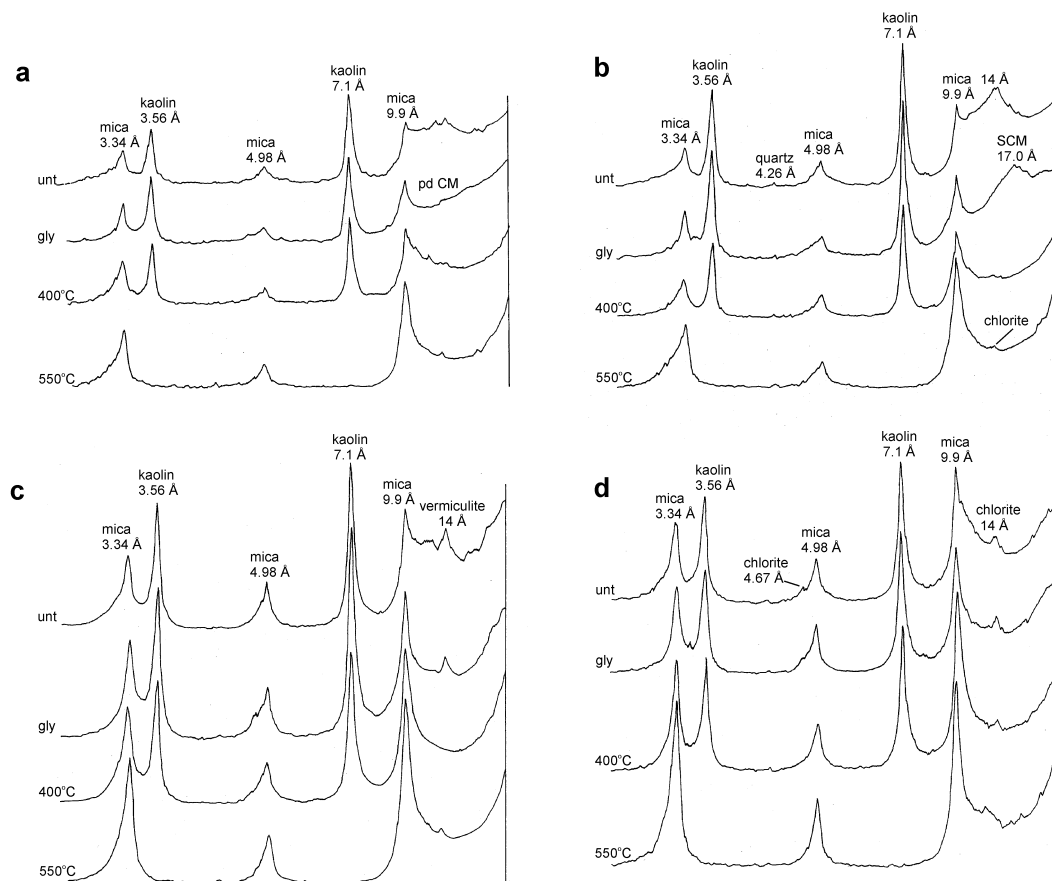
FIG. 19. XRD patterns of clay mineral assemblages (<2 μm) from the Speeton Clay, Speeton, Yorkshire. The samples were collected by B.N. Fletcher and donated by Mr Maurice Black (Black, 1971). Abbreviations as in Fig. 7. (a) Kaolin-mica assemblage with poorly defined collapsible mineral, Sample H706, Bed D8, Berriasian. (b) Kaolin-mica assemblage with poorly defined collapsible mineral containing minor smectite, Sample H707, Bed 2E, uppermost Valanginian/lowest Hauterivian. (c) Kaolin-mica assemblage with poorly defined collapsible mineral containing vermiculite, Sample H711, Bed C8, Hauterivian. (d) Kaolin-mica assemblage with poorly defined collapsible mineral, Sample H712, Middle B Cement Beds, Barremian.

et al., 1991). Considerable attention (Knox, 1991; Allen, 1998; Jeans et al., 2005) has been given to the 'kaolinite event' of Allen (1998) in the Purbeck Limestone Group, and to the possible use of kaolinite/illite or mica/kaolin ratios for correlating between the pre-Aptian Lower Cretaceous strata situated to the south and north of the Anglo-Brabant massif.

Spilsby Basin. Perrin (1971) contains no clay mineral analyses from the pre-Aptian strata of the Spilsby Basin. Sladen (1980) has 72 analyses from these strata, including samples from boreholes at Skegness, Hunstanton, Gayton and Marham

(Fig. 5); these were summarized in Sladen (1983, his fig. 3). Jeans et al. (2000, 2001) included *REE* analyses and K/Ar data from two samples of the Roach Ironstone Formation. Tables 13−16 contain 84 unpublished clay mineral analyses from the Hunstanton, Skegness, Fordingham and Alford boreholes (Fig. 5) as well as from a surface locality between Spilsby and Partney in Lincolnshire. The XRD patterns of a range of typical clay mineral assemblages are illustrated in Fig. 20. Examples of grain size-related mineralogical variation within the clay assemblages are shown in Fig. 21.
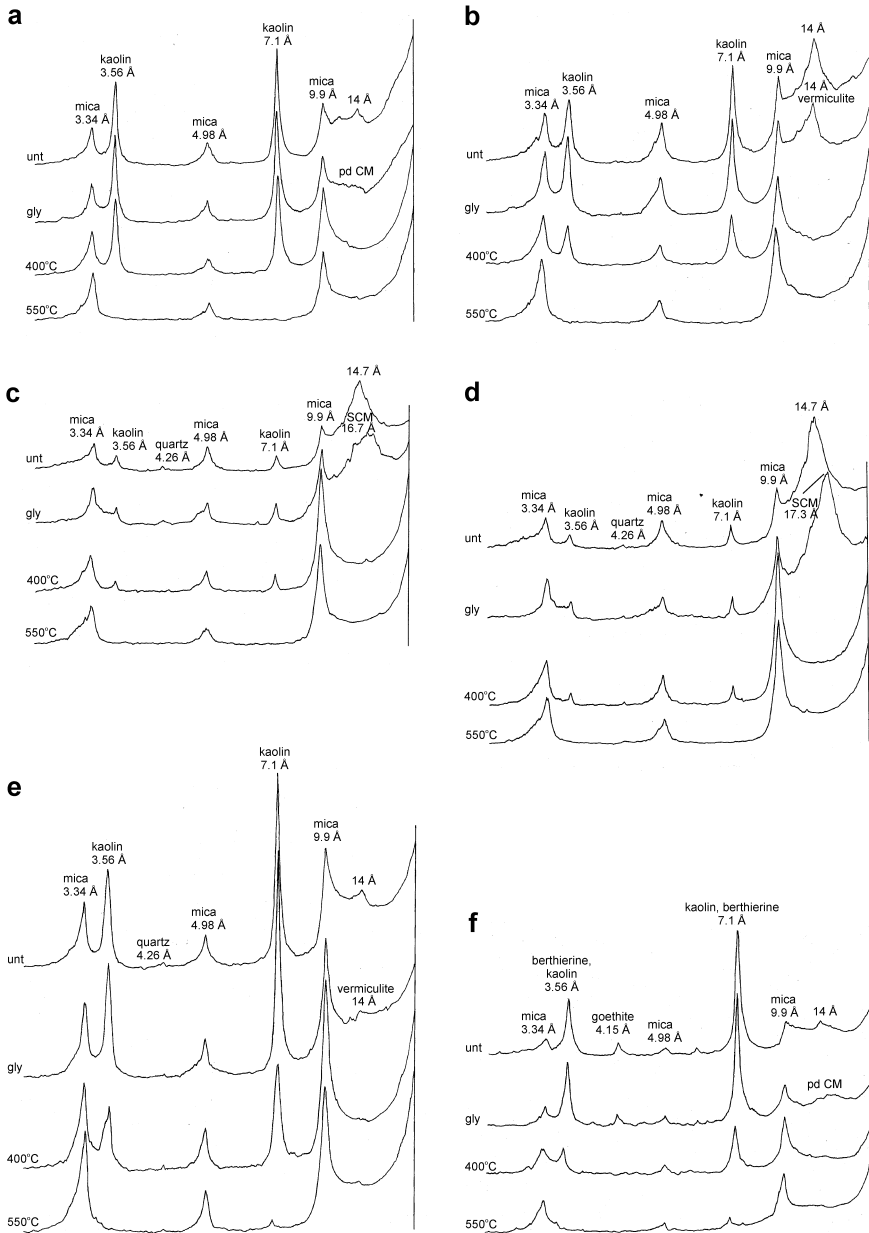
FIG. 20. XRD patterns of clay mineral assemblages (<2 μm) from the pre-Aptian Lower Cretaceous strata of the Spilsby Basin. Abbreviations as in Fig. 7. (a) Kaolin-mica assemblage with poorly defined collapsible mineral, Spilsby Sandstone, Fordington Borehole, 69.98 m. (b) Kaolin-mica assemblage with poorly defined collapsible mineral with vermiculite, Lower Tealby Clay, Alford Borehole, 68.58 m. (c) Smectite-mica assemblage with collapsible mineral containing smectite and vermiculite, Tealby Limestone, Alford Borehole, 64.50−64.92 m. (d) Smectite-mica assemblage with conspicuous smectite, Upper Tealby Clay, Alford Borehole, 58.52−60.96 m. (e) Berthierine in a kaolin-mica assemblage with poorly defined collapsible mineral containing vermiculite, Roach Ironstone Fm., Skegness Borehole, 59.44 m. (f) Berthierine dominated clay assemblage from the Roach Ironstone Fm., Skegness Borehole, 62.64 m.

Spilsby Basin: Spilsby Sandstone Formation. Seven analyses show that the clay mineral assemblages contain varied proportions of kaolin, mica and poorly defined collapsible minerals (Table 13). Those from the Fordingham Borehole are dominated by mica and poorly defined collapsible minerals, whereas those from the Skegness Borehole are dominated by mica and kaolin. Sand-grade glauconite is abundant in the lower part of Spilsby Sandstone.

Spilsby Basin: Claxby Ironstone Formation. Three clay mineral analyses from the Alford
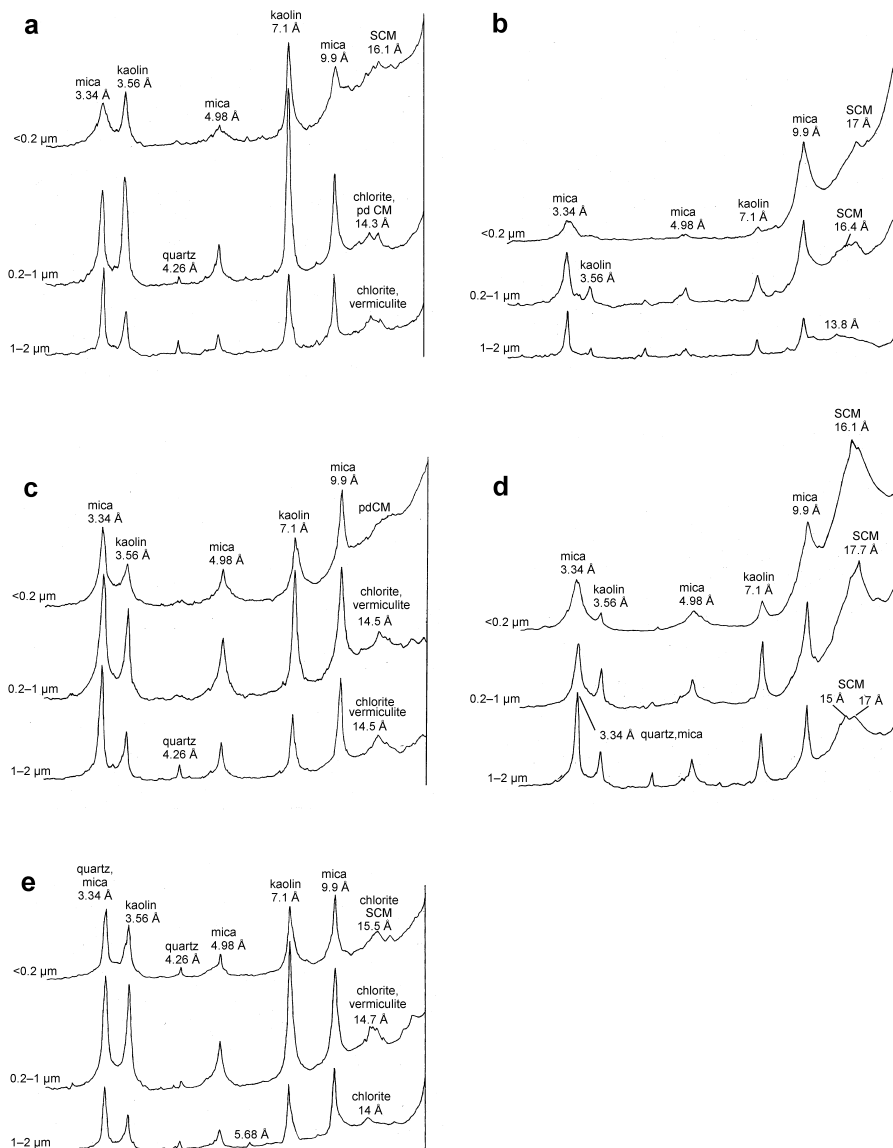
FIG. 21. XRD patterns of glycerolated clay fractions (<0.2 μm, 0.2−1 μm, 1−2 μm) showing the grain size-related mineralogical variations in <2 μm clay mineral assemblages form the pre-Aptian Lower Cretaceous strata of the Spilsby Basin. Abbreviations as in Fig. 7. (a) Roach Ironstone Fm., Skegness Borehole, 59.44 m. (b) Roach Ironstone Fm., Skegness Borehole, 65.53 m. (c) Tealby Fm., Skegness Borehole, 79.25 m. (d) Tealby Fm., Skegness Borehole, 85.34 m. (e) Tealby Fm., Skegness Borehole, 97.54 m.

Borehole and six from the Skegness Borehole are shown in Table 13. The assemblages are dominated generally by mica and poorly defined collapsible minerals containing vermiculite; kaolin occurs throughout both as a major and lesser component.

Spilsby Basin: Tealby Formation. Twelve clay mineral analyses from the Alford Borehole and 20 from the Skegness Borehole are shown in Table 14. All the assemblages are dominated by mica and collapsible minerals, with kaolin as a lesser component. There are major stratigraphical and regional differences in the composition of the collapsible minerals. In the Alford Borehole, smectitic minerals are widespread and are particular prominent in the Tealby Limestone and lower part of the Upper Tealby Clay. Vermiculite is also present but it displays an overall antipathetic relationship to the smectitic minerals. In the Skegness Borehole, the Tealby Limestone is not present and the three-fold subdivision of the Tealby Formation is not recognized. The collapsible minerals are generally poorly defined and contain vermiculite; smectitic minerals are not conspicuous and are restricted to a few samples only. Sample 85.34 from the Skegness Borehole contains a green glauconitic clay mineral assemblage, with its glauconitic components (glauconite/nontronite) being restricted largely to the <0.2 μm and 0.2−1 μm fractions (Fig. 21d). Sand-grade glauconite may be abundant in the Lower Tealby Clay.

Spilsby Basin: Runcton Member. The single clay mineral analysis (Table 15) contains kaolin, mica and poorly defined collapsible minerals in approximately equal amounts. Sand-grade glauconite may be very abundant (Gallois, 1994).

Spilsby Basin: Mintlyn Member. The three analyses in Table 15 contain mica, kaolin and poorly-defined collapsible minerals with vermiculite as their major components. Sand-grade glauconite may be abundant (Gallois, 1994).

Spilsby Basin: Leziate Member. Six clay mineral analyses are shown in Table 15: the majority are dominated by kaolin (up to 79%) with lesser amounts of mica; poorly defined collapsible minerals with or without vermiculite are usually present. Sladen (1980) reports the presence of both quartz overgrowths on the sand grains as well as authigenic kaolin. Sand-grade glauconite may occur locally in the Leziate Member (Gallois, 1994).

Spilsby Basin: Dersingham Formation. The four analyses in Table 15 contain mica, poorly defined,

collapsible minerals and kaolin as major components. Vermiculite is present.

Spilsby Basin: Roach Ironstone Formation. Twenty two clay mineral analyses are shown in Table 16. They reveal lateral variations in the clay mineral assemblages between the Alford, Skegness and Hunstanton boreholes. Berthierine is abundant in the Alford and Skegness boreholes making up to 50% of the clay mineral assemblage. Kaolin is restricted to the lower part of the formation. Mica or collapsible minerals are usually dominant. The collapsible mineral in the Alford Borehole is poorly defined: it lacks vermiculite, but shows traces of smectitic mineral. In the Skegness Borehole, most of the analyses contain poorly defined collapsible minerals with vermiculite; a few contain traces of a smectitic component. The Roach Ironstone Formation in the Hunstanton Borehole contains no berthierine, only kaolin in association with mica and usually poorly defined collapsible minerals containing vermiculite. Sample 65.53 from the Skegness Borehole contains a green glauconitic clay mineral assemblage with the glauconitic components being restricted largely to the <0.2 μm and 0.2−1 μm fractions (Fig. 21b).

Discussion. The relationship between the clay mineralogy and chronostratigraphy of the pre-Aptian strata of the Cromer Knoll Group in the Cleveland and Spilsby basins is shown in Figs 22−24. The analyses of Knox (1991) have been used for the Cleveland Basin; however, these were based on the <4 μm fraction and are therefore not strictly comparable to the <2 μm analyses used for the Spilsby Basin. Knox (1991) does not differentiate between poorly defined collapsible minerals, vermiculite and smectitic minerals, but instead referred to these three different types of collapsible minerals as smectite, whereas in the Spilsby Basin both vermiculite and smectitic minerals are present (Fig. 22). The distribution of mica (Fig. 24) does not display any clear stratigraphical pattern; in the Ryazanian-Lower Barremian it is most abundant in the Skegness Borehole and decreases in abundance to the north towards Alford and Speeton, and south towards Hunstanton. In the Lower and Upper Barremian large values for mica are most widespread at Hunstanton. The distribution of collapsible minerals (Fig. 22) shows a strong regional pattern. There is an oscillatory up-sequence increase in the Alford Borehole where the Ryazanian-Hauterivian strata are dominated by values of 20−49%, whereas the
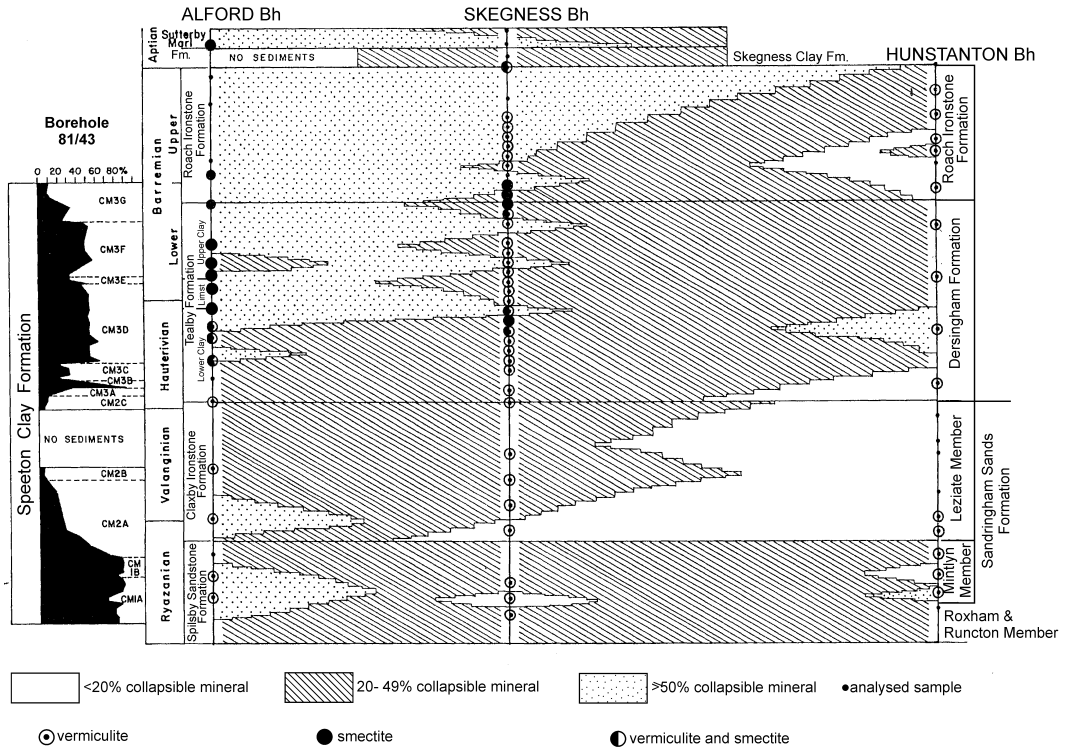
FIG. 22. Chronostratigraphical distribution of the total collapsible clay minerals, smectite and vermiculite in the <2 μm clay assemblages from the pre-Aptian Lower Cretaceous strata of the Cleveland and Spilsby Basins. The data and clay mineral zonation (CM1A–CM3G) for the Cleveland Basin are from Knox (1991). The vertical scale varies both within and between the different boreholes.

upper part of the section is dominated by values of 50% and more. In the Skegness Borehole, this change takes place within the Barremian stata. The clay mineral assemblages from the Hunstanton Borehole usually have relatively small contents of collapsible minerals. There is no obvious correlation between the variations in the mica and collapsible minerals in the Speeton Clay and in the various formations of the Spilsby Basin. Smectite is largely restricted to the Hauterivian and Lower Barremian beds of the Alford and Skegness boreholes: they are best developed in the Tealby Limestone and Upper Tealby Clay of the Alford Borehole. Vermiculite occurs widely and shows no obvious stratigraphical or regional pattern. In samples enriched in smectitic minerals, vermiculite is usually absent. Figure 23 shows that there is no clear stratigraphical correlation with the kaolin distribution. High kaolin values typify the pre-Aptian succession in the Hunstanton Borehole but the kaolin values decrease northwards to Skegness and Alford.

There is no obvious correlation between the kaolin patterns in the Spilsby and Cleveland Basins. The high kaolin contents in the Leziate Member and the lower part of the Dersingham Formation could be considered as stratigraphically equivalent to the presumably detrital kaolin high in the Valanginian beds of the Speeton Clay (Hallam *et al.*, 1991; Knox, 1991); however, Sladen's (1980) recognition of authigenic kaolin in the Leziate Member indicates that this correlation may have little significance. Berthierine is restricted to the Roach Ironstone Formation in the Alford and Skegness boreholes.

APTIAN–LOWER ALBIAN STRATA

The stratigraphical scheme used for the Aptian–Lower Albian strata is shown in Fig. 25.

The strata, of marine facies, occur in eastern and southern England (Fig. 26) but do not extend over the London Platform. In the Cleveland Basin they
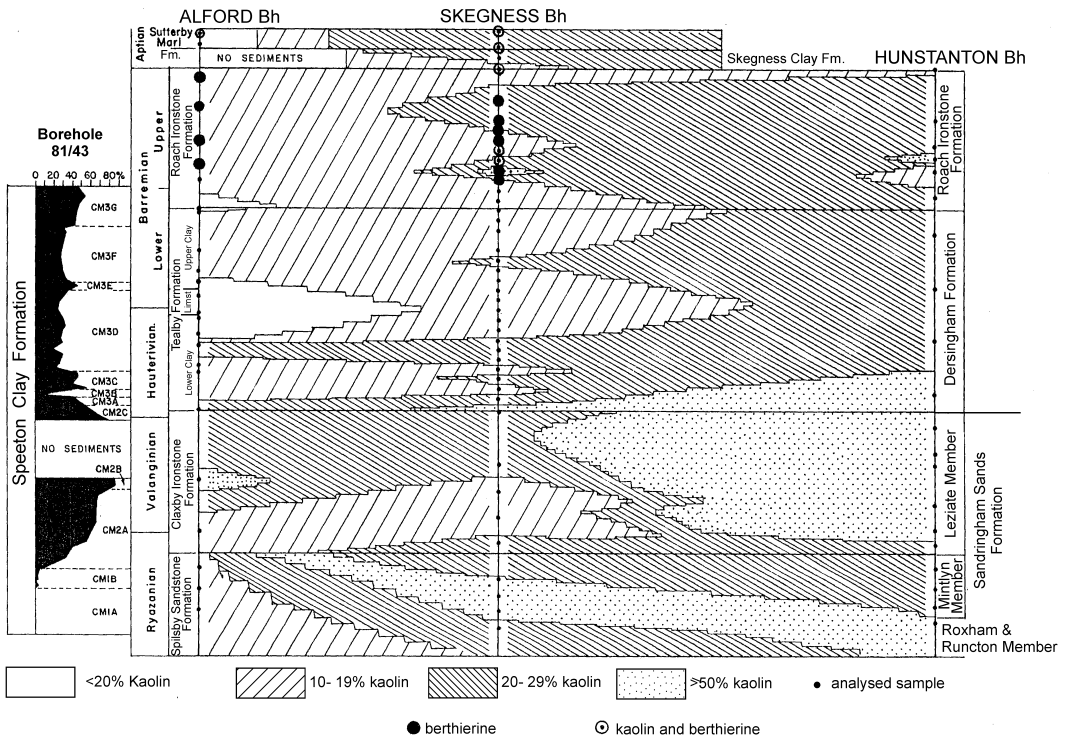
FIG. 23. Chronostratigraphical distribution of kaolin and berthierine in the <2 μm clay assemblages from the pre-Aptian Lower Cretaceous strata of the Cleveland and Spilsby Basins. Nature of vertical scales and source of Cleveland Basin data as for Fig. 21.

consist of ~3 m of clay that forms the top part of the Upper B Beds and Beds A4 and A5 of the Speeton Clay. In the Spilsby Basin the Aptian–Lower Albian strata form part of the Cromer Knoll Group; they consist of ~4 m of clay (Skegness Clay, Sutterby Marl formations) which are overlain by the ferruginous, gritty and sandy Carstone Formation (up to 19 m). In southern England, the Aptian and Lower Albian are represented by the Lower Greensand Group comprising the Atherfield Clay Formation (clays, silts) overlain by predominantly sandy strata which display considerable lateral and vertical variation and includes cherts, limestones and beds of clay (fullers' earths) and silts. In the Wealden Basin, the sandy part of the Lower Greensand is divided into the Hythe Formation (locally with cherts/limestones), the Sandgate or Bargate Formation (locally with fullers' earth seams) and the Folkestone Sand Formation. Sand-grade glauconite is widespread and may be locally abundant. In the southern part of the Weald Basin, the Atherfield Clay appears to

be missing and the overlying formational divisions are not clearly differentiated. In the Wessex Basin, the sandy beds overlying the Atherfield Clay are called the Ferruginous Sands Formation; they are well exposed in the cliffs of the Isle of Wight and south Dorset. In Bedfordshire, Buckinghamshire and Oxfordshire, outliers of sandy Lower Cretaceous strata are included in the Lower Greensand. The XRD patterns of a range of typical clay assemblages from the Lower Greensand are illustrated in Figures 27 and 28.

Sutterby Marl and Skegness Clay Formations. Table 17 includes five analyses from these formations. The clay mineral assemblage from the Skegness Clay is dominated by collapsible minerals with lesser amounts of mica and kaolin; vermiculite is present. The clay mineralogy of the Sutterby Marl is dominated by collapsible minerals and mica with lesser amounts of kaolin and berthierine.

Carstone Formation. Perrin (1971) included seven analyses from locations in Norfolk, Cambridgeshire and Bedfordshire. The clay mineralogy is dominated
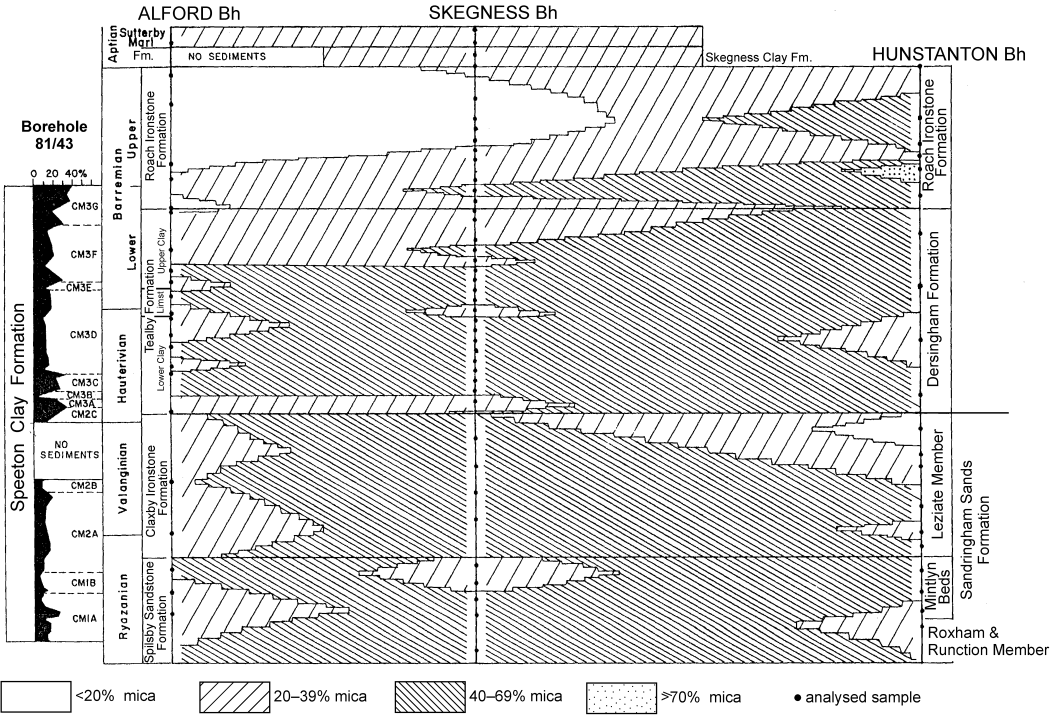
FIG. 24. Chronostratigraphical distribution of mica in the <2 μm clay assemblages from the pre-Aptian Lower Cretaceous strata of the Cleveland and Spilsby Basins. Nature of vertical scales and source of Cleveland Basin data as for Fig. 21.

by mica and kaolin associated with an abundance of goethite and amorphous Fe oxides/hydroxides; vermiculite is present in two of the analyses. Four new analyses are shown in Table 17. Assemblages are dominated by vermiculitic and smectitic collapsible minerals with lesser amounts of mica

FIG. 25. Stratigraphical scheme used in the description of the clay mineralogy of the Aptian-Albian strata in England.
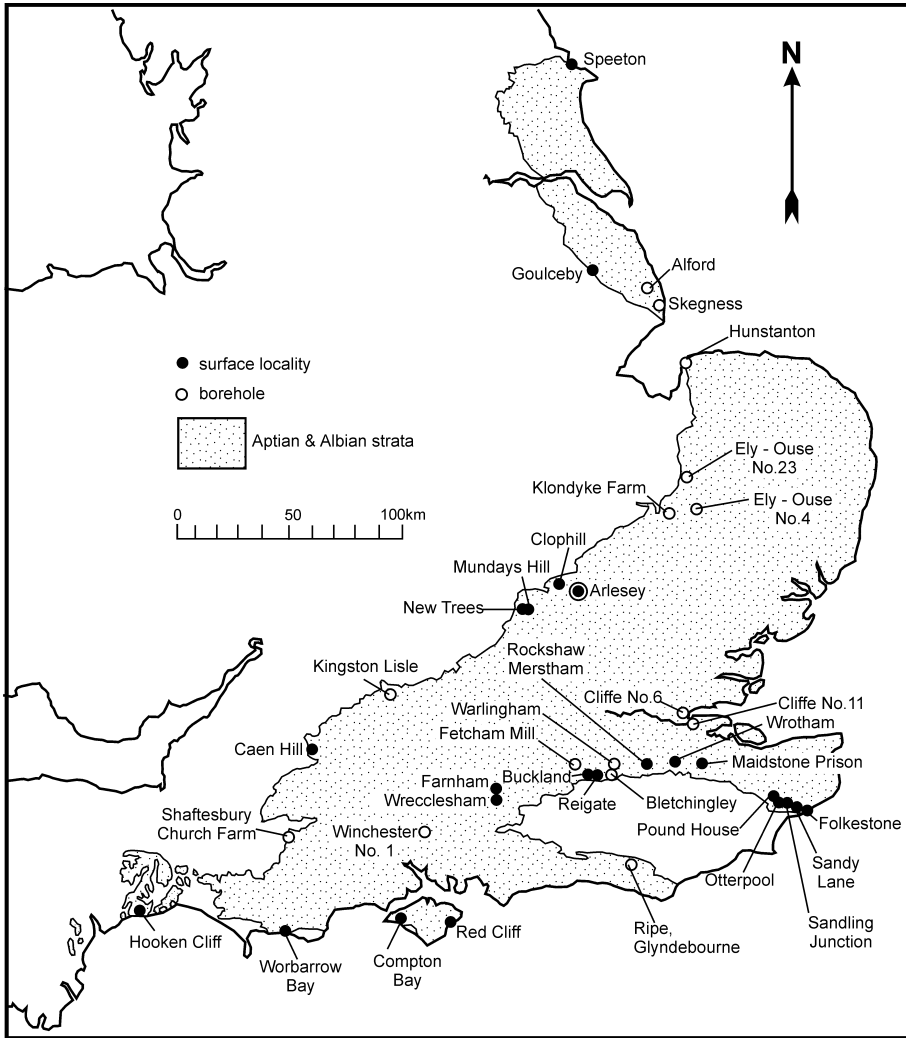
FIG. 26. Outcrop and sub-crop distribution of Aptian-Albian strata in England (based on Whitaker, 1985). Boreholes and locations mentioned in the text are shown.

and kaolin. In the Carstone of the Hunstanton Borehole, berthierine occurs as a cement and as ooliths (Gallois, 1994, p. 103) although it has not be found in sample 36.58 (Table 17).

Lower Greensand Group

Atherfield Clay Formation. The Atherfield Clay is represented by 19 analyses (Table 18). In the Weald Basin the most complete succession is the Maidstone Prison No. 6 Borehole (Jeans *et al.*, 1982, their fig. 15). Here, the lower and main part

of the formation is characterized by mica, kaolin and collapsible minerals dominated by vermiculite, whereas in the upper part mica and kaolin decrease, with an increase in collapsible minerals, which become more smectitic. To what extent this stratigraphical pattern occurs over the Weald Basin is not clear. At Sandgate and in the Warlingham Borehole it appears to be present. At Hammer (Haslemere), the clay mineral assemblages are dominated by mica and kaolin, with collapsible minerals containing minor vermiculite; these assemblages appear to be similar to those that
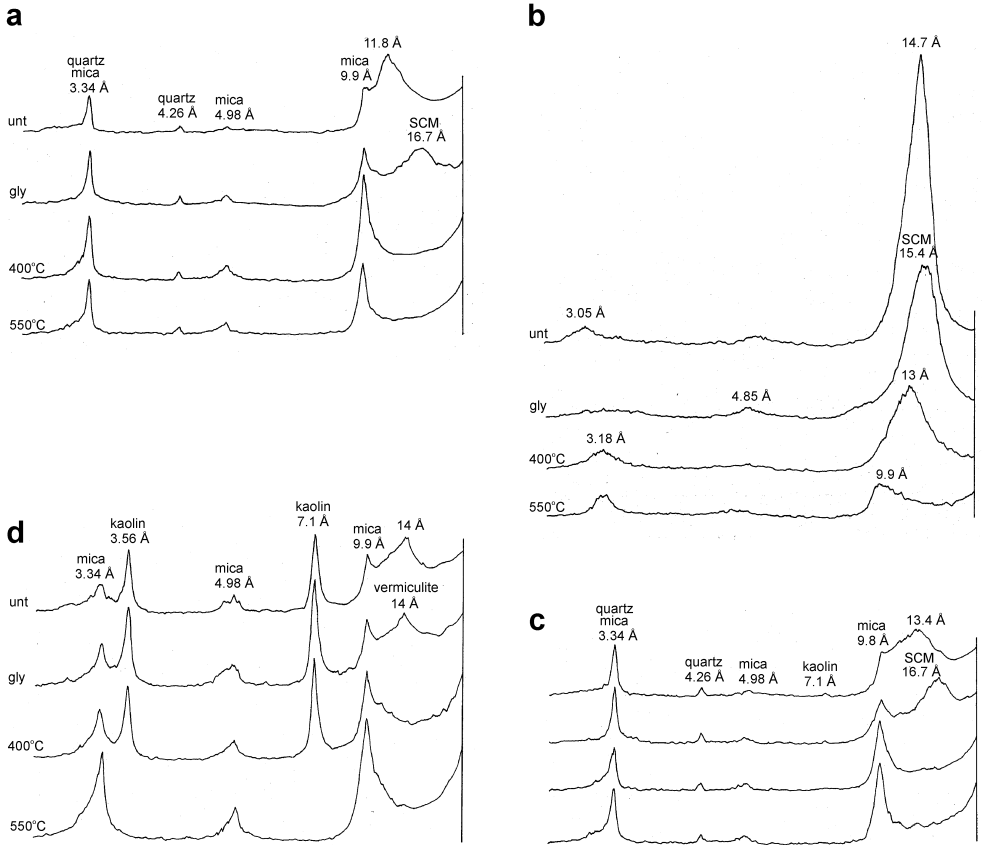
FIG. 27. XRD patterns of clay mineral assemblages (<2 μm) from the Lower Greensand (Aptian−Lower Albian) of southern England. Abbreviations as in Fig. 7. (a) Smectite-mica assemblage of Sample KR55 from the Hythe Beds, Otterpool, Kent. (b) Smectite assemblage of fullers' earth sample 204/5 from the Sandgate Beds, Bletchingley, Surrey. Water House Farm Borehole, 24.03 m. (c) Smectite-mica assemblage of Sample 204/7 from the Sandgate Beds, Bletchingley, Surrey. Water House Farm Borehole, 24.56 m. (d) Kaolin-mica assemblage with poorly defined collapsible mineral containing vermiculite from Sample IOW31, Ferruginous Sands, Compton Bay, Isle of Wight.

occur at the base of the formation at Maidstone (Sample KR36, Jeans et al., 1982, their fig. 15). The Atherfield Clay is not recognized in the Ripe or Hampden Park boreholes in Sussex (Lake et al., 1987). In the Wessex Basin (Winchester no. 1 Borehole and in the Isle of Wight) the Atherfield Clay does not appear to display any systematic stratigraphical change in clay mineralogy, albeit the number of analyses is small.

Hythe Formation. There is a single clay mineral analysis in Perrin (1971) and 16 new analyses are shown in Table 19. The clay mineral assemblages are typically lacking in kaolin (or it is present in very minor amounts) whereas smectitic collapsible

minerals and mica predominate; some of these assemblages were illustrated by Jeans et al. (1982, their fig. 9). Sand-grade volcanogenic glauconite grains have been recorded from Otterpool, Kent (Jeans et al., 1982, their fig. 6a,b).

Sandgate Formation. Eleven new clay mineral analyses are shown in Table 19. Knowledge of the clay mineralogy of the Sandgate Formation is very patchy. In those areas where fullers' earths have been discovered, considerable attention has been paid to the mineralogy, origin and use of the seams (Robertson, 1986), whereas little or no attention has been given to the intervening sandy strata. The clay mineral assemblages of these sandy beds are
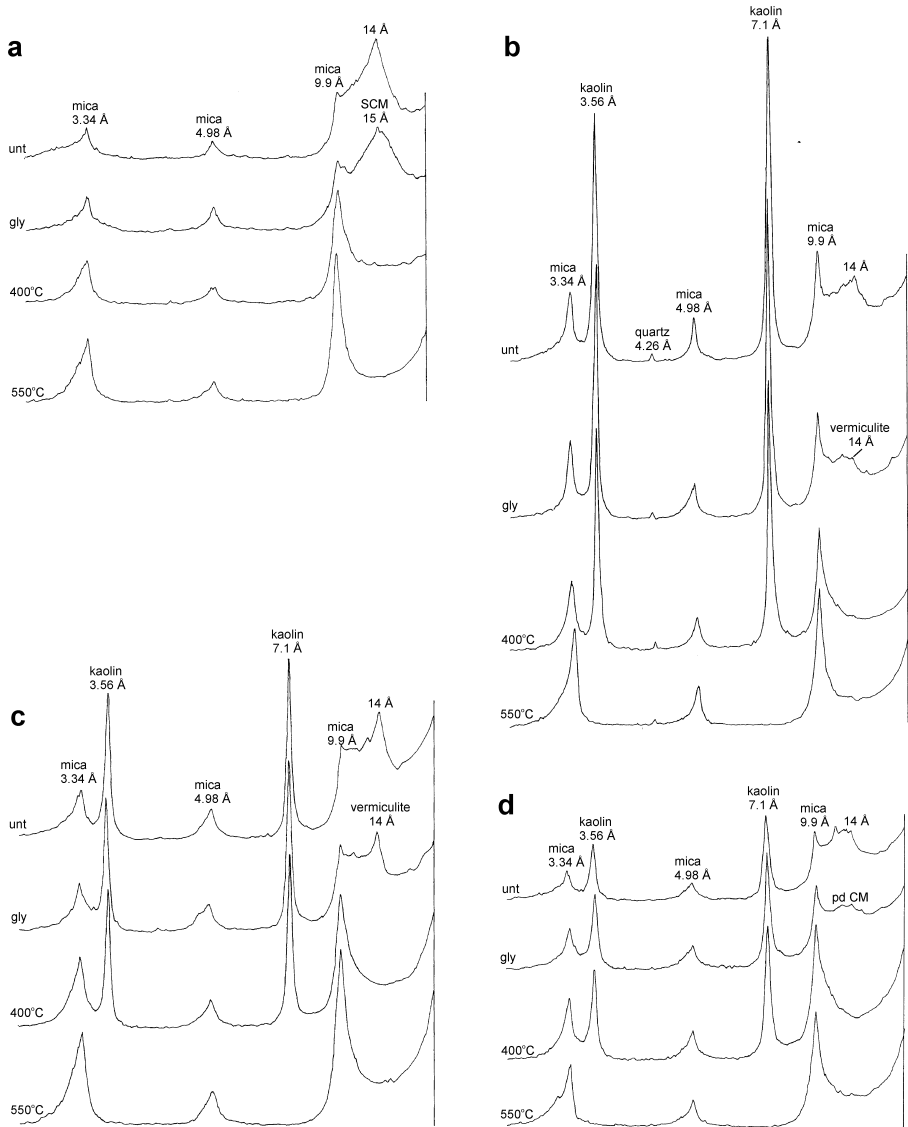
FIG. 28. XRD patterns of clay mineral assemblages (<2 µm) from the Lower Greensand (Aptian−Lower Albian) of southern England. Abbreviations as in Fig. 7. (a) Smectite-mica assemblage with conspicuous poorly defined smectitic collapsible mineral, Sample KR41, Folkestone Beds, Sandy Lane, Kent. (b) Kaolin-rich assemblage with mica and vermiculitic collapsible mineral, sample SuS15, Folkestone Beds (Silt Band; Morgan *et al*., 1979), Reigate. (c) Kaolin-mica assemblage with conspicuous vermiculitic collapsible mineral, Sample SuR5, Folkestone Beds (clay lenticle inside an Fe oxide concretion), Coxbridge, Farnham. (d) Kaolin-mica assemblage with poorly defined collapsible mineral, Sample IOW 30, Sandrock Formation, Compton Bay, Isle of Wight.

different from the fullers' earth seams. They are commonly glauconitic, and consist of smectite and other collapsible minerals with or without mica, in some cases with a trace of kaolin; their XRD patterns (Fig. 27c) are usually of low relative intensity, resulting from the presence of clay-grade quartz and possibly amorphous diluents. The clay mineralogy assemblages of the fullers' earth seams consist only of smectite (Fig. 27b). The smectite is a Ca^{2+} montmorillonite with lath-shaped

crystals (Perrin, 1971; Neumann, 1976) which may form >90% of the bulk sediment. In fresh, unoxidized samples of fullers' earth seams the montmorillonite occurs as sand-to-clay grade aggregates (Jeans *et al.*, 1977, their fig. 7) which represent the argillization product of volcanic glass particles laid down as sediment on the seafloor and subsequently been altered during diagenesis. In oxidized or weathered fullers' earth seams, these clay aggregates have commonly broken down into their component crystals of clay minerals. Other volcanoclastic grains are present: these include high-temperature feldspar, zircon, sphene, apatite, volcanic rock fragments and devitrified and zeolitized glass (Jeans *et al.*, 1977). Further details on the structure, chemistry (major and trace elements including *REE* elements: K/Ar, ^{40}Ar/^{39}Ar isotopes) and origins were given by Jeans *et al.* (1977, 1982, 2000, 2001).

The fullers' earth seams in the Sandgate Formation may by up to >5 m thick and are of lenticular form, up to hundreds of metres in extent (Knox *et al.*, 1998). They are considered to be secondary bentonites derived from volcanic ash predominantly of trachytic composition that was either washed in from adjacent land areas and concentrated locally in the marine environment or, perhaps less likely, represent the concentration by marine currents of volcanic ash that fell directly into the shallow marine environment in which the Sandgate Beds were deposited (see also Young & Morgan, 1981; Knox *et al.*, 1998; Goldring, 1999). The ash contained material of more than one age. The high-temperature sanidine feldspar gives a ^{40}Ar/Ar^{39} date of 112 Ma (Jeans *et al.*,1982) whereas Dr A.J. Hurford (pers. comm.) obtained dates of 136±15, 141±17 and 142±15 Ma by fission-track methods for sphene crystals, coming from the main fullers' earth seam at Patteson Court, Redhill. Jeans *et al.* (1977) suggested that the volcanic ash might have been derived from the Zuidwal volcano, now buried beneath a thick cover of Lower Cretaceous and younger rocks. Volcanic rocks, containing abundant accessory titanite (Jeans *et al.*, 1977, p. 41), from the throat of this volcano have given total rock K/Ar ages ranging from 92 to 119 Ma (Jeans *et al.*, 1977); ^{40}Ar/^{39}Ar ages of 144±1 Ma) (Dixon *et al.*,1981), and ^{40}Ar/^{36}Ar-^{40}K/^{36}Ar of 152±3 Ma (Perrot & van der Poel, 1987). The Zuidwal volcano is covered by Valanginian sediments (Cotterçon *et al.*, 1975; Perrot & van de Poel, 1987) which predate the Aptian age of the Sandgate Beds. The source or sources of the volcanic ash that gave rise to the Aptian fullers' earths are most likely undiscovered volcanoes in the southern North Sea Basin. Analyses of samples from the Sandgate Beds in areas where fullers' earths are not present (Sandgate; Saltwood; Seale; Cliffe No. 6 Borehole) show clay assemblages dominated by smectitic collapsible minerals with varying amounts of mica. In the Cliffe No. 6 Borehole, some samples contain only smectite (Fig. 37; Table 23c).

Folkestone Sands Formation. Thirty-two new analyses from the Folkestone Sands Formation are listed in Table 19. This formation consists predominantly of cross-bedded sands, generally with little or no clay. Clay seams may occur as thin drapes on the foresets of current-bedded sands as well as thicker seams associated with the bottom-set (Jeans *et al.*, 1982, their fig. 9: see Allen, 1982 for an alternative explanation). Late-stage diagenetic Fe oxide/hydroxide beds and concretions of limited lateral extent are not uncommon and may replace clay seams (e.g. Jeans *et al.*, 1982, their fig. 10). Samples of unaltered clay can sometimes be obtained from inside the diagenetic concretions (Fig. 28c; Table 19, Coxbridge analyses). Sand-grade glauconite may be common, particularly in the eastern part of the Weald Basin in the Folkestone area. The sandy sediments at and near the top of the Folkestone Beds commonly contain some clay-and silt- grade material. It is possible that some of this may have its origin by translocation from the overlying clays of the Gault (e.g. Wrecclesham, Table 19).

There is considerable lateral and vertical variation in the clay mineralogy of the Folkestone Beds (Jeans *et al.*, 1982, their fig. 16). Samples from the eastern part of the Weald Basin (i.e. Kent) have assemblages dominated by mica and smectitic collapsible minerals (e.g. Fig. 28a) with glauconitic clay assemblages being common. Kaolin, if present, is a minor or trace component. The XRD patterns from such assemblages were illustrated by Jeans *et al.* (1982, their figs 9, 10). In the northern part of the Weald Basin, the clay mineral assemblage is very different with kaolin or kaolin and mica being the dominant components (Table 19), whereas glauconite is much less common, and ferruginous sands and ironstones are much more common. Morgan *et al.* (1979) have interpreted the glauconitic silt band (up to 3 m) described by Dines & Edmunds (1933, p. 74) from the upper part

of the Folkestone Beds of Reigate as an impure smectitic fullers' earth which has been extensively kaolinitized during late-stage diagenesis (Fig. 28b, Table 19). Assemblages from the western part of the Weald (Coxbridge, Wrecclesham, Great Holt, Table 19) are dominated by mica and kaolin, in some cases with vermiculite also (Fig. 28c). The presence of glauconite sand grains of volcanogenic origin in the Folkestone Beds in the eastern part of the Weald Basin, and their association with clay mineral assemblages rich in smectite and glauconite (Jeans *et al.*, 1982, their figs 6c,d,e, 9, 10) suggest a volcanic source of unstable silicate material. The westward change to clay mineral assemblages dominated by kaolin and mica is paralleled by a loss of glauconite, the development of late-stage diagenetic ironstones and the presence of ferruginous sands. On present evidence it is possible that the circulation of acidic and oxidizing porewater through the very permeable Folkestone Beds has been the major cause, but not necessarily the only factor, in these lateral changes in clay mineral assemblages. It is also possible that original regional variations in the assemblages are still partially preserved.

Undifferentiated Lower Greensand Group, Wealden Basin

Table 20 shows new clay mineral analyses from the Lower Greensand Group of the Ripe and Hampden Park boreholes from the Lewes district, Sussex. The XRD patterns from the Ripe Borehole are illustrated in Fig. 29. Lithologically the beds are variable with green glauconitic clays, sandy clays and silts overlain by fine-grained sands; the undifferentiated successesion here is considered to be stratigraphically equivalent to the Hythe Beds and part of the Sandgate and Folkestone Beds (Lake *et al.*, 1987, pp. 36–40). The basal part of the succession in the Ripe Borehole is characterized by glauconitic clay mineral assemblages with traces of kaolin. These pass up into assemblages dominated by smectitic collapsible minerals with lesser amounts of mica and traces of kaolin. Above the ~20 m level, kaolin and mica increase at the expense of collapsible minerals, which may vary from being poorly defined, to vermiculitic or smectitic. In the Hampden Park Borehole, the clay mineral assemblages are dominated by mica and collapsible minerals (usually smectite) with kaolin as a persistent but minor component. Two thin

fullers' earth seams (27.60–27.83 m, 30.27–30.59 m), presumably smectitic, are present (Lake *et al.*, 1987, p. 40).

Ferruginous Sands Formation, Wessex Basin

The clay mineral stratigraphy of the Lower Greensand Group of the Wessex Basin is poorly known in spite of the excellent cliff exposures on the east and west coasts of the Isle of Wight. Perrin (1971) included two clay mineral analyses from the Ferruginous Sands: one sample came from the Carstone (not to be equated with the Carstone Formation of eastern England), the other from the Sandrock Formation. Both samples were dominated by mica and kaolin. A single clay mineral analysis from the Sandrock Formation, Isle of Wight, is illustrated in Jeans *et al.* (1982, their fig. 16; see also Fig. 28d). Ruffell *et al.* (2002) described the chemistry of a thin smectitic fullers' earth from the Ferruginous Sands, and McCarty *et al.* (2004) described clay mineral assemblages containing glauconite (*sensu stricto*), nontronite and mixed-layer clay minerals of glauconite, nontronite and berthierine.

Twenty three new analyses from the Isle of Wight and from Worbarrow Bay are included in Table 21. The Ferruginous Sand sequence at Compton Bay, Isle of Wight, contains clay mineral assemblages dominated by mica and collapsible minerals. Kaolin is an important component (up to 30%) in most assemblages, although at two levels (samples IOW 22 and 27, Table 20) it drops below 10%. The collapsible mineral is often strongly vermiculitic (Fig. 27d) The Worbarrow Bay section (Fig. 30) of the Ferruginous Sands contains clay mineral assemblages dominated usually by mica with considerable kaolin, although at the base a poorly ordered kaolin mineral is dominant (86%). The collapsible mineral is typically poorly defined.

Outliers of Lower Greensand Group

Woburn Sand Formation, Leighton Buzzard, Bedfordshire. This formation consists predominantly of brown sands, silver sands with Fe-cemented sandstone (Carstone), silty beds and red sands (see Shephard-Thorn *et al.*, 1994 for further details). Lenticular fullers' earth seams (up to 3.75 m) consisting largely of Ca^{2+} smectite, occur at several horizons. Some thin fullers' earth seams
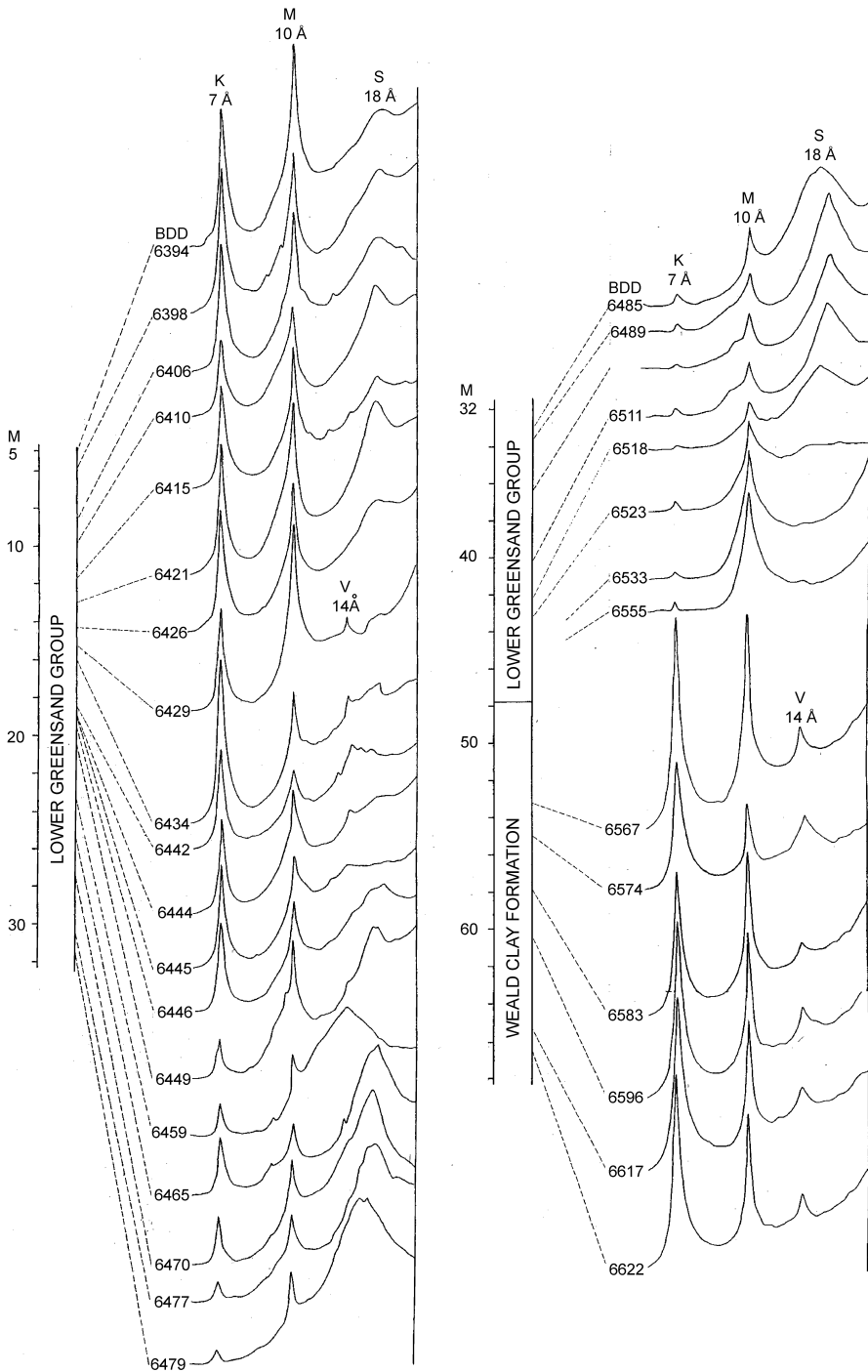
FIG. 29. Clay mineral stratigraphy of the undifferentiated Lower Greensand (Aptian, Lake *et al.*, 1987) of the Ripe Borehole, Sussex. K = kaolin, M = mica, V = vermiculite, S = smectite.
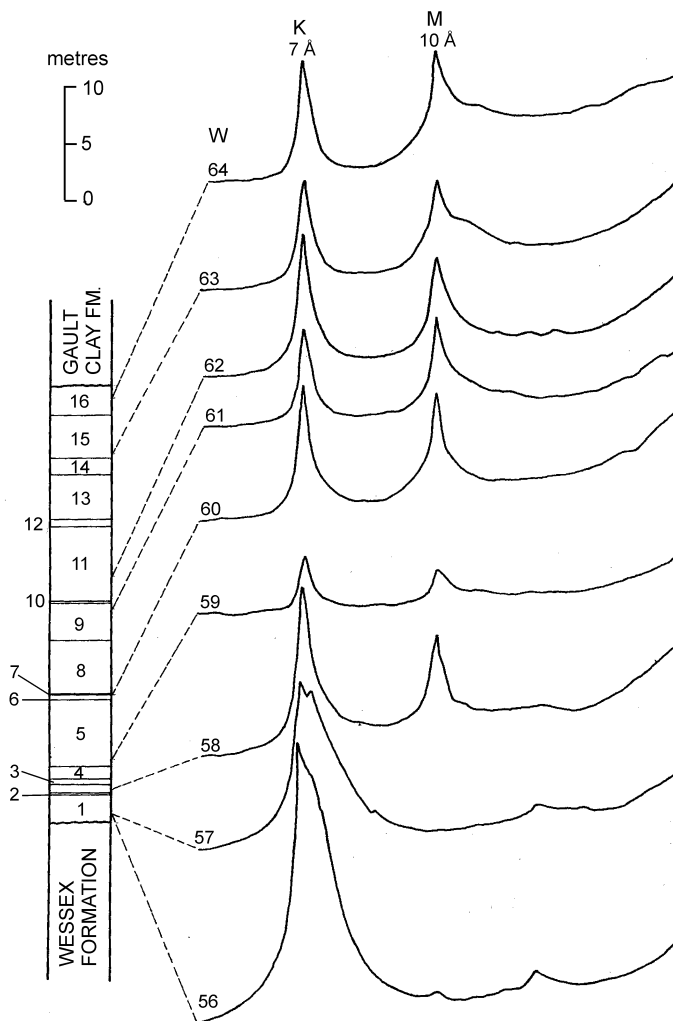
FIG. 30. Clay mineral stratigraphy of the Lower Greensand at Worbarrow Bay, Dorset. Bed numbering follows Arkell (1947, pp. 175−176). Samples collected and donated by Mr N.F. Hughes. K = kaolin, M = mica.

show considerable variation in clay mineralogy (Shephard-Thorn *et al*., 1994, p. 39) ranging from pure smectite to mixed-layer smectite-mica and mica with only traces of smectite. Samples from the main fullers' earth seam at Aspley Heath have been analysed in detail (Cowperthwaite *et al*., 1972; Jeans *et al*., 1977, 2000, 2001). A point of particular interest is that the main fullers' earth seam displays small-scale cross-bedding in spite of its clay composition (Cowperthwaite *et al*., 1972), a feature that was also present in the fullers' earth main seam in the Sandgate Formation at Patterson Court, Surrey (Jeans *et al*., 1977). This cross-

bedding is not present in the thin seams, although it may have been destroyed by bioturbation and by late-stage diagenesis. Twelve new analyses from the Woburn Sands at three locations are listed in Table 22. The clay mineral assemblages from the Red, Silver and Brown Sands in Munday Hills Pit and the New Trees Pit at Leighton Buzzard are dominated by smectitic collapsible minerals and mica with lesser amounts of kaolin; the same assemblage also characterizes a 12 m sequence of sands, ferruginous sands alternating dark clay and sand located to the east of Clophill which was sampled in 1975.

Faringdon Sponge Gravels and associated strata, Berkshire. In the Fernham and Baulking areas of Berkshire the Lower Greensand consists of a lower, commonly glauconite-rich, sandy unit and an upper clay unit with some thin sands and ironstones. The Faringdon Sponge Gravels are a local facies at the base of the Lower Greensand, and its clay mineralogy (based on three samples) is dominated by mica and smectite, although in one sample there is some kaolin (Perrin 1971, p. 144). The Institute of Geological Sciences carried out in 1969 a detailed exploration and research programme of these Lower Greensand deposits in a search for fullers' earth seams (Poole *et al*., 1971; Poole & Kelk, 1971). Two important seams were found in the lower sandy division of the Lower Greensand and their sedimentology was discussed by Goldring (1996, 1999). The fullers' earth seams consist of Ca^{2+} montmorillonite only, but the clay mineral assemblages of the sandy beds may contain mica and a little kaolin in addition. The upper clayey division of the Lower Greensand contains clay mineral assemblages dominated by mica and kaolin with minor smectite (Poole *et al*., 1971, p.11).

MIDDLE–UPPER ALBIAN STRATA

The stratigraphical scheme used for the Middle-Upper Albian is shown in Fig. 31. Strata of this age lying to the north of a line running approximately E-W through north Norfolk are referred to as the Red Chalk Formation (the uppermost part of the Cromer Knoll Group) and those to the south of the line are included in the Selborne Group.

Selborne Group

The Selborne Group consists of two formations, the Gault Clay (Gault) and the Upper Greensand. The Gault consists predominantly of silty clays and clayey silts with layers of phosphate nodules and pebbles; it is the sole representative of the Selborne Group in southeast and eastern England and, when traced westwards, its upper part passes vertically and laterally into the coarser-grained Upper Greensand. The Upper Greensand consists of sandstones, silty sands and clayey silts which are commonly glauconitic and contain silica-cemented horizons (malmstones, hearthstones, cherts). Twenty eight clay mineral analyses from the Selborne Group are included in Perrin (1971). Those from the Gault are dominated generally by mica and

kaolin with lesser amounts of smectite, vermiculite and mixed-layer clay minerals, whereas those from the Upper Greensand consist of smectite with lesser amounts of mica or, in one sample, of 'degraded mica' (possibly glauconite or a smectitic mica).

The regional distribution pattern of the clay mineral assemblages in the Selborne Group (based on unpublished data) was summarized by Jeans (1978, his fig. 4). Two points are of particular interest. First, the recognition of zones in the lower and upper parts of the Gault that are characterized by clay mineral assemblages dominated by smectite and mica; and second, the complex sequence of clay and other authigenic silicate minerals (zeolites, feldspar, quartz, opal-CT) preserved in the silica-cemented horizons of the Upper Greensand (see also Milodowksi *et al*., 1982; Milodowski & Wilmot, 1985). The possible volcanic origin of

Stage	Ammonite Zone	Abbrev.	Ammonite Subzone	Abbrev.
UPPER ALBIAN	S. dispar	SD	M. (D.) perinflatum	Mp
			M. (M.) rostratum	Mr
	M. (M.) inflatum	MI	C. auritus	Ca
			H. varicosum	Hv
			H. orbignyi	Ho
			D. cristatum	Dc
MIDDLE ALBIAN	E. lautus	ELA	A. daviesi	Ad
			E. nitidus	En
	E. loricatus	ELO	E. meandrinus	Em
			M. subdelaruei	Ms
			D. niobe	Dn
			A. intermedius	Ai
	H. dentatus	HD	H. spathi	Hs
			L. lyelli	Ll

FIG. 31. Stratigraphical scheme (including ammonite zones and subzones) used in the description of the clay mineralogy in the Middle and Upper Albian strata of England. Two additional subzones (H. benettianus, Hb, and H. eodentatus, Hc) may occur at the Middle/Lowers Albian boundary.

the Selborne Group's smectite-mica assemblages and their associated sand-grade glauconite has been discussed (Jeans *et al.*, 1982, 2000). K-Ar signatures of four clay samples from the Gault (Folkestone, Glyndebourne) were given by Jeans *et al.* (2001). The clay mineral stratigraphy of the Gault at various locations in Kent, Sussex, Hampshire, Bedfordshire and Cambridgeshire are illustrated by Jeans *et al.* (1982), Bloodworth (1990), Prior *et al.* (1993) and Gale *et al.* (1996). Selective trace element analyses of 45 samples from the Gault are given by Jeans *et al.* (1982).

New clay mineral analyses of the Selborne Group from 22 localities (Fig. 26) are shown in Tables 23 (a−r). Whenever possible the biostratigraphical information for each analysis is shown. Sample coverage is still too incomplete to allow the clay mineral variation to be discussed at the level of ammonite sub-zones. This level of detail is likely to prove particularly important in the study of the changing sediment sources associated with the major changes in sea level, palaeogeography and climate linked to the onset of the Upper Cretaceous Chalk Seas in western Europe.

The XRD patterns of typical clay mineral assemblages from the Selborne Group are shown in Fig. 32. Examples of grain-size mineralogical variation within the clay assemblages are shown in Fig. 33. The overall clay mineral pattern in the Selborne Group is shown in Fig. 34. There are two main clay mineral assemblages. One is characterized by an abundance of mica and kaolin, associated with a range of collapsible clay minerals (vermiculite, smectitic, smectite-mica, poorly defined); this is referred to as the kaolin-mica assemblage and is restricted to the Gault Clay Formation. The other assemblage, referred to as the smectite-mica assemblage, is dominated by smectitic collapsible minerals and mica; it occurs throughout the Upper Greensand and the envelope of surrounding Gault (Figs 34, 35a, 36) and also in the basal part of the Gault in regions where fullers' earths are present in the underlying Lower Greensand (Fig. 37a; Jeans *et al.*, 1982, his fig. 11). Between these two major clay mineral assemblages there is a complete gradation (Fig. 35a). There is very little variation in the smectite-mica assemblage within the Upper Greensand and the Gault; the main variation is the enhanced content of clay-grade quartz or other forms of silica (opal-CT) within the Upper Greensand which results in low-intensity XRD patterns for the clay minerals (Figs 35a, 36). However, in the Gault of the Cliffe No. 6 Borehole (Fig. 37a, samples BD7028, BS7035) and the Gault and Upper Greensand of the Kingston Lisle Borehole (Fig. 38, e.g. samples BDB6422, BDB6451), the smectite-mica assemblage is partially replaced by another kaolin-poor assemblage, which is dominated by mica and mixed-layer clay minerals.

The kaolin-mica assemblage displays considerable vertical and lateral variations in the composition of its collapsible minerals. Vermiculite is often a conspicuous component of the collapsible minerals; this may occur in association with smectitic clay minerals or alone, although poorly-defined collapsible minerals are invariably present. Figure 39 shows available data on the stratigraphical variation within the clay mineral assemblages of the Selborne Group.

Petrographic investigations of the smectite-mica assemblage in the Gault and Upper Greensand indicate the extensive development of neoformed clay minerals. In the silica-cemented horizons in the Upper Greensand, various generations of authigenic clay minerals are evident and have intergrown with authigenic feldspar, zeolites of the clinoptilolite-heulandite group and silica minerals (Fig. 40: see also Jeans, 1978; Milodowksi *et al.*, 1982; Milodowski & Wilmot, 1985). In the Gault, on the other hand, the smectite-mica assemblage is dominated by elongated euhedral clay crystals and extensively overgrown detrital clay crystals (Fig. 41). This petrographic evidence, and the consistent spatial association of pattern B of Jeans *et al.* (2000) between the smectite-mica assemblage and the relative coarse-grained Upper Greensand and its finer-grained envelope of Gault, is perhaps the most important line of argument for its volcanogenic origin (Jeans *et al.*, 2000). The lateral passage of the smectite-mica assemblage into one dominated by mica and mixed-mixed layer clay mineral suggests that the latter may have a similar volcanogenic origin. It is postulated that in the assemblage containing mica and mixed-layer clay mineral, the greater proportion of K-bearing clay minerals is a result of enhanced K^+/volcanic glass ratios, either within the ash itself, or in the volcanic rock/water ratios of the marine sediments in which argillization took place.

The kaolin-mica assemblage is mainly of detrital origin, although there is evidence of the presence of at least trace amounts of authigenic kaolin (Gale *et*
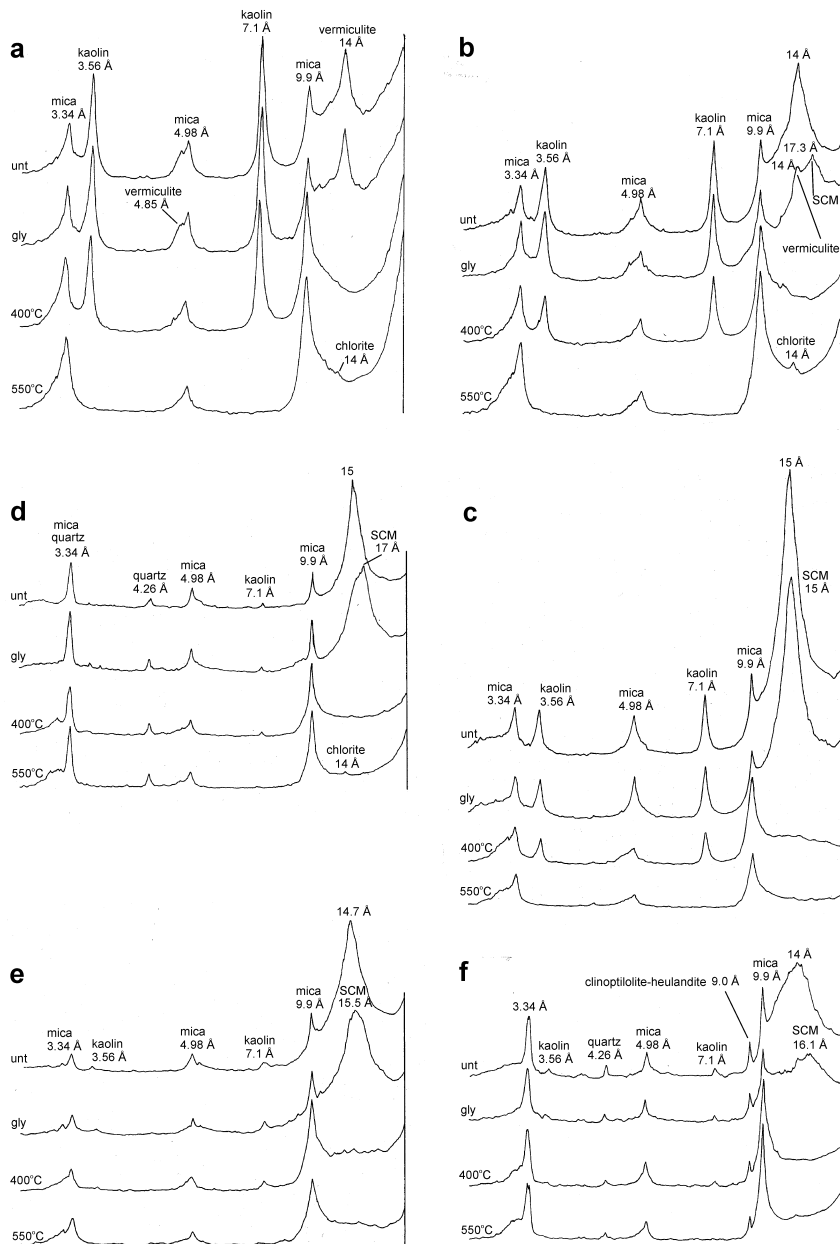
FIG. 32. XRD patterns of clay mineral assemblages (<2 μm) from the Selborne Group of England. Abbreviations as in Fig. 7. (a) Kaolin-mica assemblage with poorly defined collapsible mineral containing vermiculite, *orbignyi* subzone (Inflatum Zone), Gault, Glyndebourne Borehole, 116.97 m. (b) Kaolin-mica assemblage with vermiculite and smectite, *varicosum* subzone (Inflatum Zone), Gault, Arlesey Borehole (non BGS), 43.63 m. (c) Kaolin-mica assemblage with conspicuous smectite, *auritus* subzone (Inflatum Zone), Gault, Glyndebourne Borehole, 91.39 m. (d) Smectite-mica assemblage, *auritus* subzone (Inflatum Zone), Gault, Glyndebourne Borehole, 71.37 m. (e) Smectite-mica assemblage, *spathi* subzone (Dentatus Zone), Gault, Folkestone. (f) Smectite-mica assemblage with clinoptilolite-heulandite zeolite, *rostratum* subzone (Dispar Zone), Upper Greensand, Kingston Lisle Borehole, 21.79 m.
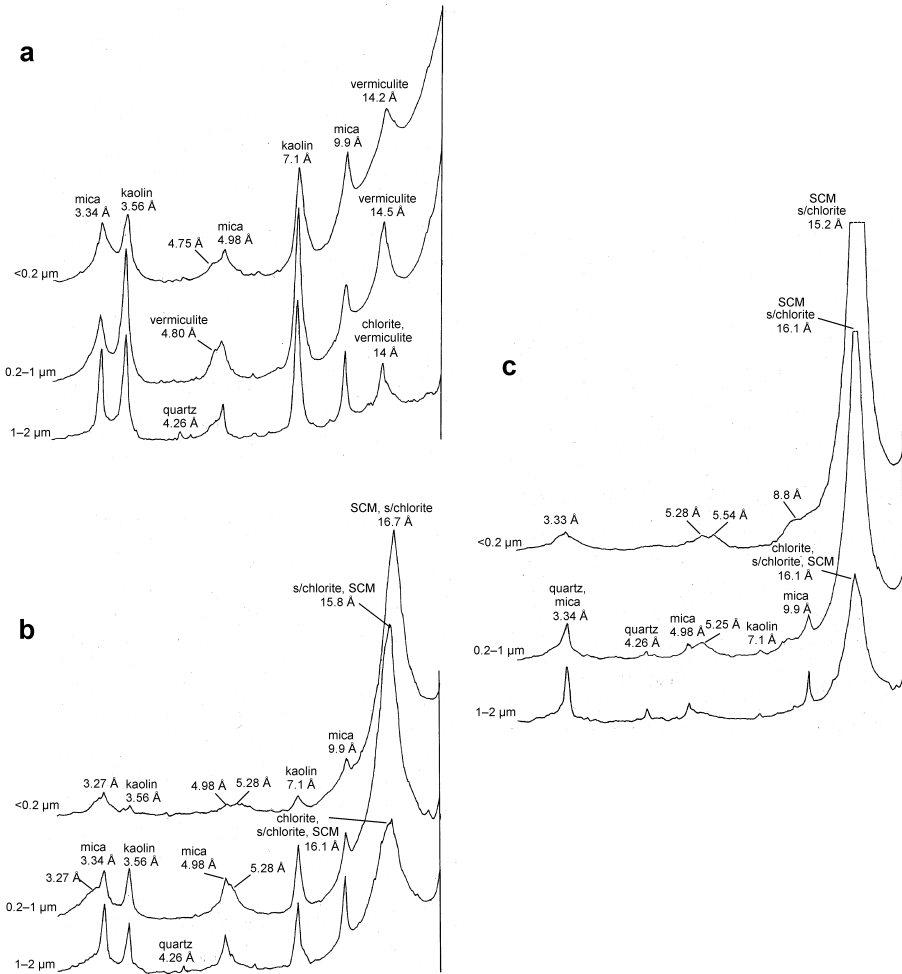
FIG. 33. XRD patterns of glycerolated clay fractions (<0.2 µm, 0.2−1 µm, 1−2 µm) showing grain size-related mineralogical variation in the <2 µm clay mineral assemblages from the Gault (Selborne Group). Abbreviations as in Fig. 7. (a) Gault, *orbignyi* Subzone (Inflatum Zone), Glyndebourne Borehole, 116.97 m. (b) Gault, *auritus* Subzone (Inflatum Zone), Glyndebourne Borehole, 91.39 m. (c) Gault, *auritus* Subzone (Inflatum Zone), Glyndebourne Borehole, 71.37 m.

al., 1996, p. 296) and of a K-bearing neoformed clay mineral (Jeans *et al.*, 2001). The dominant variety of the kaolin-mica assemblage in southern England is one containing appreciable amounts of vermiculite but lacking in smectitic or mixed-layer collapsible minerals. Similar assemblages are widespread in the Atherfield Clay and are present in the Wealden Group. This vermiculite-bearing clay assemblage is replaced generally in eastern England, Berkshire and Buckinghamshire by assemblages containing smectitic collapsible minerals, usually in association with vermiculite.

There is no petrographic evidence for the origin of either the vermiculite or smectitic mineral. If a detrital origin is assumed, a possible explanation is that there are two detrital sources, a more northerly one providing a kaolin-mica assemblage and a southerly one providing a kaolin-mica-vermiculite assemblage.

Jeans *et al.* (2002) argued that the kaolin-mica detrital assemblage is essentially of Caledonian age with a neoformed component, possibly of soil or early diagenetic origin. There is evidence that the Gault, at least locally, contains an abundance of
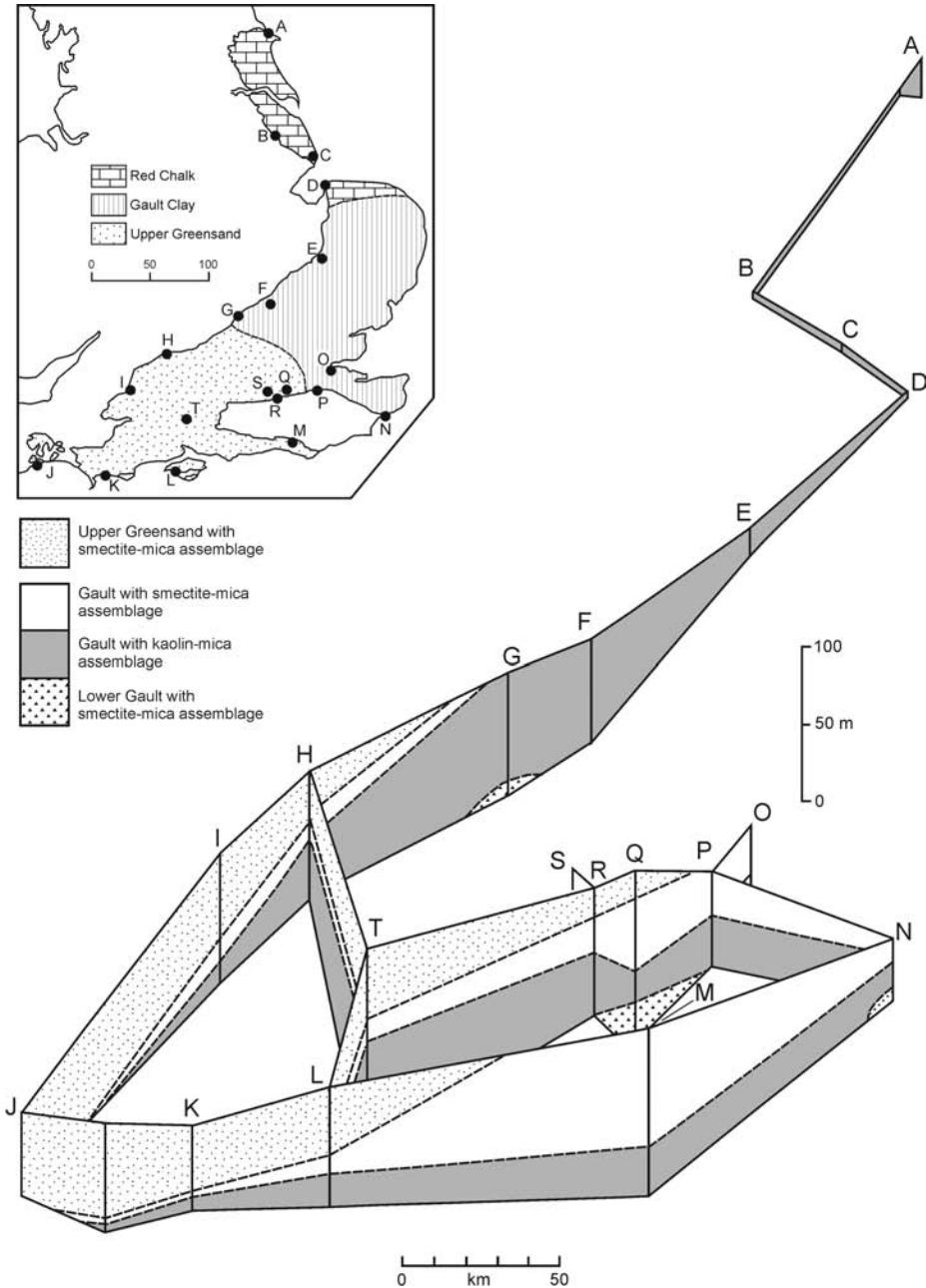
Fɪɢ. 34. Fence diagram from Jeans (1978) showing the regional distribution of the main lithofacies and clay mineral assemblages in the Middle and Late Albian strata of England. Insert shows locations and distribution of lithofacies at the top of the Albian. A: Speeton, Yorkshire; B: Goulceby, Lincolnshire; C: Skegness, Lincolnshire; D: Hunstanton, Norfolk; E: Hockwold cum Wilton, Norfolk; F: Arlesey, Bedfordshire; G: Leighton Buzzard, Bedfordshire; H: Kingston Lisle, Berkshire; I: Devizes, Wiltshire; J: Sidmouth, Devon; K: White Nothe, Dorset; L: Compton Bay, Isle of Wight; M: Glyndebourne, Sussex; N: Folkestone, Kent; O: East Tilbury/Higham, Essex/ Kent; P: Trotiscliffe, Kent; Q: Warlingham, Surrey; R: Buckland, Surrey; S: Fetcham Mill, Surrey; T: Winchester, Hampshire.
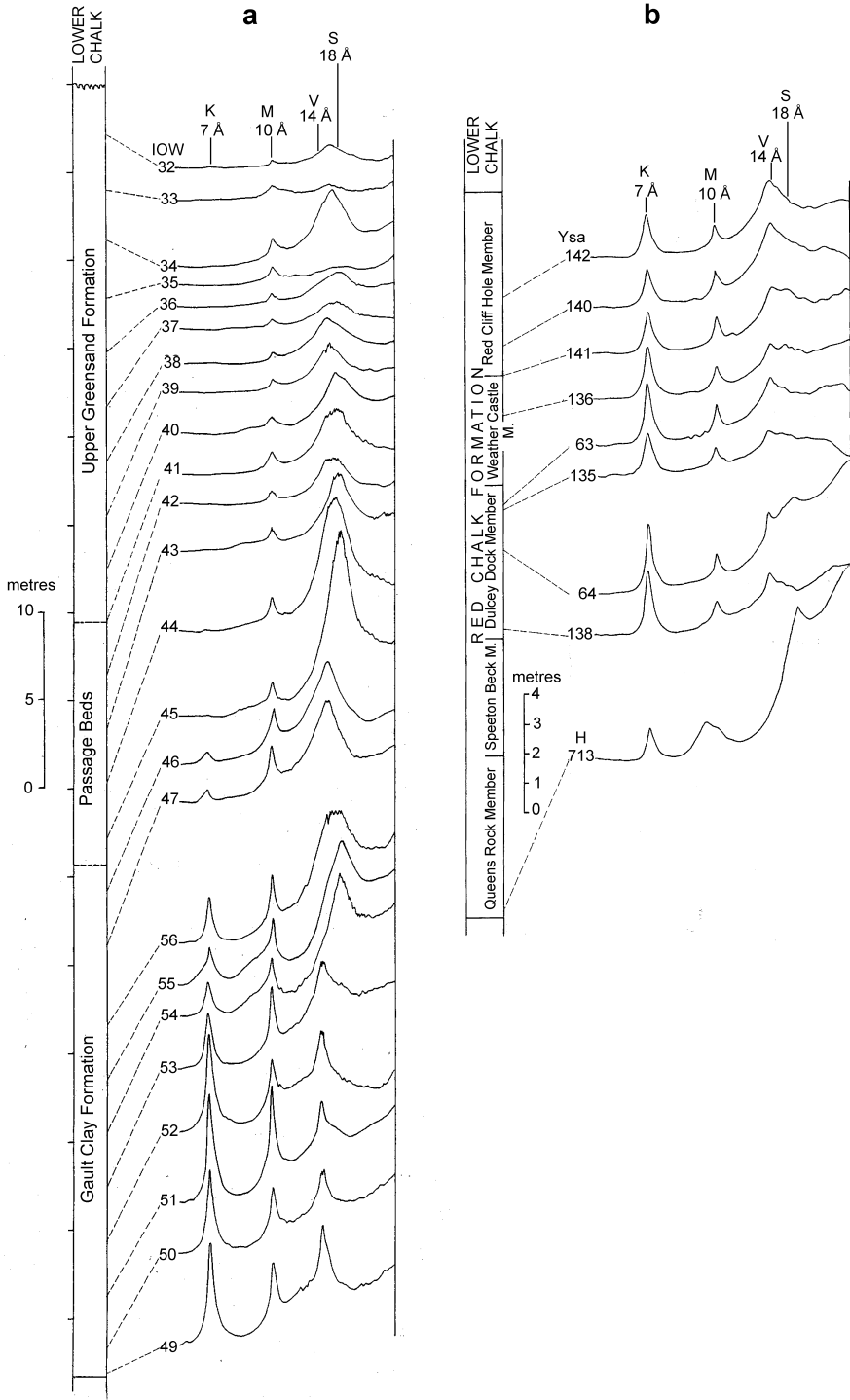
FIG. 35. (a) Clay mineral stratigraphy of the Selborne Group, Compton Bay, Isle of Wight. (b) Clay mineral stratigraphy of the Red Chalk (Middle–Upper Albian) at Speeton, Yorkshire. The lithostratigraphical terminology is based on Mitchell (1995). K = kaolin, M = mica, V = vermiculite, S = smectite.
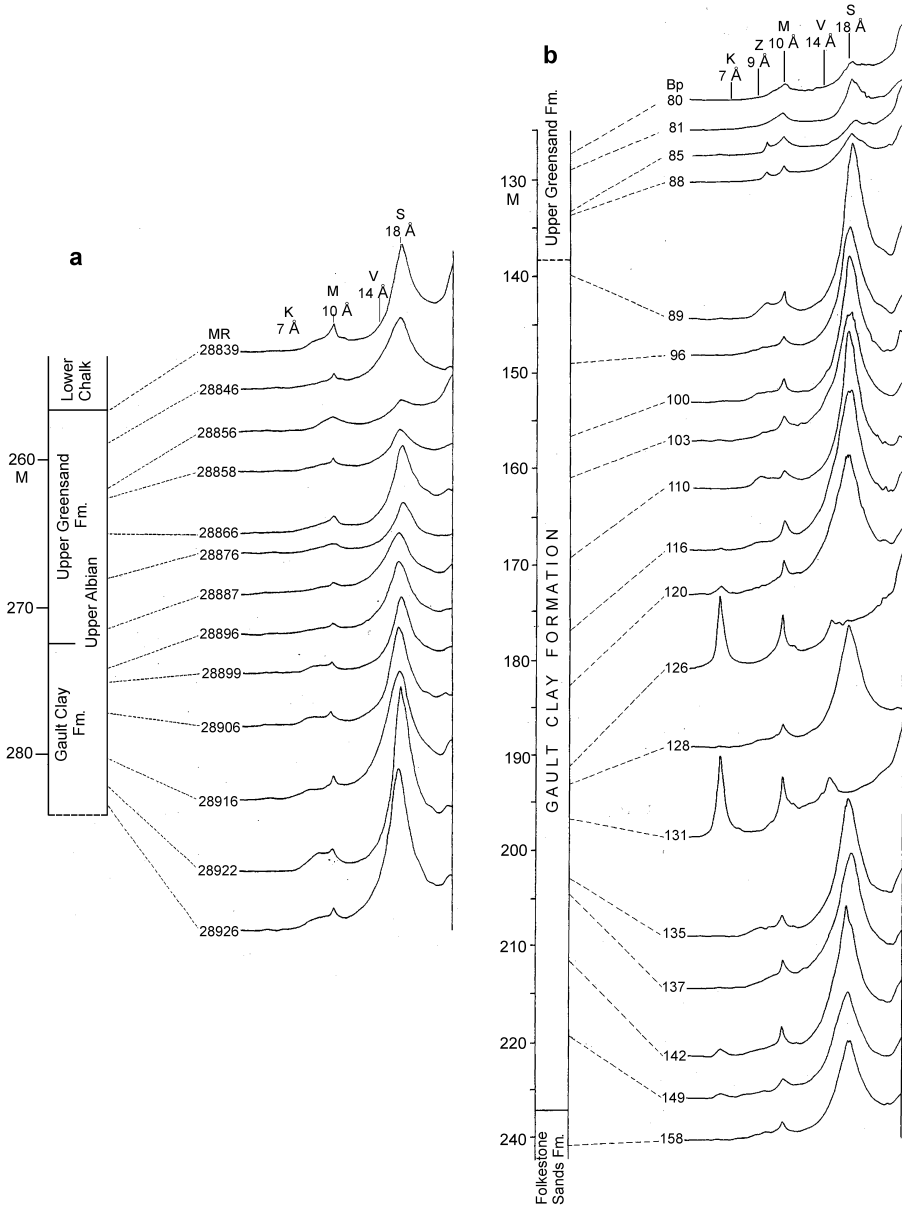
Fig. 36. Clay mineral stratigraphy in the Selborne Group of the Fetcham Mills (a) and Warlingham (b) boreholes (stratigraphy based on Gray (1965) and Worssam & Ivimey-Cook, (1971)). K = kaolin, Z = heulandite-clinoptilolite, M = mica, V = vermiculite, S = smectite.

derived Upper Jurassic microfossils (Gale *et al.*, 1996), and it is possible that much of this detrital assemblage is simply recycled Jurassic clays. The range of mica/kaolin ratios displayed by the Upper Jurassic clays and the Gault are similar (Jeans, 2006), their K-Ar signatures are little different

(Jeans *et al.*, 2001), and their *REE* chemistries are similar (Jeans *et al.*, 2000). There are two main differences: (1) vermiculite is largely absent from the Jurassic clay assemblages, whereas it is widespread in the Gault, Atherfield Clay and Wealden Group; (2) trace to minor amounts of
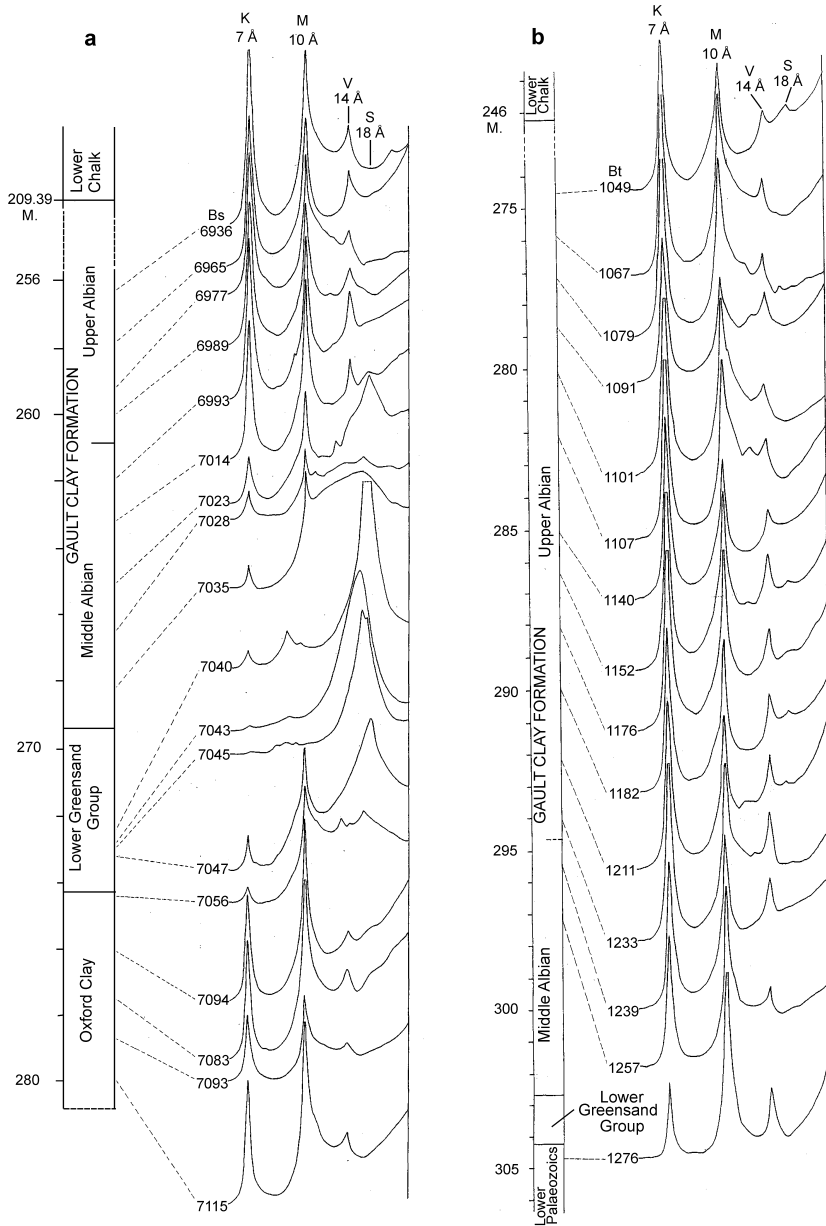
FIG. 37. Clay mineral stratigraphy in the Gault and Lower Greensand of the Cliffe No. 6 (a) and No. 11 (b) boreholes, Essex (stratigraphy based on Owen, 1971b). K = kaolin, M = mica, V = vermiculite, S = smectite.

chlorite may occur in the Jurassic clays but it is generally absent from the Cretaceous. It is unlikely that vermiculite is the weathering product of the Jurassic chlorite and its origin is probably linked to the associated mica and kaolin. The kaolin-mica detrital assemblage of southern England may be

either recycled clay material from the erosion of Wealden Group sediments, or it may be derived from one of the sources supplying the Wealden Group. Other varieties of the mica-kaolin clay mineral assemblage in the Gault could have been derived by mixing either with the smectite-mica
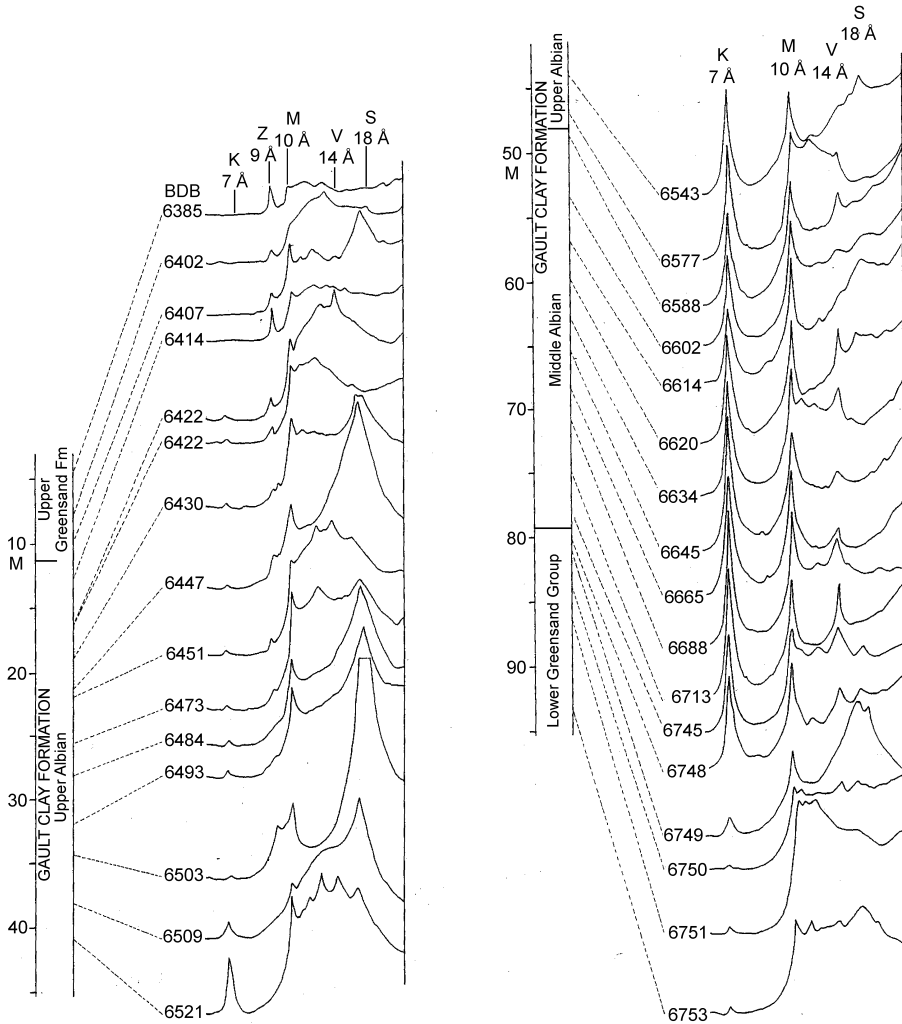
FIG. 38. Clay mineral stratigraphy in the Selborne Group and Lower Greensand of the Kingston Lisle borehole, Berkshire (stratigraphy based on an unpublished log by Mr A.A. Morter held at the British Geological Survey). K = kaolin, Z = heulandite-clinoptilolite, M = mica, V = vermiculite, S = smectite.

assemblage or with the assemblage of mica and mixed-mixed layer clay mineral.

Red Chalk Formation

In Norfolk the Gault thins northwards and passes into the Red Chalk, a thin and highly condensed red limestone and marl sequence that is excellently exposed in the cliffs at Hunstanton (1.1 m) and occurs in the Spilsby and Cleveland basins (0.5−24 m). Because of the scarcity of ammonites, the biostratigraphy of the Red Chalk is relatively

poorly known (see Morter in Gaunt *et al*., 1992) and it cannot be readily compared in detail to the Selborne Group in southern England. The clay mineralogy of the Red Chalk is known from a single analysis published in Perrin (1971) and 14 new analyses shown in Table 24. Clay assemblages are dominated by kaolin, mica and collapsible minerals. Although there are regional variations in the composition of the clay assemblages, there is little evidence of the stratigraphical variation evident in the coeval strata of southern England. The Red Chalk clay analyses from Speeton
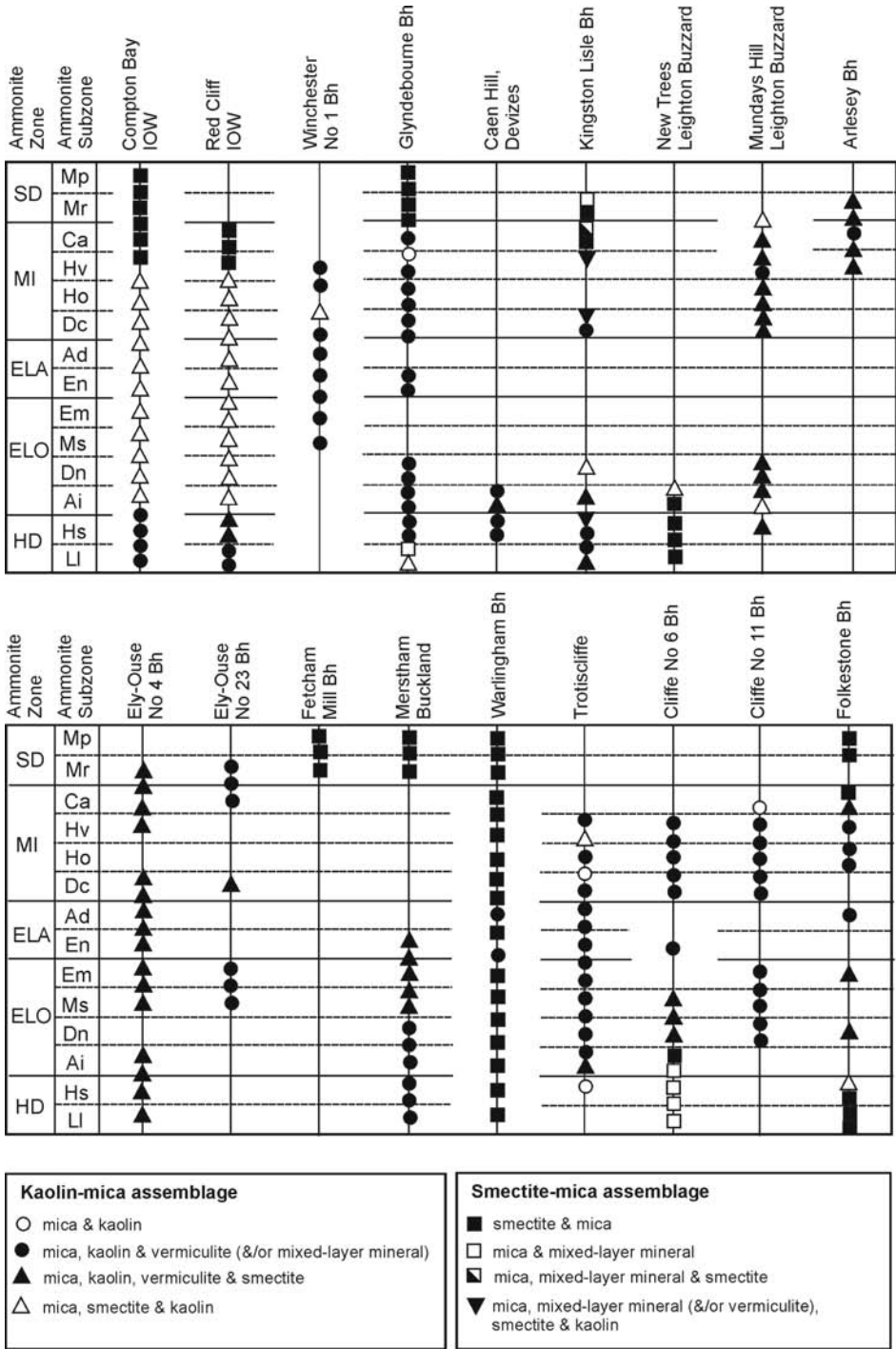
FIG. 39. Summary of the stratigraphical and regional distribution of the different types of clay mineral assemblages in the middle and late Albian strata of England. The absence of zonal/subzonal divisions indicates that the biostratigraphy is unestablished.
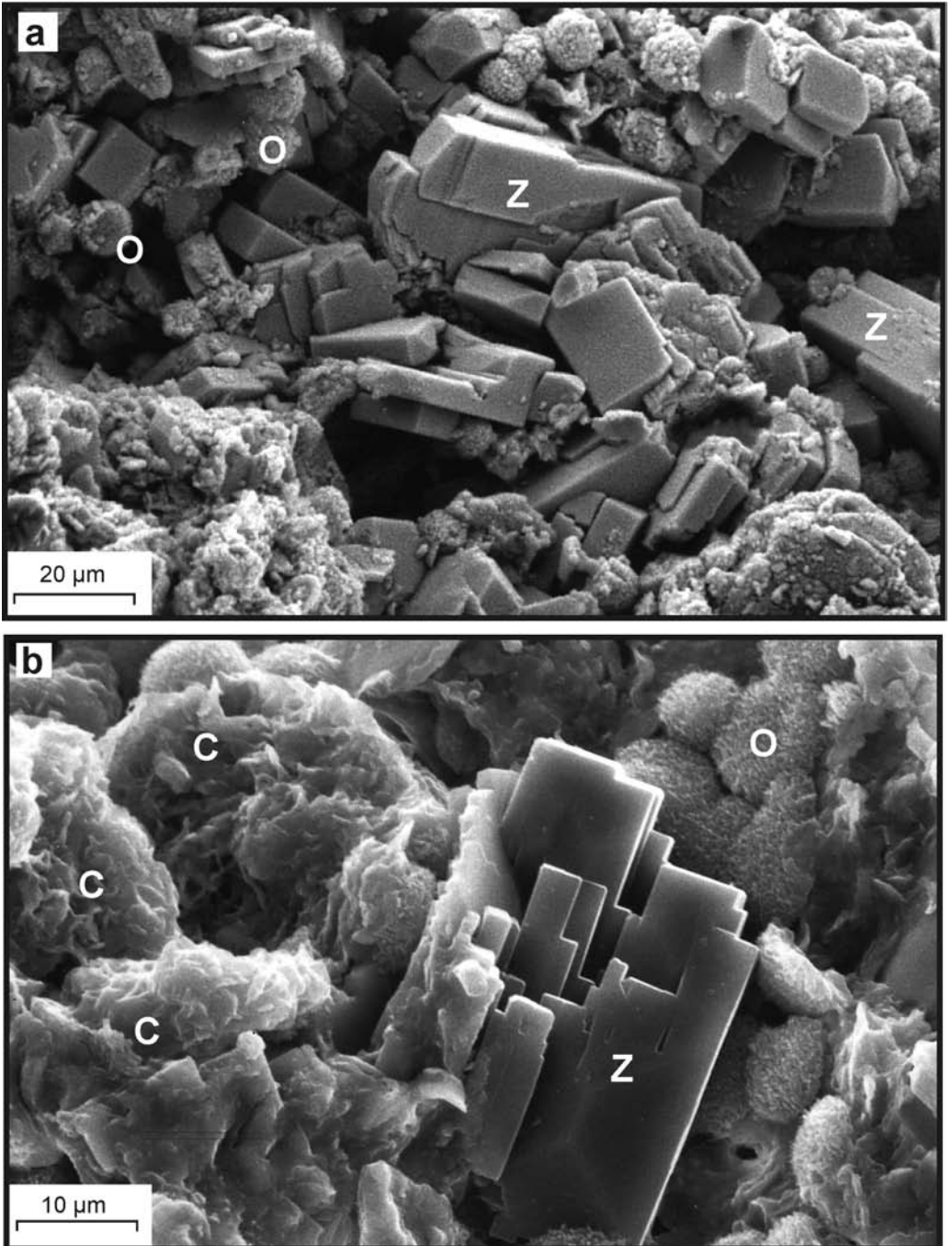
FIG. 40. Scanning electron micrographs of silica-cemented lithologies from the Upper Greensand showing the textural relationships between authigenic silicate minerals (courtesy of A.E. Milodowski (BGS)). (a) Intergrowth of tabular heulandite-clinoptilolite zeolite crystals (z) and opal-CT lepispheres (o). Harwell Borehole No. 4, 80.32−80.47 m. (b) Intergrowth of heulandite-clinoptilolite zeolite (z), opal-CT (o) and clay minerals (c). Esso Research Centre Borehole E3, 16.55−16.63 m.
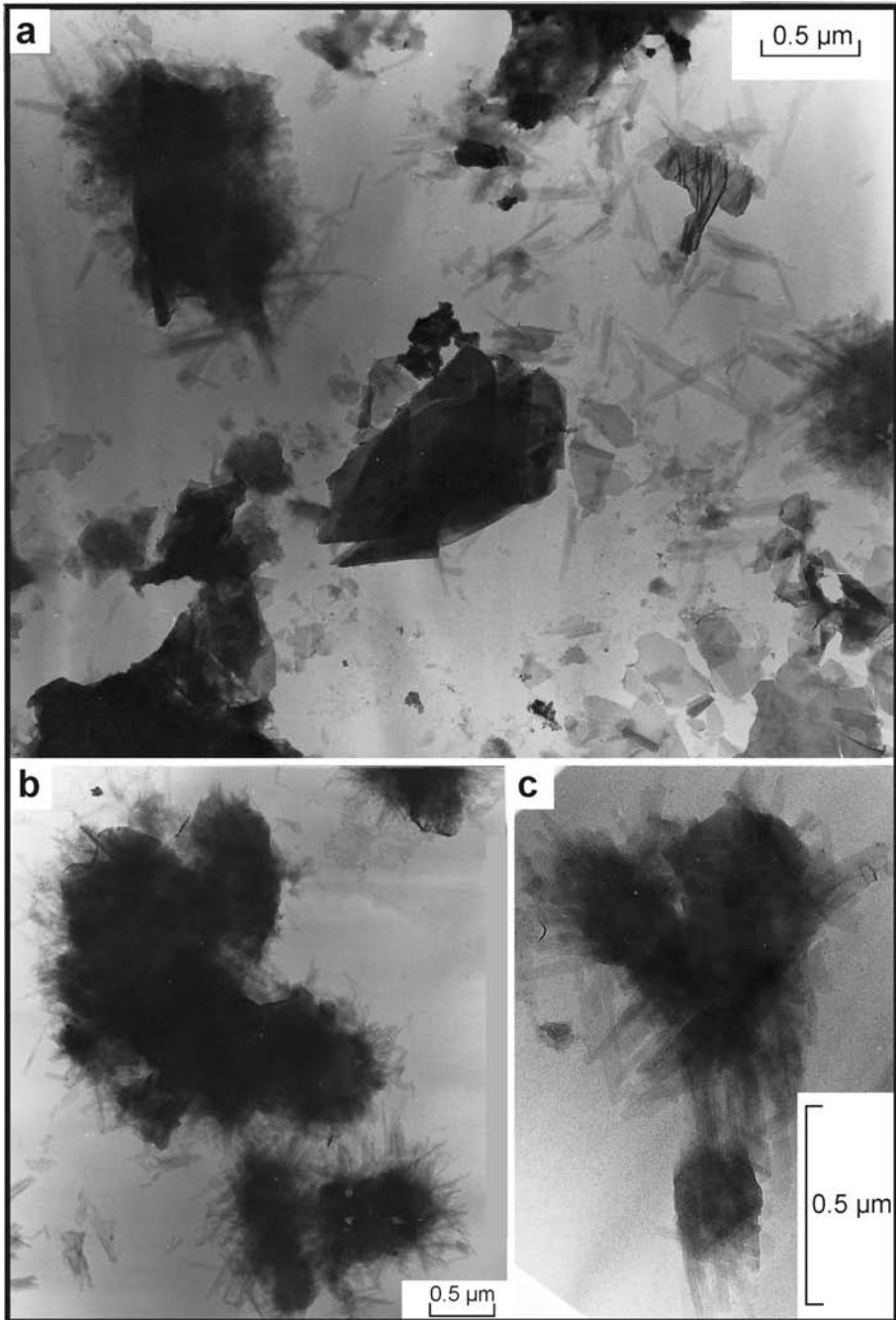
FIG. 41. TEM images of fine clay fractions (<0.2 µm) from the smectite-rich unit at the base of the Gault, New Trees Pit, Leighton Buzzard. Sample Beds 112, Intermedius Subzone (see Jeans *et al.*, 1982, their fig. 22 for horizon). (a) Mixture of anhedral grains, extensively overgrown clay particles and delicate euhedral elongate clay crystals. (b) Dense clay particles, extensively overgrown and coated with thin euhedral elongate clay crystals. The dense particles may represent very fine volcanic ash which has been argillized. (c) Anhedral clay grains with euhedral lath-shaped crystal overgrowths.

(Table 24; Fig. 35b) contain approximately equal amounts of kaolin, mica and collapsible minerals, and chlorite is present in trace amounts. In the Spilsby Basin (Goulceby, Skegness) collapsible minerals are dominant, with mica and kaolin occurring as lesser but equal components. Both vermiculitic and smectitic collapsible minerals occur in most samples.

UPPER CRETACEOUS STRATA

The Upper Cretaceous strata of the British Isles are preserved in England, Scotland and Ireland They consist of two main lithofacies, the siliciclastic facies (non-Chalk facies of Perrin, 1971) and the Chalk facies. The siliciclastic facies consists of variable sandstones, siltstones and marls of near-shore marine origin that are often rich in sand- and silt-grade glauconite. The siliciclastic facies always underlies the Chalk facies. In England they are relatively thin (up to 5 m) and are generally a lithological transition from the variable lithologies of the uppermost Albian strata to the overlying and much thicker Chalk facies (up to 500 m). The siliciclastic facies in Scotland and Northern Ireland rest directly on much older rocks ranging from Dalradian metasediments to strata of Devonian to early Jurassic age. In the west of Scotland, the thin Upper Cretaceous sequence (up to 20 m) is dominated by the siliciclastic facies and is overlain by thin silicified chalks (Mortimore *et al.*, 2001). In Northern Ireland the siliciclastic facies is very thin (<1 m) over the Londonderry Shelf and North Antrim Basin, although in the Midland Valley and the northern margin of the Southern Uplands it ranges up to 30 m, whereas the total thickness of the Chalk facies in Ireland may be up to 125 m (Fletcher, 1977).

The Chalk facies consists of a predominantly white, fine-grained marine limestone made up mainly of the debris of the skeletons of coccolitho-phorid algae and other nanofossils; foraminiferids and shells typically make up <5%, except in the case of shell-detrital chalks (Black, 1980). Horizons of penecontemporaneous calcite cementation are represented by nodular chalks and by hardgrounds, which are commonly stained by pigmentary glauconite. Beds and nodules of diagenetic macro-scopic silicifications (flints) may be abundant; α-quartz is the predominant mineral although opal-CT and amorphous silica may occur. There are marked regional variations in the presence and extent of a pervasive late diagenetic calcite cement in the Chalk facies. In southeast England this late calcite cement is essentially absent and the Chalk is uncemented, with bulk specific gravities of 1.65. In southern England (Isle of Wight, Dorset) in association with the Tertiary tectonics, and in Lincolnshire and Yorkshire, the late calcite cement is very evident and bulk specific gravities up to 2.35 (cf. calcite 2.70) are not uncommon. In Northern Ireland, the Chalk facies is completely cemented and is referred to as the Ulster White Limestone Formation. The acid-insoluble residues (1 M acetic acid) of the Chalk facies vary typically from 5 to 10% by weight for uncemented chalk to <1% for samples completely cemented by calcite; ~50% of the acid-insoluble residues is of clay grade (<2 μm). Thin marl bands, up to several centimetres thick, may be present; some are of very wide extent and have been traced as far afield as north Germany. In England the lower part of the Chalk facies (Lower Chalk) contains higher proportions of acid-insoluble residue than typical chalk with values up to 30% (cf. 5−10%). Typical of this lower and more clay-rich part are conspicuous alterations of more or less marly chalks, the so-called marl-limestone couplets, which are inferred to represent orbitally controlled (precession) productivity (Hart, 1987; Gale, 1995).

The stratigraphical scheme used in this account for the Upper Cretaceous siliciclastic and Chalk facies of England is shown in Fig. 42. For Ireland and Scotland it follows Fletcher (1977), Griffiths & Wilson (1982) and Mortimore *et al.* (2001). For England, the new stratigraphical scheme used by the British Geological Survey (Mortimore *et al.*, 2001) consists of 19 formations; this has replaced the Lower, Middle and Upper Chalk subdivisions that have been in use since the last two decades of the 19th century, and is the scheme used by Perrin (1971) in his compilation of 106 clay mineral analyses from the Chalk facies. Most of the analyses listed by Perrin (1971) have details of their biozonal horizons and these can usually be assigned to one of the 19 new formations by inspection of Fig. 42. In this paper the new stratigraphical scheme is not used in the discussion of the regional and stratigraphical variation in the clay mineralogy of the Lower Chalk. In the new scheme (see Fig. 42), the Lower Chalk is replaced by three formations and two part-forma-tions: West Melbury Marly Chalk, Zig-zag Chalk, and the basal members (Plenus Marls Member) of the Holywell Nodular Chalk, in southern England;

STAGE	BIOZONES North	BIOZONES South	LITHOSTRATIGRAPHY North	Jeans 1968 Perrin 1971	South				Subgroup
CAMPANIAN ("SENONIAN")	Belemnitella mucronata		Rowe Fm.	UPPER CHALK	Portsdown Fm.				White Chalk Subgroup
	?	Gonioteuthis quadrata			Culver Chalk Fm.				
	Sphenoceramus lingua	Offaster pilula	Flamborough Chalk Fm.		Newhaven Chalk Fm.				
SANTONIAN	Uintacrinus anglicus								
	Marsupites testudinarius								
	Uintacrinus socialis								
CONIACIAN	"Hagenowia rostrata"	Micraster coranguinum	Burnham Chalk Fm.		Seaford Chalk Fm.				
	Micraster cortestudinarium				Lewes Nodular Chalk Fm.				
TURONIAN	Sternotaxis planus	P. germari		MIDDLE CHALK	New Pit Chalk Fm.				
		S. neptuni							
	Terebratulina lata	Collignoniceras woollgari	Welton Chalk Fm.		Holywell Nodular Chalk Fm.				
	Mytiloides spp.	M. nodosoides / F. catinus / W. devonense							
CENOMANIAN	Neocardioceras juddii		Plenus Marls Black Band Member		Plenus Marls Member	10 / 9	H. trecensis Zone	LOWER CHALK	Grey Chalk Subgroup
	Metoicoceras geslinianum								
	Calycoceras guerangeri						Holaster subglobosus Zone		
	Acanthoceras jukesbrownei				Zig Zag Chalk Fm.	8 / 7	H. subglobosus Zone		
	Acanthoceras rhotomagense / C. inerme		Ferriby Chalk Fm.			6 / 5			
	Mantelliceras dixoni					4 / 3	Schloenbachia varians Zone		
	Mantelliceras mantelli				West Melbury Marly Chalk Fm.	2 / 1			

FIG. 42. Stratigraphical scheme used in the description of the clay mineralogy of the Upper Cretaceous strata of the British Isles.

Ferriby Chalk, and the basal part of the Welton Chalk in eastern England. Different formational names are used to the north and south of an East−West line in north Norfolk in spite of the fact that the main stratigraphical marker horizons are continuous throughout southern and eastern England (see Jeans, 1968, his fig. 4). The effect of these unnecessary complexities is to obscure the relationships between the clay mineral variations and the actual stratigraphical framework. The locations of Upper Cretaceous clay mineral data are shown in Fig. 43.

Siliciclastic facies of Scotland and Ireland

The only clay mineral analyses from the Scottish Upper Cretaceous Inner Hebrides Group are three listed by Perrin (1971, p. 150) from Beinn Iadain, Morvern (Fig. 1). Stratigraphical details for these analyses are as follows: the greenish-grey clayey sand (kaolin 18%, mica 74%, smectite trace) is from the Morvern Greensand Formation; the dark grey carbonaceous silty shale (mica 95%, smectite 5%) is from the Gribun Chalk Formation; and the glauconite sand (kaolin 15%, mica 58%, smectite 22%, chlorite 5%) is from the Coire Riabhach
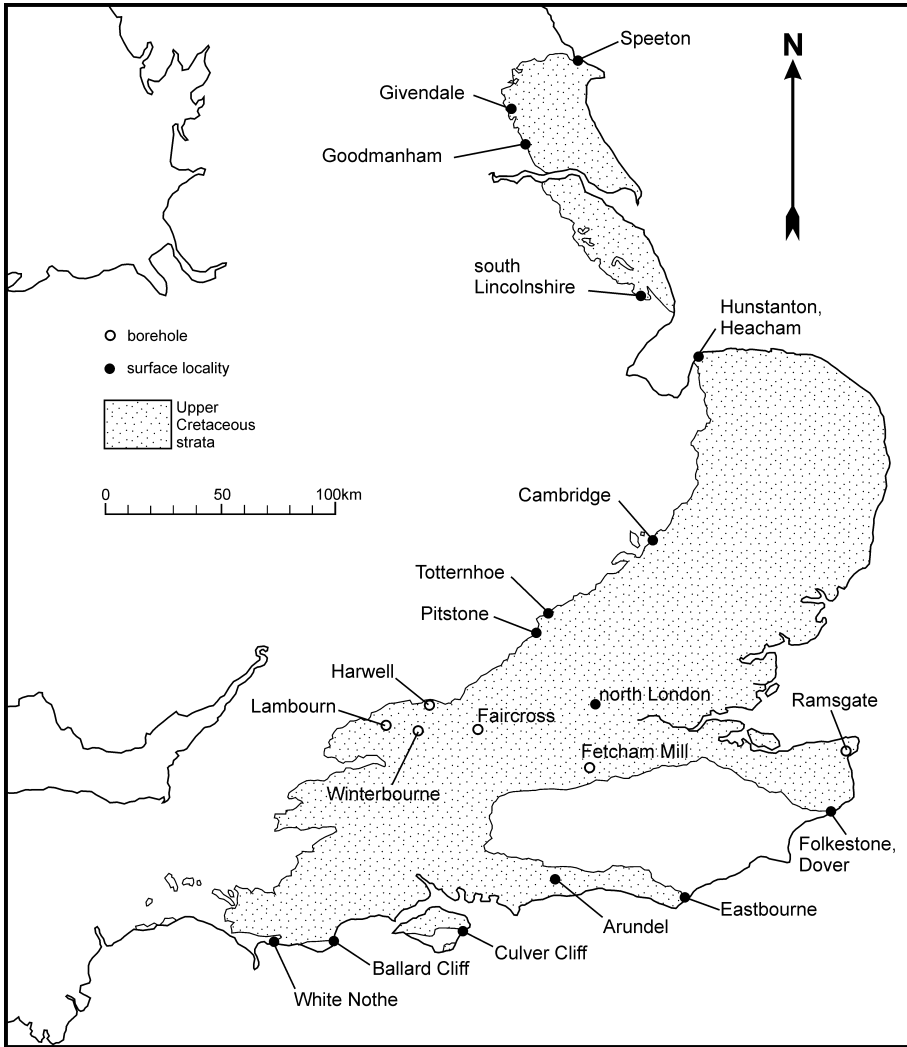
FIG. 43. Outcrop and sub-crop distribution of Upper Cretaceous strata in the British Isles. Boreholes and other locations mentioned in the text are shown.

Phosphatic Formation. The Morvern Greensand (Cenomanian) is particularly rich in sand-grade glauconite.

The siliciclastic facies in Northern Ireland is referred to as the Hibernian Greensands Formation. Ten clay mineral analyses from three locations have been illustrated (Jeans *et al.*, 1982, their fig. 12). Kaolin is absent. Samples IR18, IR20 and IR21 from Keady Mountain (Coniacian–Santonian) consist only of mica (glauconite). Samples IR27 and IR30 from White Park Bay (Coniacian–Santonian) are dominated by smectite with minor

mica. There are five samples from Cloghfin Port; samples IR47 and IR48 from the Island Maggee Siltstones (Yellow Sandstone of Jeans *et al.*, 1982, their fig.12; Cenomanian) and samples IR51 and IR52 from Kilcoan Sands (Upper Glauconitic Beds of Jeans *et al.*, 1982, their fig. 12; Coniacian–Santonian) are dominated by smectite and/or mica with or without clinoptilolite-heulandite zeolite; sample IR49 from the Kilcoan Sands (Upper Glauconitic Beds) consists only of mica (glauco-nite). Many of the glauconite sand grains associated with the Hibernian Greensands display evidence of

their origin as particles of volcanic rocks or ash that have been glauconitized on the Cretaceous seafloor (Jeans *et al.*, 1982).

Chalk facies of England and Ireland

The clay mineralogy of the Upper Cretaceous Chalk facies has been a topic of considerable interest since Millot *et al.* (1957) described the predominance of montmorillonite in samples from France. In England and Northern Ireland the Chalk facies is no different. Weir and Catt (1965) have shown that the clay assemblages extracted from the Turonian−Lower Campanian Chalks of Sussex are dominated by montmorillonite with lesser amounts of mica, silica minerals and occasional traces of palygorskite; kaolin is absent. The morphology of the clay-grade particles is striking, because of the abundance of euhedral crystals of clay minerals and silica, occurring either singly, or in clusters, or as overgrowths (Weir & Catt 1965). Chalk montmorillonite from the Cenomanian and Turonian Chalks of northern France consists of three morphologies (Deconinck & Chamley, 1995); two of these contain considerable mica interlayering, one type displaying a fleecy morphology, the other occurring as euhedral crystals. The third type, displaying euhedral crystal form, is a cheto-type smectite with little mica interlayering. The Chalk montmorillonite in England displays considerable variation in its XRD peak profile, its degree of expandability with glycerol and the extent of its collapse on 400ºC and 550ºC heating. It is clearly a heterogenous mixture of different collapsible minerals and for convenience will, in this account, be referred to as smectite.

The general clay mineral stratigraphy of the English Chalk is known from Perrin (1957, 1964, 1971), Weir & Catt (1965), Young (1965), Morgan-Jones (1977), Pitman (1978), Spears (1979), Kimblin (1992) and Wray & Wood (1998). Kaolin is absent except in the Lower Chalk where it may be associated with a relative abundance of mica and lesser amounts of smectite and vermiculite and occasionally traces of chlorite. In the main part of the English Chalk, dominant smectite is associated with minor mica. Estimates of the smectite:mica ratio varies from 1.8−4.9 when based upon XRD and chemical analyses (Weir & Catt, 1965; Pitman, 1978) to 0.7−1.1 when based solely on XRD (Perrin, 1957; Young, 1965). Palygorskite has been reported from the Fetcham Mill Borehole (Young,

1965) and from the Middle and Upper Chalk of the Faircross Borehole (Morgan-Jones, 1977, his fig. 20). The clay mineralogy and chemistry of the extensive thin marl bands in the Turonian Chalk of Lincolnshire and east Yorkshire have been investigated by Pacey (1984) and by Wray & Wood (1998) who identified two types of marl band. Both types have a smectite-dominated clay assemblage. One has a *REE* pattern with a negative Eu anomaly and a slightly lower mica content in its clay assemblage − this is interpreted as derived from the argillization of volcanic ash. The other type without a negative Eu anomaly in its *REE* pattern but with a slightly higher mica content is interpreted to be of detrital origin. These various detrital marl seams and bentonites have now been correlated to southern England and to northern Germany. In particular, there are five Turonian bentonites in both the UK and northern Germany that provide an isochronous stratigraphical framework; the detrital marls can also be correlated within this framework (Wiese *et al.*, 2004).

The clay mineralogy of the Irish Chalk facies (Ulster White Limestone) is known from six analyses from Keady Mountain, White Park Bay and Clogfin Port (Fig. 1) which have been illustrated by Jeans *et al.* (1982, their fig. 12). Clay mineral assemblages are dominated by smectite with some mica; palygorskite is present in some samples from all three locations. The stratigraphical details of these samples is as follows: Keady Mountain, samples IR25 and IR26 (Portrush Chalk, Campanian); White Park Bay, sample IR28 (Cloghastucan Chalk, Upper Santonian), samples IR32 (7 m above base of Upper Cretaceous section) and IR34 (12.3 m above base) (Boheeshane Chalk, Campanian); Cloghfin Port, sample IR55 (Creggan Chalk, Lower Campanian).

The transition from the regional clay mineral patterns at the top of Albian strata in England to the typical Chalk clay assemblage takes place in the lower part of the Chalk facies (Lower Chalk, Cenomanian−Lower Turonian). This transition has been studied in detail by Jeans (1968) in the chalk facies of the Lower Chalk and in the siliciclastic facies that forms its basement beds. The siliciclastic basement beds are typically transitional lithologies between those of the underlying topmost Albian strata and the Chalk. Figure 44 shows the XRD patterns of typical clay mineral assemblages and Fig. 45 examples of grain size-related mineralogical
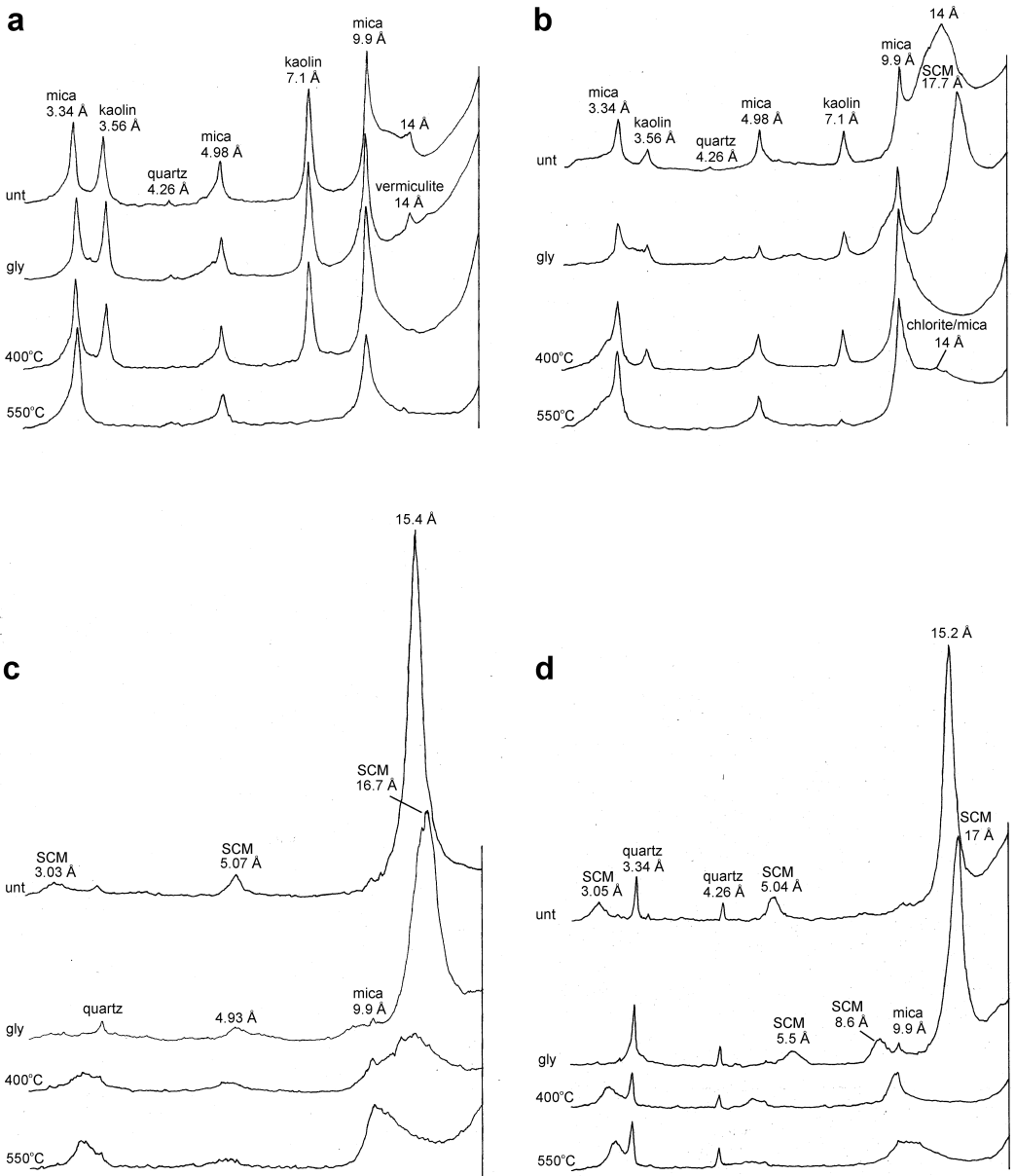
FIG. 44. XRD patterns of clay mineral assemblages (<2 μm) from the Chalk Group of England. Abbreviations as in Fig. 7. (a) Kaolin-mica assemblage with poorly defined collapsible mineral containing vermiculite, Sample KR112, Lower Chalk, Folkestone. (b) A clay assemblage intermediate between the kaolin-mica and the smectite-mica assemblages, Sample 102, Lower Chalk, Folkestone. (c) Smectite-mica assemblage, sample LR349, Melbourn Rock of Jeans *et al.* (1991, their fig. 10), Elsham, Lincolnshire. (d) Smectite assemblage, sample Ysa85, Bed 5 of Jeans *et al.* (1991, their fig. 10), Plenus Marls, Flixton, Yorkshire.

variation within these assemblages. Figure 46 summarizes the regional and stratigraphical varia-

tion in the clay mineral assemblages of the Lower Chalk.
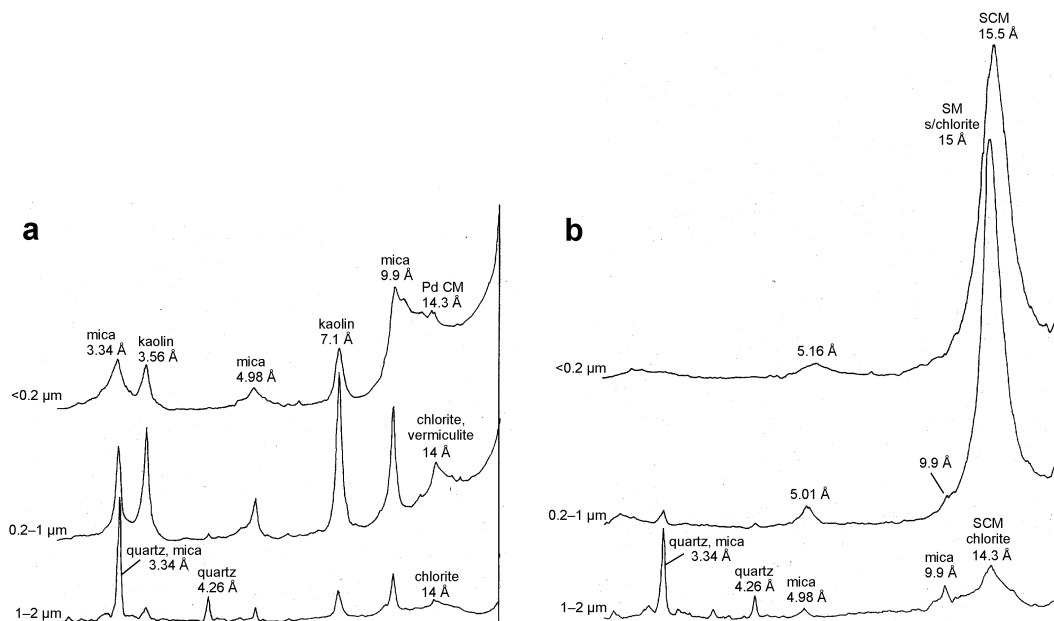
FIG. 45. XRD patterns of glycerolated clay fractions (<0.2 μm, 0.2−1 μm, 1−2 μm) showing grain size-related mineralogical variation in the <2 μm clay mineral assemblages from the Lower Chalk. Abbreviations as in Fig. 7. (a) Kaolin-mica assemblage, Sample KR15, Lower Chalk, Folkestone. (b) Smectite assemblage, Sample Ysa85, Plenus Marls, Flixton, Yorkshire.

The clay mineral pattern of the uppermost Albian strata with its two assemblages, one dominated by smectite and mica, the other by mica and kaolin, extend upwards through the siliciclastic basement beds into the overlying Chalk with little change. Within the main body of the Lower Chalk these two antipathetic clay mineral assemblages maintain their identity, although some subtle differences can be found. The collapsible minerals of the mica-kaolin assemblage are usually smectitic, although vermiculite and traces of chlorite may be present. The proportion of smectite in the smectite-mica assemblage tends to be higher than in the Albian strata and quartz is more widespread; heulandite-clinoptilolite zeolite (misidentified as pyrophyllite by Jeans (1968)) and opal-CT may be present (Fig. 47); this smectite-rich assemblage is typical of the Chalk facies. Both the regional and stratigraphical distribution of these antipathetic clay mineral assemblages in the Lower Chalk exhibit major changes that are not clearly related to the stratigraphy, lithologies or facies of the Chalk strata (Jeans, 1968, his figs 4−9). There is no evidence of systematic variations in the clay mineral assemblages associated with either the alternating marl-chalk facies,

widespread in southern England (Fig. 48), or with the well-defined upward-fining chalk cycles in east England (Jeans, 1968). The mica-kaolin assemblage is restricted largely to parts of the Lower Chalk in south and southeast England and eastern England south of the Wash. The smectite-mica assemblage is most extensively developed in the Lower Chalk north of the Wash, and in southern and southwest England. In the Plenus Marls, at the top of the Lower Chalk, the mica-kaolin assemblage is restricted to southeast England and to a sub-Black Band succession of black shales preserved in a fault trough at Melton Ross in Lincolnshire (Wood *et al.*, 1997); above the level of the Plenus Marls, this clay assemblage does not appear again in the English Chalk. Jeans (1968) has argued that the mica-kaolin assemblage is of detrital origin, whereas the smectite-mica assemblage is of neoformational origin. Subsequent investigations (Jeans, 1978) on the petrographic relations between the smectite-rich assemblage and opal-CT silicifications in the Lower Chalk of Wiltshire support its post-depositional origin.

Little is known about regional and stratigraphical variations of the smectite-mica clay mineral
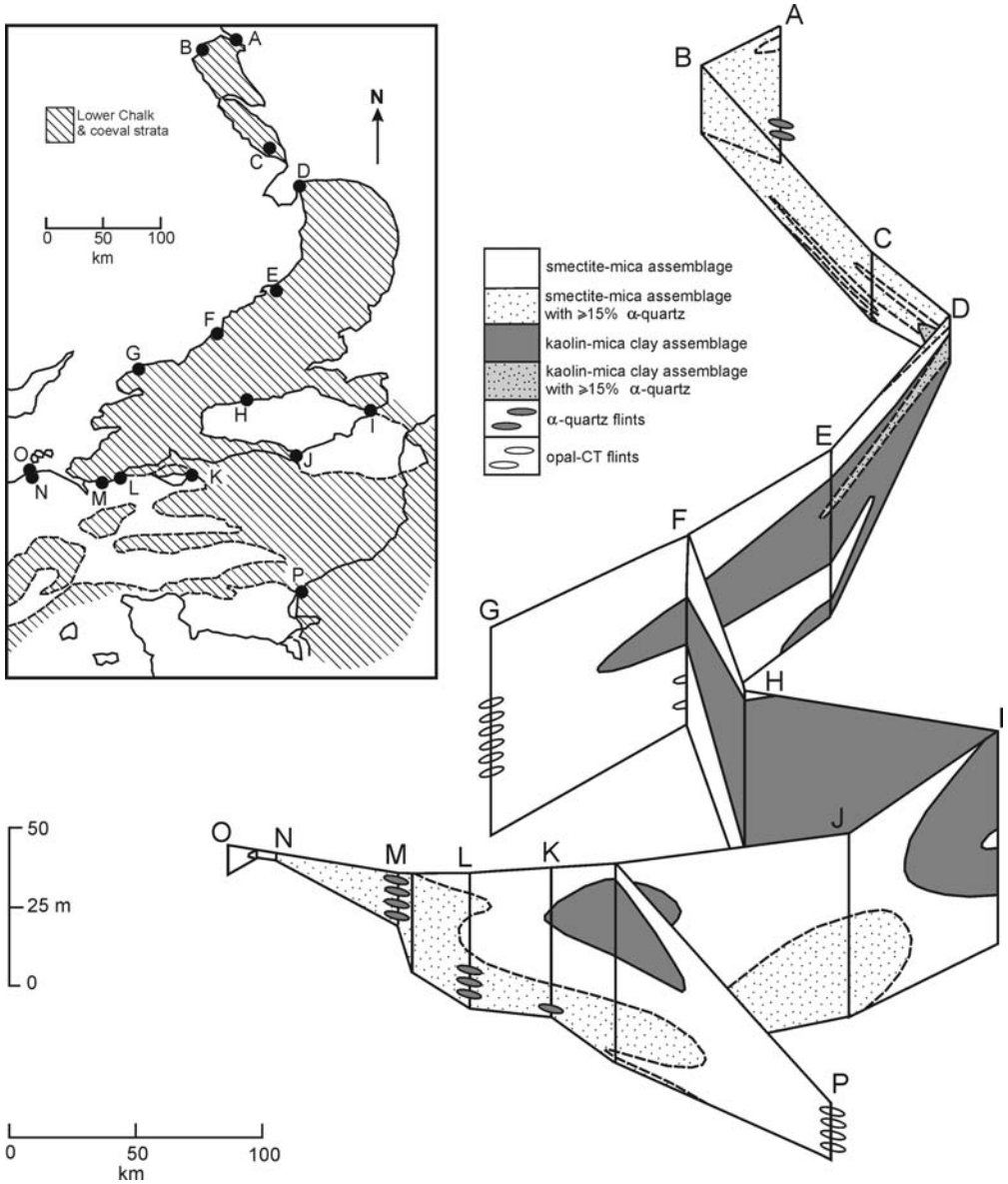
FIG. 46. Fence diagram from Jeans (1978) showing the regional distribution of the smectite-mica and the kaolin-mica assemblages in the Lower Chalk of England and Normandy, France. Silification types are also shown. Insert shows the locations and distribution of Lower Chalk and coeval strata at the surface and subsurface. A: Speeton/Flixton, Yorkshire; B: North Grimston, Yorkshire; C: South Lincolnshire; D: North Norfolk; E: Cambridgeshire; F: Bedfordshire-Buckinghamshire; G: Liddington, Wiltshire; H: Fetcham Mill, Surrey; I: Folkestone/Dover, Kent; J: Eastbourne, Sussex; K: Culver Cliff, Isle of Wight; L: Ballard Cliff, Dorset; M: White Nothe, Dorset; N: South Devon; O: Wilmington, Devon; P: St Jouin, Normandy.

assemblage in the main part of the Chalk facies (Turonian to Campanian or Lower Maastrichtian) of English and Northern Ireland. It is a topic for future investigation, especially since suitable stratigraphical and lithostratigraphical schemes (Fletcher, 1977; Mortimore et al., 2001) are now available to
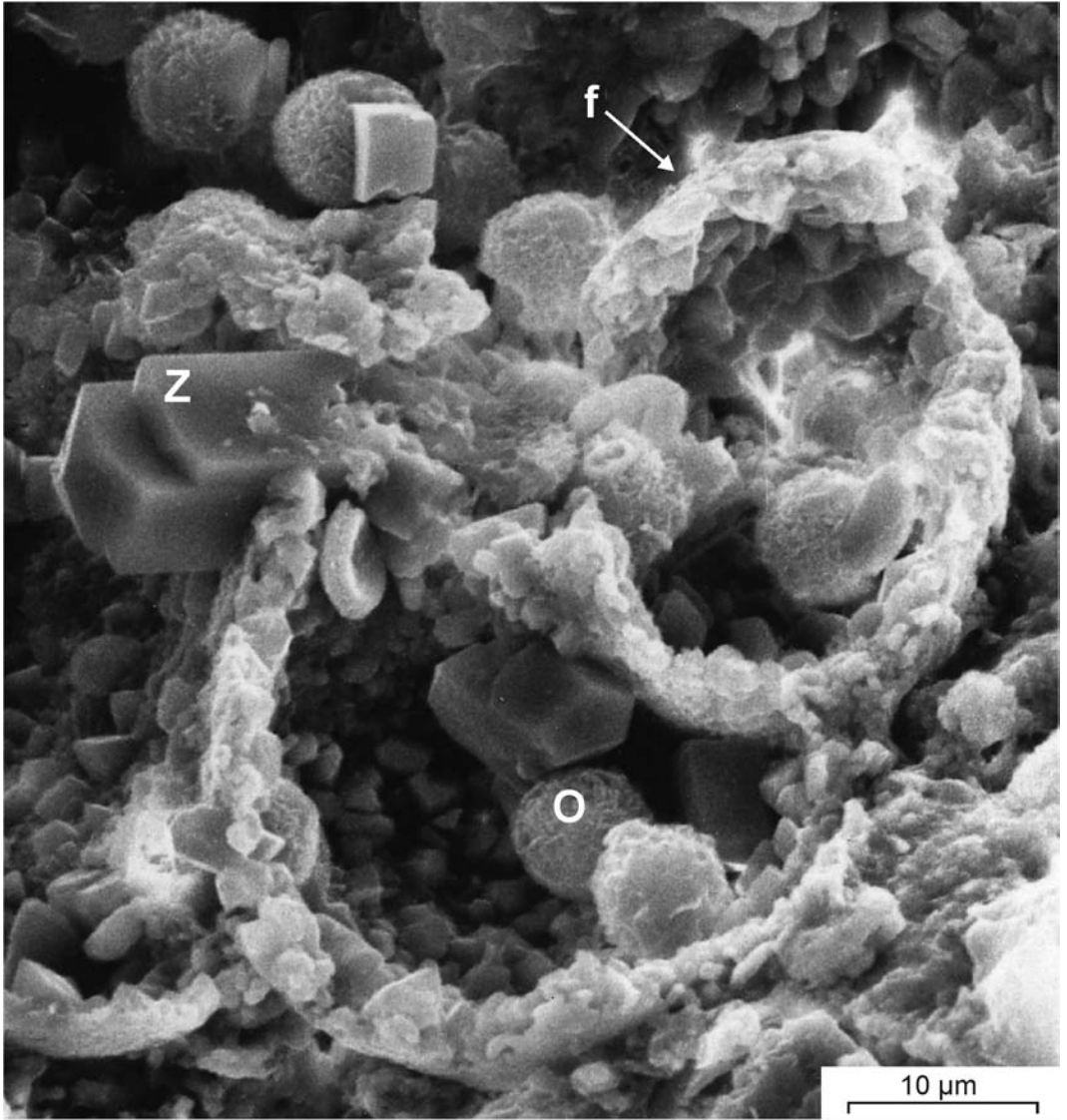
FIG. 47. SEM image of the Lower Chalk from the Harwell No. 6 Borehole (20.64 m depth) (courtesy of A.E. Milodowski (BGS)). Authgenic heulandite-clinoptilolite zeolite (Z) and Opal-CT (O) is associated with a broken foraminifera (f) with secondary calcite crystals lining its chambers.

form a framework in which the clay mineral variations can be placed.

An important question related to the neoformed smectite-dominated assemblage in the Chalk facies is the source of reactive Si and Al necessary for clay mineral-forming reactions. Several possible sources can be considered: (1) from dissolution of atmospheric dust (including volcanic ash); (2) poorly crystalline clay minerals and alumino-

siliceous gels transported by rivers into the Chalk seas, where they have been concentrated by differential flocculation and settling from the coarser and better crystalline mica and kaolin (Jeans, 1986, his fig. 1); (3) from volcanic ash washed in by rivers from adjacent continental sources; or (4) from Si and Al, originally extracted from sea water, contained in biogenic siliceous skeletons of organisms which dissolved in the
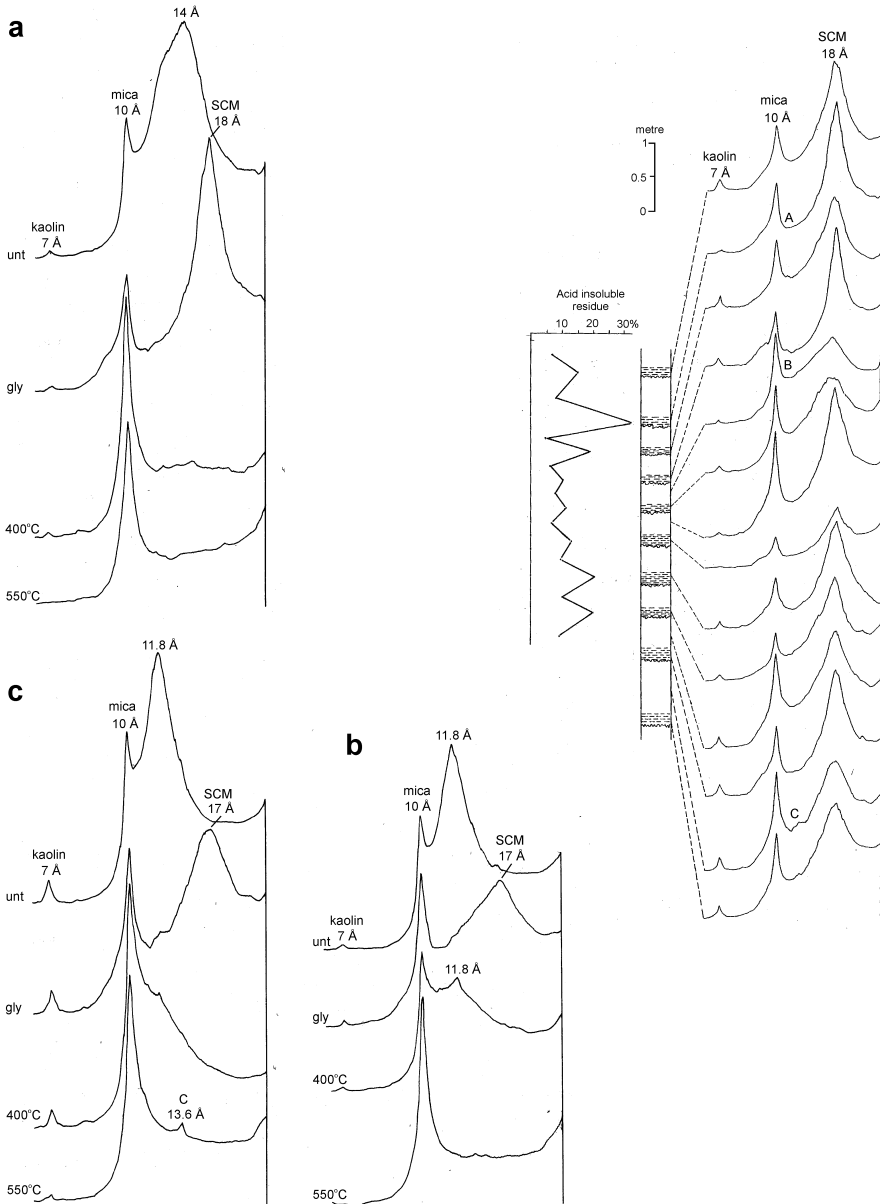
FIG. 48. The clay mineralogy and variations in acid-insoluble contents (1 M acetic acid) within the alternating chalk/marl facies of the Lower Chalk, Balland Cliff, Dorset. The XRD patterns are of the glycerolated <2 μm clay fractions. There is considerable variation in the shape, position, glycerol-expandability and heat collapse of the smectite 001 peak; this is shown for samples a, b and c. Abbreviations as in Fig. 7; unt − untreated.

porewaters of the Chalk sediment. There is evidence that volcanic ash was washed into the Lower Chalk sea in southern England from the same western source that was responsible for the volcanogenic clay facies pattern B (Jeans *et al.*,

2000) of the Upper Greensand and surrounding envelope of Gault (Fig. 34), which continues into the basement beds and the overlying Cenomanian Chalk in southern England (Fig. 46). Glauconitized grains of volcanic rocks and ash are common in the

glauconite-rich basement beds where they have been investigated in detail (Jeans *et al.*, 1982).

Antipathetic relationships between the mica-kaolin and the smectite-mica assemblages in the Lower Chalk suggest that differential flocculation and/or settling of a mixed riverine load of well crystallized and poorly crystalline clay minerals and alumino-siliceous gels could have been the main factor in controlling their distribution. Thus the coarser, better crystallized mica and kaolin formed the detrital mica-kaolin assemblage, whereas the poorly crystalline clay minerals and amorphous gels underwent neoformation reactions in the Chalk sediment to form the smectite-dominated assemblage. The source of this detritus during the deposition of the Lower Chalk is likely to have been the Brabant Massif which Jeans *et al.* (2001) suggested was the source of the mica-kaolin assemblage. In the main part of the Chalk facies (Turonian-Campanian or Lower Maastrichtian) the very low clay mineral content and lack of the detrital mica-kaolin assemblage, suggests that atmospheric dust (Kimblin, 1992) and biogenic silica were important sources of reactive Al and Si for the clay neoformation reactions.

The relative timings of the clay neoformations during diagenesis of the Chalk sediment have been investigated in the Lower Chalk. The earliest phase is the development of green pigmentary glauconite, which is associated with beds that have undergone early lithification by calcite cementation. In east England, glauconite is mainly associated with two types of lithification (Jeans 1980, types 1, 3). Type 1 lithification takes place in the sediment below a long-established surface of non-deposition. The pigmentary glauconite occurs in one or more thin Liesegang zones in the uppermost 5−20 mm of the Chalk immediately below the non-depositional surface. Jeans (1980, p. 101) suggested that glauconite formation took place in the anaerobic zone of the sediment by reaction between ions diffusing from ambient seawater and porewaters enriched in dissolved Si, Al and Fe. However, such a reaction is more likely to be restricted to the suboxic zone of the original Chalk sediment. Type 3 lithification resulted from calcite cementation associated with very slow but continuous deposition on the Chalk seafloor. The resulting chalk contains glauconite as irregular flecks and films which appear to be the partial infilling of voids developed in the sediment by the dissolution of aragonite shells during the early stages of

lithification. Subsequently the voids collapsed by compaction or have been infilled by calcite cement. Restriction of the glauconite staining to these post-depositional voids is related probably to the much lower critical supersaturation necessary for the nucleation and precipitation of mineral cements in free solution (i.e. voids, large pores) than in the fine pores characteristic of the Chalk sediment (see Jeans, 1994 pp. 415−420 , for discussion of this effect). During early lithification of these chalks, the porewaters were clearly supersaturated in regard to glauconite, irrespective of the source of the reactive Si, Al and Fe.

The development of the smectite-dominated clay assemblage occurred somewhat later in the diagenetic sequence and was probably initiated within the anaerobic zone of sulphate-reduction where Fe was no longer available for clay mineral precipitation. Petrographic evidence (Weir & Catt, 1965) suggests that the smectite and possibly some of the mica developed directly from the pore solutions, whereas some of the mica also developed as overgrowths on detrital cores.

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APPENDIX

This consists of Tables 1−24 containing approximately 1400 new clay mineral analyses arranged stratigraphically and by location. Listed below are (1) the grid references of the various boreholes sampled, (2) references in the literature describing the borehole successions, and (3) the mineral abbreviations used in Tables 1−24.

	Boreholes	
Name	Grid ref.	Reference
Alford	~TF455760	Swinnerton (1935)
Arlesey	TL 186351	London Brick Co. Ltd.
Ely − Ouse No. 4	TL70127169	Bristow (1990)
Ely − Ouse No. 23	TL69168817	Gallois (1988)
Broadoak	TQ61952214	Lake & Holliday (1978)
Cliffe No. 6	TQ68907715	Owen (1971b)
Cliffe No. 11	TQ71767376	Owen (1971b)
Cooden	TQ70430641	Lake (1975)
Cuckfield No. 1	TQ29612731	Lake & Thurrell (1974); Gallois & Worssam (1993)
Fairlight	TQ85921173	Lake & Shephard-Thorn (1987)
Leatherhead (Fetcham Mill)	TQ158565	Gray (1965)
Fordington	~TF419707	Swinnerton (1941)
Glyndebourne	TQ44201141	Lake *et al.* (1987)
Glynleigh	TQ60850637	Lake *et al.* (1987)
Hampden Park	TQ61200204	Lake *et al.* (1987)
Hunstanton	TF65874078	Gallois (1994)
Kingston Lisle	SU 3142087200	Morter (unpublished BGS report)
Maidstone Prison No. 6	TQ765564	Jeans *et al.* (1982, their fig. 15)
Ripe	TQ50591052	Lake *et al.* (1987)
Sandgate Encombe Estate	~TR200355	−
Skegness	TF 57116398	Gallois (1972, p. 116)
Warlingham	TQ34765719	Worssam & Ivimey-Cook (1971)
Water House Farm, Bletchingley	TQ 33945062	Laporte Industries Ltd. Borehole 204
Winchester No. 1	SU 50172830	Owen (1971a, p. 69)

MINERAL ABBREVIATIONS

K(c) Kaolin, possibly with minor/trace amounts of chlorite.

C Chlorite or mixed-layer mica-chlorite identified in the XRD pattern of the 550ºC heated sample by the presence of a peak at ~ 14Å (A) or 10−14Å (B).

X No data as XRD pattern of 550ºC−heated sample is missing

B Berthierine

M Mica (illite)

CM Collapsible minerals

pd Poorly defined collapsible mineral displaying no obvious peak in the XRD pattern of the glycerolated sample. Relative abundance within the collapsible minerals indicated by C (minor) and D (major).

D* Collapsible mineral with pronounced peak in the XRD pattern of the glycerolated sample between 10 and 14 Å (e.g. Fig. 38, sample B-DB 6422). This is referred to as the mixed-layer clay mineral in the text.

V Vermiculite identified by the presence of a 14 Å peak in the XRD patterns of the untreated and glycerolated sample which is lost on heating at 400ºC. E, F, G indicates the increasing prominence of this component within the collapsible minerals.

S Smectite, smectitic collapsible mineral identified by a peak in the XRD pattern of the glycerolated sample between 14 and 18 Å which is lost on heating. A minor peak is indicated by $\sqrt{}$ (e.g. Fig. 32b), a major peak by $\sqrt{}$(vs) (e.g. Fig. 32c).

mQ Major quartz is indicated by $\sqrt{}$.

Z Heulandite-clinoptilolite zeolite.

TABLE 1. Clay mineral analyses (<2 μm) from the Purbeck Limestone Group. GLM = Grey Limestones Member, ABM = Arenaceous Beds Member, CB = Cinder Bed, PBBM = Plant and Bone Beds Member, BCM = Broadoak Calcareous Member. Mineral abbreviations and borehole locations are on page 117.

Depth m (Member)	K(c)	C	M	CM	pd	V	S
			Purbeck Limestone Group				
Warlingham Borehole (575.77−655.32 m)							
576.07 (GLM)	20	A	52	28	D	F	−
582.17 (GLM)	16	−	34	51	D	F	−
588.04 (GLM)	15	−	32	54	D	−	√
595.12 (GLM)	20	A	53	27	D	F	−
606.22 (CB)	9	−	33	58	D	−	√
612.23 (PBBM)	−	−	76	24	D	−	−
618.27 (BCM)	−	−	48	52	D	−	−
Fairlight Borehole (219.00−339.82 m)							
219.46 (GLM)	20	−	52	28	D	−	−
222.50 (GLM)	35	−	52	13	D	−	−
232.87 (GLM)	24	−	56	20	D	−	−
235.92 (GLM)	20	−	35	45	D	E	−
238.96 (ABM)	14	−	42	44	D	−	−
242.01 (ABM)	27	A	44	29	D	E	−
248.11 (ABM)	9	−	47	44	D	−	−
260.30 (BCM)	5	−	35	60	D	−	−
266.40 (BCM)	4	X	49	47	D	−	−
269.44 (BCM)	3	−	64	33	D	−	−
272.49 (BCM)	4	X	96	−	−	−	−
278.59 (BCM)	8	A	44	48	D	−	−
281.64 (BCM)	−	X	71	29	D	−	−
287.73 (BCM)	−	X	53	47	D	−	√
290.78 (BCM)	−	−	53	47	D	−	−
293.83 (BCM)	−	−	66	34	D	−	−
296.88 (BCM)	−	−	78	22	D	−	−
299.92 (BCM)	−	X	100	−	−	−	−
302.97 (BCM)	2	X	30	68	D	F	−
309.07 (BCM)	−	−	62	38	D	−	−
315.16 (BCM)	−	−	74	26	D	−	−
318.21 (BCM)	−	−	68	32	D	−	−
Broadoak Borehole (0−133.67 m)							
5.86 (GLM)	14	−	38	48	D	−	−
7.59 (GLM)	17	A	40	43	D	F	−
10.43 (GLM)	20	A	62	18	D	−	−
11.42 (GLM)	16	−	42	42	D	E	−
19.88 (GLM)	16	−	43	41	D	−	√
25.25 (ABM)	13	−	53	35	D	−	−
30.70 (ABM)	19	−	47	34	D	−	−
31.14 (ABM)	10	−	42	48	D	−	−
39.77 (ABM)	77	A	10	14	C	E	√
42.29 (ABM)	11	−	46	43	D	−	√
45.50 (PBBM)	7	−	65	28	D	−	√
49.57 (PBBM)	3	−	49	48	D	−	−
52.30 (PBBM)	7	−	34	59	D	−	√
55.34 (PBBM)	7	−	46	47	D	−	√
57.85 (PBBM)	7	−	56	37	D	−	−
62.00 (BCM)	8	−	57	35	D	−	−
66.34 (BCM)	3	X	77	20	D	−	−
69.30 (BCM)	2	−	63	35	D	−	√
71.78 (BCM)	−	−	67	33	C	−	√(vs)
80.39 (BCM)	tr.	−	33	67	D	−	√
92.19 (BCM)	−	−	84	16	D	−	√
101.98 (BCM)	3	A	40	57	D	F	−
104.01 (BCM)	5	−	66	29	D	−	−
107.49 (BCM)	3	−	49	48	D	−	−
116.61 (BCM)	1	−	30	69	D	E	−

TABLE 2. IR and XRD analysis of kaolin from selected Wealden Group and Lower Greensand samples.

Location (borehole)	Rock unit	Sample depth (m)	IR	XRD
Cooden	Ashdown Fm	166.12	kaolinite/dickite 50:50 mixture of separate phases or areas of dickite stacking within kaolinite phase. Some Fe^{3+} substitution in kaolinite	moderately well-ordered kaolinite, no dickite
Fairlight	Ashdown Fm	161.54	kaolinite/dickite 60:40 mixture	moderately well-ordered kaolinite, no dickite
Cuckfield	Upper Tunbridge Wells Sand	154.53	kaolinite/dickite 40:60 mixture	–
	Grinstead Clay Mbr	183.79	halloysite/disordered kaolinite	kaolinite, no dickite
	Lower Tunbridge Wells Sand	209.09	kaolinite/dickite 50:50 with some Fe^{3+} substitution in kaolinite	–
	Lower Tunbridge Wells Sand	217.63	kaolinite/dickite 40:60 mixture	–
	Lower Tunbridge Wells Sand	218.85	kaolinite/dickite 40:60 mixture	kaolinite, no dickite
Worbarrow Bay	Lower Greensand Grp (Fig. 30, Bed 1)	Bed 34	Disordered kaolinite with possibly dickite/nacrite stacking in kaolinite structure. Fe^{3+} substitution in kaolinite structure	poorly ordered kaolinite
	Wessex Fm (Table 9)	Bed 31 1.22	kaolinite/dickite 60:40 mixture	poorly ordered kaolinite
		Bed 31 8.84	kaolinite/dickite 60:40 mixture	–
		Bed 31 20.73	Disordered kaolinite with possibly dickite/nacrite stacking in kaolinite structure. Fe^{3+} substitution in kaolinite structure	–
		Bed 15 198.12	Kaolinite/dickite 50:50 mixture with Fe^{3+} substitution in kaolinite	–
		Bed 15 209.70	Kaolinite/dickite 50:50 mixture with Fe^{3+} substitution in kaolinite	–
		Bed 12 247.80	Kaolinite/dickite 50:50 mixture	–

Analysis was carried out by A. Fraser and M.J. Wilson, MLURI, Aberdeen.

TABLE 3. Clay mineral analyses (<2 μm) from the Ashdown Beds Formation (Wealden Group). Mineral abbreviations and borehole locations are on page 117.

Depth m	K(c)	B	C	M	CM	pd	V	S
				Ashdown Formation				
Fairlight Borehole (7.52−219.00 m)								
3.05	60%	—	—	31%	9%	D	—	—
7.92	52	—	—	38	10	D	—	—
11.28	32	—	—	42	26	D	E	—
15.24	38	—	—	42	20	D	—	—
18.59	38	—	—	62	—	D	E	—
22.45	38	—	—	58	4	D	F	—
23.62	38	—	X	42	19	C	E	—
26.52	50	—	—	44	6	C	E	—
29.87	43	—	—	37	20	C	E	—
32.92	34	—	—	45	21	C	—	—
35.97	23	—	X	47	30	C	E	—
39.01	48	—	X	41	11	C	E	—
42.06	27	—	A	51	22	D	E	—
45.11	32	—	X	32	36	D	G	—
48.16	29	—	—	39	32	D	F	—
51.21	52	—	—	36	12	C	—	—
54.25	44	—	—	36	20	D	—	—
57.30	24	—	—	52	24	D	—	—
60.35	24	—	X	35	41	D	—	—
63.40	37	—	—	46	17	D	E	—
66.45	31	—	X	37	32	D	F	—
69.49	49	—	A	39	12	C	E	—
71.63	27	—	X	43	30	D	F	—
75.59	28	—	X	38	34	D	E	—
78.64	35	—	B	35	30	D	G	—
82.60	29	—	—	56	15	D	E	—
84.73	30	—	B	53	17	C	E	—
87.78	29	—	A	49	22	C	E	
90.83	21	—	A	46	33	C	E	
96.93	49	—	B	22	29	D	G	—
100.04	22	—	X	45	33	C	E	—
103.07	16	14%	B	54	16	C	E	—
106.14	29	—	A	52	19	C	E	—
109.12	21	—	A	46	33	C	E	—
112.17	26	—	—	54	20	D	E	—
115.21	32	—	—	41	27	D	E	—
118.26	27	—	X	73	—	C	E	—
121.31	30	—	A	56	14	C	E	—
125.20	27	—	A	53	20	C	E	—
127.41	29	—	A	52	19	C	E	—
130.45	27	—	A	50	23	C	E	—
133.50	41	—	A	42	17	C	E	—
135.64	41	—	—	41	18	C	E	—
137.39	20	—	X	40	40	C	E	—
139.60	28	—	—	41	31	D	—	—
146.30	47	—	B	36	17	D	E	—
149.35	43	—	B	36	21	D	—	—
152.40	42	—	—	42	16	D	—	—
155.45	42	—	—	52	6	D	—	—
161.54	63	—	—	33	4	D	—	—
164.59	47	—	B	34	19	D	E	—
167.67	49	—	X	35	16	C	—	—

TABLE 3 (*contd.*).

Depth m	K(c)	B	C	M	CM	pd	V	S
170.69	30	—	B	53	17	C	E	—
173.74	33	—	—	46	21	D	—	—
176.78	29	—	—	57	14	C	E	—
179.83	31	—	—	44	25	D	E	—
182.88	31	—	—	38	31	D	—	—
185.93	23	41	B	33	4	C	E	—
188.98	17	19	B	48	16	D	E	—
192.02	24	—	—	45	31	D	—	—
195.07	27	—	—	36	37	D	—	—
198.12	24	—	—	45	31	D	E	—
201.17	22	—	—	36	43	D	—	—
204.22	60	16	B	21	3	C	E	—
207.26	22	—	—	53	25	D	—	—
210.31	31	—	—	55	14	D	—	—
213.36	27	—	—	52	21	D	—	—
216.41	30	—	B	54	16	C	E	—
Cuckfield Borehole (283.53−325.22 m)								
284.99	85	—	—	11	4	D	—	√
288.65	34	29	X	28	9	C	E	—
292.30	47	10	A	39	4	C	E	—
295.05	38	18	B	31	13	C	E	—
299.31	35	12	B	34	19	C	E	—
302.67	50	—	—	50	—	—	E	—
306.63	33	—	B	50	17	D	E	—
309.98	35	—	B	49	16	D	E	—
313.64	34	12	B	52	2	C	E	—
317.91	41	26	B	22	11	C	E	—
321.26	55	28	B	13	4	D	E	√
325.83	40	—	A	48	12	C	E	—
Glynleigh Borehole (71.40−96.52 m)								
75.02	36	—	—	31	32	C	F	—
77.82	19	—	—	37	44	C	E	—
80.35	30	—	B	45	25	C	F	—
85.25	36	—	B	42	22	C	E	—
90.95	30	—	—	46	24	C	F	—
95.25	41	—	B	31	28	D	E	—
Warlingham Borehole (557.78−575.77 m)								
563.88	23	—	—	53	24	D	F	—
569.98	14	—	—	60	26	D	F	—
Cooden Borehole (144.96−166.42 m)								
146.61	44	—	A	47	9	D	F	—
149.66	56	—	—	34	10	D	G	√
166.12	44	—	—	38	18	D	F	—

TABLE 4. Clay mineral analyses (<2 μm) from the Wadhurst Clay Formation (Wealden Group). Mineral abbreviations and borehole locations are on page 117.

Depth m	K(c)	B	C	M	CM	pd	V	S
				Wadhurst Clay Formation				
Cuckfield Borehole (219.46−283.53 m)								
221.28	8%	7%	−	69%	17%	D	−	−
225.86	18	−	−	50	32	D	E	−
228.60	20	−	A	47	53	D	E	−
231.34	9	−	−	46	45	D	−	−
234.70	10	−	A	39	51	D	−	−
238.66	7	7	−	48	38	D	E	−
242.62	17	−	A	57	26	D	E	−
246.58	19	17	A	53	11	C	E	−
249.94	11	11	A	53	25	D	E	−
253.59	14	8	A	64	14	D	−	−
257.25	12	7	−	57	25	D	E	−
261.21	20	−	B	34	47	D	F	−
265.18	17	8	−	65	10	D	E	−
269.44	20	−	−	45	35	D	E	−
273.10	21	−	A	44	35	D	E	−
275.54	19	9	B	57	15	D	E	−
280.42	25	11	B	63	1	D	E	−
Warlingham Borehole (538.58−557.78 m)								
539.50	13	−	−	54	33	D	F	−
545.59	19	−	−	56	26	D	F	−
551.77	16	−	−	44	39	D	G	−
556.97	18	−	−	35	48	D	G	−
Cooden Borehole (120.35−145.03 m)								
121.62	27	−	A	37	36	D	F	−
122.23	14	−	A	46	40	D	−	−
128.02	36	−	−	22	42	D	F	√
131.06	30	−	−	33	37	D	F	√
134.11	28	−	−	50	22	D	F	−
137.16	23	−	−	45	32	D	F	−
140.82	27	−	A	64	9	D	F	−
Glynleigh Borehole (41.00−71.40 m)								
45.14	16	−	A	46	39	D	E	−
48.66	21	−	A	47	32	D	F	−
50.52	23	−	B	41	36	D	F	−
55.25	17	−	A	39	44	D	E	−
60.00	17	−	B	50	33	D	E	−
64.88	20	−	B	50	30	D	F	−
67.69	19	−	A	35	46	D	−	√
70.00	20	−	B	38	43	D	F	−

TABLE 5. Clay mineral analyses (<2 μm) from the lower part of the Tunbridge Wells Sand Formation and the Lower Tunbridge Wells Sand (Wealden Group). Mineral abbreviations and borehole locations are on page 117.

Depth m	K(c)	B	C	M	CM	pd	V	S
			Tunbridge Wells Sand Formation					
Glynleigh Borehole (0−41.00 m)								
8.40	26%	–	–	34%	40%	D	E	–
9.88	33	–	–	58	9	D	–	–
13.53	42	–	B	27	31	D	E	–
17.90	28	–	–	33	39	C	F	–
20.24	26	–	–	45	29	D	–	–
25.14	17	–	–	33	50	D	F	–
29.11	33	–	B	46	21	C	F	–
32.90	45	–	–	38	17	D	–	–
35.58	16	–	–	31	51	D	E	–
40.10	18	–	B	58	23	D	–	–
Ripe Borehole (206.65−214.02 m)								
210.34	28	–	–	40	33	D	E	–
212.00	28	–	–	41	30	D	E	–
			Lower Tunbridge Wells Sand					
Cuckfield Borehole (192.94−219.46 m)								
195.68	33	30	B	25	12	D	E	–
199.64	66	14	–	14	6	C	E	–
203.00	63	23	B	11	3	C	E	–
206.65	33	20	B	47	–	C	E	–
209.09	60	16	–	22	2	D	E	–
212.75	45	17	–	38	–	–	E	–
215.49	26	19	A	55	–	–	E	–
218.85	19	27	A	41	13	C	E	–
Warlingham Borehole (531.62−538.58 m)								
533.40	23	–	–	74	2	D	G	–

TABLE 6. Clay mineral analyses (<2 μm) from the Grinstead Clay Member (Wealden Group). Mineral abbreviations and borehole locations are on page 117.

Depth m	K(c)	B	C	M	CM	pd	V	S
			Grinstead Clay Member					
Cuckfield Borehole (166.04−192.94 m)								
167.64	10%	10%	A	62%	18%	D	–	–
171.60	15	–	A	51	34	D	–	–
174.96	15	–	–	36	49	D	–	–
179.83	36	28	–	23	13	C	–	–
185.32	18	45	B	32	5	C	E	–
188.37	15	10	–	60	15	D	E	–
192.33	50	20	B	27	3	D	–	–
Warlingham Borehole (512.98−531.62 m)								
505.11	29	–	–	45	26	D	F	?
520.29	31	–	–	54	16	D	–	–
527.00	13	–	–	42	45	D	G	–

TABLE 7. Clay mineral analyses (<2 μm) from the Upper Tunbridge Wells Sand Formation. Mineral abbreviations and borehole locations are on page 117..

Depth m	K(c)	B	C	M	CM	pd	V	S
			Upper Tunbridge Wells Sand Formation					
Cuckfield Borehole (64.74−166.04 m)								
66.32	34%	−	−	57%	9%	D	−	−
69.98	47	9%	−	33	11	D	−	−
70.76	35	−	B	54	11	D	−	−
71.32	32	−	−	63	5	D	−	−
73.46	27	26	−	27	20	D	−	−
76.50	21	16	B	56	8	D	F	−
79.10	33	18	B	38	11	D	E	−
79.60	19	14	B	55	12	D	E	−
82.35	22	24	B	46	8	D	F	−
85.57	25	14	B	53	8	D	F	−
88.54	33	−	−	65	2	D	−	−
90.22	33	18	B	38	12	D	E	−
91.44	34	24	B	35	7	C	E	−
93.19	28	−	B	60	12	D	E	−
101.19	46	21	X	28	6	C	−	−
104.09	23	15	−	49	13	C	E	−
107.59	25	22	B	41	12	C	E	−
108.51	36	25	−	38	−	−	E	−
112.78	31	26	B	33	10	C	E	−
116.43	30	22	B	34	14	C	E	−
121.01	21	20	−	45	14	D	−	−
124.97	69	−	−	26	5	D	−	−
127.10	44	−	−	26	30	D	−	−
130.76	36	−	−	46	18	C	E	−
133.81	21	21	B	42	16	C	F	−
136.86	18	22	B	40	20	D	−	−
140.21	23	23	−	36	18	D	E	−
144.17	59	−	−	34	7	D	−	−
148.44	30	22	−	27	21	D	E	−
152.10	22	20	−	52	6	D	−	−
154.23	23	41	−	21	15	C	E	−
155.14	39	18	−	43	−	D	E	−
159.41	27	22	B	44	7	D	E	−
163.07	27	36	B	25	12	C	E	−
Warlingham Borehole (495.07−512.98 m)								
496.82	24	−	−	48	28	D	G	−
502.92	26	−	B	54	20	C	G	−
509.02	30	−	B	48	22	C	G	−
Cooden Borehole (13.54−120.35 m)								
16.41	32	−	−	48	21	D	F	−
21.64	28	−	−	45	26	D	F	−
25.12	29	−	−	46	25	D	F	−
28.30	33	−	−	45	22	D	F	−
28.50	32	−	A	42	25	−	G	−
35.66	47	−	B	48	6	D	G	−
39.34	32	−	B	51	18	D	F	−
42.65	32	−	−	53	16	D	G	−
46.36	47	−	−	34	20	D	G	−
51.46	59	−	−	21	20	D	−	−
53.62	33	−	−	46	20	D	F	−
57.61	33	−	−	53	15	D	F	−

TABLE 7 (*contd.*).

Depth m	K(c)	B	C	M	CM	pd	V	S
60.88	25	−	B	57	18	−	G	−
63.96	26	−	B	54	20	−	G	−
72.54	42	−	−	45	13	D	F	−
75.57	24	−	−	53	23	D	F	−
77.72	32	−	−	45	23	D	F	−
81.36	28	−	−	47	24	D	G	−
84.51	32	−	−	32	36	D	F	−
88.21	−	40	−	40	20	D	F	−
95.98	22	−	−	42	36	D	F	−
96.93	63	−	−	13	25	D	F	−
101.52	32	−	−	52	16	D	G	−
105.21	34	−	−	47	19	D	G	−
107.92	32	−	−	34	34	D	E	−

TABLE 8. Clay mineral analysis (<2 μm) from the Weald Clay Formation. Mineral abbreviations and borehole locations are on page 117.

Depth m	K(c)	B	C	M	CM	pd	V	S
				Weald Clay Formation				
Warlingham Borehole (319.13−495.97 m)								
322.33	19%	−	−	56%	25%	D	F	√
326.81	21	−	−	66	13	D	G	−
329.34	26	−	−	51	24	D	F	√
332.23	20	−	−	46	34	D	F	√
337.41	19	−	−	40	41	D	F	√
344.42	19	−	−	41	40	D	F	−
350.52	19	−	−	34	47	D	F	√
356.62	2	−	−	46	52	D	−	√ (vs)
356.62	20	−	−	42	38	D	F	√
362.71	17	−	−	52	31	D	F	−
368.81	18	−	−	36	46	D	F	√
374.90	18	−	−	31	51	D	−	−
381.00	14	−	−	57	29	D	F	−
387.10	19	−	−	39	42	D	F	√
393.19	18	−	−	48	34	D	F	−
399.29	17	−	−	42	41	D	F	−
405.45	22	−	−	44	34	D	F	√
411.58	18	−	−	49	33	D	−	−
417.58	21	−	−	51	28	D	F	−
423.67	19	−	−	39	42	D	F	−
429.85	17	−	−	40	43	D	F	−
436.02	16	−	−	45	39	D	F	−
441.96	16	−	A	39	45	D	G	−
448.06	17	−	−	42	41	D	G	−
454.15	22	−	−	58	21	D	G	−
460.25	15	−	−	42	43	D	G	−
466.34	17	−	−	48	35	D	F	−
472.44	23	−	−	54	23	C	G	−
478.54	22	−	−	44	34	C	G	−
484.94	21	−	−	40	39	D	F	−
490.73	24	−	−	46	30	C	G	−

TABLE 8 (*contd.*).

Depth m	K(c)	B	C	M	CM	pd	V	S
Cuckfield Borehole (0−64.74 m)								
2.29	23%	−	B	71%	6%	D	F	−
5.79	15	14%	B	66	5	D	F	−
9.37	17	18	B	57	9	D	F	−
12.19	18	16	B	53	13	D	F	−
15.29	23	18	B	60	−	D	E	−
18.29	20	18	B	46	15	D	E	−
21.26	18	11	−	29	42	D	E	−
24.64	21	18	B	62	−	D	E	−
27.66	22	22	B	56	−	D	E	−
30.71	22	23	B	51	3	D	E	−
33.60	22	22	B	48	8	D	E	−
36.78	25	18	−	52	5	D	E	−
39.78	18	22	B	58	2	D	E	−
42.77	24	21	B	51	4	D	E	−
45.72	23	17	B	55	5	D	F	−
49.07	24	16	B	57	3	D	E	−
51.82	29	−	B	64	7	D	E	−
55.02	31	−	B	47	22	D	F	−
57.91	35	−	B	44	21	D	F	−
61.14	19	20	A	50	11	D	F	−
64.21	33	12	A	55	−	D	F	−
Cooden Borehole (1.78−13.54 m)								
3.81	22	−	−	50	28	D	F	−
6.63	27	−	A	73	−	D	F	−
11.28	30	−	−	45	25	D	F	−
Ripe Borehole (47.79−200.65 m)								
49.86	15%	−	−	34%	51%	D	X	−
53.19	20	−	−	46	34	D	F	−
55.00	22	−	−	31	47	D	G	−
57.85	22	−	−	55	23	D	F	−
60.42	24	−	−	47	29	D	F	−
66.32	18	−	−	32	50	D	F	−
70.06	22	−	−	28	50	D	F	−
71.90	23	−	B	42	35	D	F	−
75.06	22	−	B	36	43	D	F	−
80.08	24	−	−	58	18	D	F	−
85.08	20	−	−	46	34	D	F	−
90.35	19	−	−	36	45	D	F	−
93.15	21	−	B	30	48	D	−	−
95.00	25	−	−	47	28	D	−	−
98.86	16	−	−	67	17	D	−	−
100.16	15	−	B	45	40	D	E	−
106.89	23	−	−	46	31	D	G	−
109.95	22	−	B	28	26	D	F	−
112.63	24	−	−	37	39	D	E	−
115.04	22	−	B	38	40	D	E	−
120.04	24	−	−	40	36	C	F	−
125.44	31	−	−	49	20	D	−	−
130.00	24	−	A	37	39	D	−	−
135.30	20	−	−	34	46	D	F	√
137.82	24	−	−	41	35	D	E	√
140.00	21	−	−	40	38	D	F	−
145.05	19	−	−	41	40	D	−	−
150.02	26	−	B	63	10	D	E	−

TABLE 8 (*contd.*).

Depth m	K(c)	B	C	M	CM	pd	V	S
155.00	16	–	B	42	42	D	E	–
160.50	14	–	B	41	45	D	E	–
165.14	17	–	–	46	37	D	E	–
170.37	20	–	–	57	23	D	E	–
175.26	23	–	–	68	9	C	E	–
180.34	20	–	–	53	26	D	F	–
184.92	26	–	–	72	2	D	F	–
190.11	38	–	B	43	42	D	F	–
195.10	22	–	–	40	39	D	E	–
200.04	25	–	–	51	24	D	F	–
205.07	21	–	–	37	43	D	E	–

TABLE 9. Clay mineral analyses (<2 μm) from the Wessex Formation (Wealden Group). Mineral abbreviations are on page 117. Worbarrow Bay, numbering of beds based on Arkell (1947, pp. 157−8), sample depths from top of Bed 35. Brightstone Bay, numbering of beds based on Jeans *et al.* (2001, their fig. 12). Yaverland, numbering of beds based on Radley (1994, his fig. 2), sample depths from the top of the Wessex Formation.

Bed no.	Depth m	K(c)	B	C	M	CM	pd	V	S
					Wessex Formation				
Worbarrow Bay, Dorset (grid ref. SY863803−SY870797)									
34	1.22	75%	–	–	19%	6%	C	–	–
31	8.84	69	–	–	30	1	C	–	–
"	15.54	37	–	–	40	23	D	–	–
"	20.73	27	–	–	39	34	D	–	–
"	25.91	31	–	–	41	28	D	–	–
30	32.00	35	–	–	42	23	D	–	–
"	33.83	75	–	–	18	7	D	–	√
28	40.23	40	–	–	21	39	D	–	√
"	45.72	38	–	–	62	–	D	–	–
"	54.86	28	–	–	67	5	D	–	–
"	59.44	17	–	–	37	46	D	–	–
"	85.65	28	–	–	47	25	D	–	–
"	85.65	22	–	–	31	47	D	–	–
"	101.80	20	–	–	63	17	C	–	–
"	104.24	50	–	–	38	12	C	–	–
"	105.46	60	–	–	40	1	C	–	–
26	109.73	27	–	–	61	12	D	–	–
"	119.79	29	–	–	56	15	D	–	–
23	138.07	16	–	–	50	34	D	–	–
"	142.95	20	–	–	44	36	D	–	–
"	150.88	24	–	–	62	14	D	–	–
15	163.37	39	–	–	42	19	D	–	–
"	198.12	24	–	–	46	30	D	–	–
"	202.39	46	–	–	42	12	D	–	–
"	203.91	44	–	–	47	9	C	–	–
"	209.70	49	–	–	45	6	C	–	–
14	212.45	52	–	–	42	6	C	–	–
13	227.38	44	–	–	54	2	C	–	–
12	231.65	29	–	–	71	–	–	–	–
"	234.70	43	–	–	45	12	C	–	–
"	247.80	37	–	–	42	21	C	–	–
"	259.70	29	–	–	49	22	C	–	–

TABLE 9 (*contd.*).

Bed no.	Depth m	K(c)	B	C	M	CM	pd	V	S
10	267.61	28	—	—	69	3	C	—	—
"	274.93	40	—	—	42	18	C	—	—
9	281.64	33	—	—	59	8	C	—	—
8	288.04	27	—	—	57	16	C	—	—
"	302.36	38	—	—	51	11	C	—	—
4	308.76	44	—	—	38	18	C	—	—
"	324.61	29	—	—	53	18	D	—	—
2	330.71	20	—	—	59	21	D	—	—
"	333.15	17	—	—	62	21	D	—	—
"	339.85	34	—	—	43	23	D	—	—
"	344.73	46	—	—	23	31	D	—	—
"	352.35	20	—	—	48	32	D	—	—
"	360.58	19	—	—	29	52	D	—	—
"	370.94	23	—	—	34	33	D	E	—
"	372.47	27	—	—	39	34	D	—	—
"	381.00	20	—	—	48	32	D	—	—
1	407.82	11	—	—	43	46	D	—	—
"	417.58	38	—	—	46	16	E	—	—
"	422.15	19	—	—	65	16	D	—	—

Sample no.		K(c)	B	C	M	CM	pd	V	S
					Wessex Formation				
Brightstone Bay, Isle of Wight (grid ref. SZ435807−SZ444800)									
IOW 123		31%	—	A	49%	20%	D	E	—
IOW 124		19	—	—	67	14	D	—	—
IOW 125		24	—	—	59	17	D	E	—
IOW 126		23	—	—	46	30	D	E	—
IOW 127		27	—	—	47	26	D	—	—
IOW 128		26	—	—	46	27	D	—	✓
IOW 129		24	—	—	42	35	D	—	✓
IOW 130		20	—	B	55	25	D	—	—
IOW 131		21	—	—	53	26	D	E	—
IOW 132		24	—	B	40	37	D	—	—
IOW 133		21	—	—	54	25	D	E	—
IOW 134		24	—	—	46	30	D	—	✓
IOW 135		24	—	—	46	30	D	—	—
IOW 138		22	—	A	50	29	D	E	—
IOW 137		20	—	—	57	23	D	—	—
IOW 136		30	—	A	41	28	D	E	—
IOW 139		25	—	A	42	33	D	E	✓
IOW 140		18	—	—	53	29	D	—	✓
IOW 141		24	—	—	59	17	C	—	—
IOW 142		18	—	—	49	33	D	E	—
IOW 143		28	—	B	47	25	C	—	—
IOW 145		20	—	—	54	26	D	—	—
IOW 146		21	—	—	65	14	D	—	—
IOW 147		20	—	A	53	26	D	—	—

TABLE 9 (*contd.*).

Bed no.	Depth m	K(c)	B	C	M	CM	pd	V	S
				Wessex Formation					
Sandown Bay (Yaverland), Isle of Wight (grid ref. SZ61108485−SZ61808525)									
40	0.4	24%	−	−	52%	24%	D	−	√
39	2.5	25	−	−	51	23	D	E	−
"	3.3	20	−	−	49	31	D	−	−
38	3.9	22	−	A	40	38	D	−	−
36	5.6	24	−	−	53	23	D	−	−
"	6.5	21	−	−	54	25	D	−	−
35	7.6	32	−	−	41	27	D	−	−
34	8.0	24	−	−	44	32	D	−	√
"	8.8	23	−	A	55	22	D	−	−
"	9.3	24	−	−	55	22	D	E	−
33	10.7	24	−	−	48	28	D	−	√
32	11.3	21	−	−	48	31	D	F	√
"	11.6	25	−	A	55	20	D	−	√
30	12.6	22	−	−	47	31	D	−	√
28	13.7	25	−	−	50	26	D	−	√
27	14.5	26	−	−	54	21	D	−	√
26	15.0	31	−	−	51	18	D	−	√
"	16.5	31	−	B	51	18	D	−	√
25	17.7	27	−	−	72	1	D	−	−
"	18.5	27	−	−	58	16	D	E	−
"	22.0	23	−	A	60	17	D	E	−
23	22.9	28	−	A	51	21	D	−	−
21	24.4	25	−	−	61	15	D	−	−
"	25.4	23	−	A	52	24	D	−	−
20	26.5	31	−	−	47	22	D	E	−
19	27.4	22	−	−	57	21	D	−	−
"	28.8	20	−	A	54	26	D	E	−
"	28.9	21	−	−	57	22	D	E	−
"	31.3	22	−	A	59	19	D	−	−
18	32.1	30	−	B	57	12	D	−	−
17	33.0	23	−	A	66	11	D	E	−
"	34.2	23	−	−	65	13	D	E	−
"	35.0	24	−	A	58	18	D	F	−
16	35.4	39	−	−	47	14	C	−	−
"	36.1	39	−	−	49	13	C	−	−
"	36.9	36	−	−	49	16	C	−	−
"	37.9	33	−	−	54	13	C	−	−
15	38.6	36	−	−	54	10	C	−	−
"	40.3	29	−	−	49	21	C	−	−
"	41.4	30	−	−	46	25	D	−	−
14	41.9	24	−	−	57	19	D	−	−
"	42.5	25	−	−	54	21	D	−	−
12	45.2	30	−	−	47	23	C	−	−

TABLE 10. Clay mineral analyses (<2 μm) from the Vectis Formation, Isle of Wight. Mineral abbreviations are on page 117. Sample depths are from the base of the Cyrena Limestone (Osborne White, 1921, p. 17).

	Depth m	K(c)	B	C	M	CM	pd	V	S
				Vectis Formation					
Sandown Bay, (Yaverland), Isle of Wight (grid ref. SZ615852−SZ621853)									
Shepherd's Chine Member	0.5	24%	−	−	53%	23%	D	F	−
	3.5	25	−	−	44	32	D	F	−
	14.6	27	−	B	44	29	D	F	−
	16.7	36	−	A	42	21	D	E	−
Cowleaze Chine Member	23.7	26	−	A	60	14	D	E	−
	25.3	28	−	−	47	25	D	F	−
	26.3	27	−	−	45	28	D	E	−
	28.1	28	−	−	61	12	D	E	−
	30.1	23	−	−	49	28	D	E	−

TABLE 11. Average and range of variation in the clay mineral analyses (<2 μm) from the formations of the Wealden Group. Mineral abbreviations and borehole locations are on page 117.

	Sample nos.	K(c)	B	M	CM	M/K
			Weald Clay Formation			
Total	95	21 (2−38)%	3 (0−23)%	47 (28−73)%	30 (0−52)%	2.2
Warlingham Bh	31	19 (2−26)	−	45 (31−66)	36 (13−52)	2.4
division a	13	18 (2−26)	−	46 (31−66)	36 (13−52)	2.6
division b	9	19 (16−22)	−	44 (39−51)	37 (28−43)	2.4
division c	9	20 (16−24)	−	46 (39−58)	34 (21−45)	2.3
Cuckfield Bh						
division c	21	23 (15−35)	14 (0−23)	54 (29−71)	9 (0−42)	2.3
Ripe Bh	39	22 (14−38)	−	44 (28−72)	34 (2−51)	2.0
division a	15	21 (15−25)	−	42 (28−67)	37 (17−51)	2.0
division b	16	21 (14−31)	−	42 (28−63)	35 (10−46)	2.0
division c	8	24 (20−38)	−	53 (37−72)	26 (2−43)	2.2
Cooden Bh						
division c	4	28 (22−32)	−	54(45−73)	18 (0−28)	1.9

division a = base of large *Paludina* Limestones to top of Weald Clay
division b = base of large *Paludina* Limestones to top of small *Paludina* Beds
division c = top of small *Paludina* Beds to base of Weald Clay

	Sample nos.	K(c)	B	M	CM	M/K
			Upper Tunbridge Wells Sand Formation			
Total	63	32 (0−69)%	9 (0−41)%	43 (13−65)%	16(0−36)%	1.3
Warlingham Bh	3	27 (24−30)	−	50 (48−54)	23 (20−28)	1.9
Cuckfield Bh	34	32 (18−69)	16 (0−41)	41 (21−65)	11 (0−30)	1.3
Ripe Bh	2	28 (28−28)	−	40 (40−41)	32 (30−33)	1.4
Cooden Bh	24	33 (0−63)	2 (0−40)	43 (13−57)	22 (6−36)	1.3
			Grinstead Clay member			
Total	14	31 (10−66)%	14 (0−45)%	38 (11−62)%	16 (0−49)%	1.2
Warlingham Bh	3	24 (13−31)	−	47 (42−54)	29 (16−45)	1.9
Cuckfield Bh	11	32 (10−66)	18 (0−45)	35 (11−62)	13 (0−49)	1.1
			Lower Tunbridge Wells Sand Formation			
Total	15	30 (16−60)%	6 (0−27)%	42 (22−74)%	22 (0−51)%	1.4
Warlingham Bh	1	23	−	74	2	3.2
Cuckfield Bh	4	37 (19−60)	20 (16−27)	39 (22−55)	4 (0−13)	1.0
Glynleigh Bh	10	29 (16−45)	−	40 (27−58)	31 (9−51)	1.4

TABLE 11 (*contd*.).

	Sample nos.	K(c)	B	M	CM	M/K
			Wadhurst Clay Formation			
Total	36	19 (7−36)%	2 (0−17)%	48 (22−69)%	32 (1−53)%	2.6
Warlingham Bh	4	17 (13−19)	−	47 (35−56)	36 (26−48)	2.9
Cuckfield Bh	17	16 (7−25)	5 (0−17)	52 (34−69)	28 (1−53)	3.4
Glynleigh Bh	8	19 (16−23)	−	43 (35−50)	38 (30−46)	2.3
Cooden Bh	7	27 (14−36)	−	42 (22−64)	31 (9−42)	1.6
			Ashdown Formation			
Total	91	35 (14−85)%	2 (0−41)%	43 (11−73)%	20 (0−44)%	1.2
Warlingham Bh	2	19 (14−23)	−	56 (53−60)	25 (24−26)	3.1
Cuckfield Bh	12	44 (33−85)	11 (0−29)	36 (11−52)	9 (0−19)	0.8
Glynleigh Bh	6	32 (19−41)	−	39 (31−46)	29 (22−44)	1.2
Cooden Bh	3	48 (44−56)	−	40 (34−47)	12 (9−18)	0.8
Fairlight Bh	68	34 (16−63)	1 (0−41)	44 (21−73)	21 (0−43)	1.3
			Vectis Formation			
Yaverland, IOW	9	27 (23−36)%	−	49 (42−61)%	24 (12−32)%	1.8
			Wessex Formation			
Total	130	29 (11−81)%	−	50 (16−72)%	21 (0−52)%	1.4
Winchester Bh	12	29 (15−81)	−	57 (16−72)	14 (0−25)	2.0
Yaverland, IOW	43	26 (20−39)	−	53 (40−72)	21 (1−38)	2.0
Brightstone, IOW	24	23 (18−31)	−	51 (40−67)	26 (14−37)	2.2
Warbarrow Bay	51	34 (11−75)	−	46 (18−71)	20 (0−52)	1.3
Coarse Grit Band and above	27	38 (16−75)	−	43 (18−67)	19 (0−47)	1.1
Below Coarse Grit Band	24	30 (11−46)	−	49 (23−71)	21 (0−52)	1.6

TABLE 12. Clay mineral analyses (<2 μm) from the pre-Aptian Speeton Clay Formation and the immediately underlying Kimmeridge Clay at Speeton, Yorkshire. Mineral abbreviations are on page 117. Bed nomenclature is based on Neale (1974, his tables 8, 9).

	Sample no.	K(c)	C	M	CM	pd	V	S
			Pre−Aptian Speeton Clay Formation					
Speeton (grid ref. TA143764−TA162750)								
Middle B Cement Beds	H712	22%	A	43%	35%	C	−	−
Bed LB4A	H709	20	A	53	27	C	E	−
Bed LB4B	YR203	22	−	59	19	C	E	−
Bed LB4D	YR202	25	B	52	23	C	F	−
Bed LB6	YR200	19	−	50	31	C	F	−
Bed C4	H708	27	−	41	32	C	F	−
Bed C8, base	H711	27	−	42	31	C	E	−
Bed D1	H710	35	−	30	35	D	−	√
Bed D2E	H707	28	−	27	45	D	−	√
Bed D8	H706	18	A	29	53	D	−	−
Kimmeridge Clay	H705	17	−	43	40	D	−	√

TABLE 13. Clay mineral analyses (<2 μm) from the Spilsby Sandstone and Claxby Ironstone Formations. Mineral abbreviations and borehole locations are on page 117.

Sample no.	Depth m	K(c)	B	C	M	CM	pd	V	S
				Spilsby Sandstone Formation					
Fordington Borehole (52.12−73.15 m)									
	69.68	15%	−	−	21%	64%	D	−	−
	73.00−73.30	10	−	−	25	65	D	E	−
	73.30−73.67	18	−	−	61	21	D	−	−
Spilsby/Partney road widening, Lincolnshire									
		14	−	−	43	43	D	−	−
Skegness Borehole (107.32−116.81 m)									
	111.25	35	−	−	36	29	D	−	−
	112.78	35	−	−	47	18	D	E	−
	114.30	23	−	−	55	22	D	E	−
				Claxby Ironstone Formation					
Alford Borehole (78.38−86.56 m)									
	78.33−79.25	20	−	−	35	44	D	E	−
	82.02−82.33	30	−	−	38	32	D	−	−
	84.73−86.56	13	−	−	23	64	D	E	−
Skegness Borehole (99.03−107.32 m)									
	99.06	31	−	−	27	41	D	E	−
	100.58	43	−	−	54	3	C	E	−
	102.11	22	−	B	48	30	D	F	−
	103.63	18	−	−	40	42	D	F	−
	105.16	19	−	−	52	29	D	E	−
	106.68	29	−	−	52	19	D	E	−

TABLE 14. Clay mineral analyses (<2 μm) from the Tealby Formation. Mineral abbreviations and borehole locations are on page 117.

Depth m	K(c)	B	C	M	CM	pd	V	S
			Tealby Formation					
Alford Borehole								
Upper Tealby Clay (48.69−61.01 m)								
48.46−48.77	3%	−	−	13%	84%	D	E	√
48.77−49.68	12	−	−	35	53	D	E	√
54.39−56.39	10	−	−	33	57	D	−	√
58.22−58.52	12	−	−	45	43	D	−	√
58.52−60.96	4	−	−	35	61	C	−	√(vs)
Tealby Limestone (61.01−64.92 m)								
61.57−62.18	3	tr.	−	41	55	C	−	√(vs)
64.01−64.50	3	−	−	29	69	D	−	√
64.50−64.92	4	tr.	−	27	69	D	E	√
Lower Tealby Clay (64.92−78.38 m)								
65.53−67.97	5	−	−	27	68	D	F	√
68.58	21	−	−	43	36	D	F	−
70.41−71.93	10	−	−	23	68	D	E	√
72.24−76.20	11	−	−	49	34	D	E	√

TABLE 14 (*contd.*).

Depth m	K(c)	B	C	M	CM	pd	V	S
			Tealby Formation undifferentiated					
Skegness Borehole (68.22−99.03 m)								
68.58	18	−	−	36	46	D	−	√
70.10	16	−	B	38	46	D	E	√
71.78	15	−	−	34	51	D	E	−
74.68	16	−	−	37	47	D	E	−
76.20	27	−	B	44	29	D	E	−
77.72	14	−	−	32	53	D	E	−
79.25	16	−	−	42	42	D	E	−
80.77	12	−	−	44	45	D	E	−
82.30	17	−	−	41	42	D	E	−
83.82	19	−	−	52	29	D	E	−
85.34	12	−	−	37	51	D	E	√
86.87	13	−	−	44	43	D	−	√
88.39	20	−	−	49	30	D	E	√
89.92	22	−	−	52	26	D	E	−
91.44	25	−	−	43	31	D	E	−
92.96	15	−	B	42	43	D	E	−
94.49	24	−	X	42	34	D	E	−
96.01	18	−	−	44	38	D	E	−
97.54	21	−	−	43	36	D	E	−
99.06	31	−	−	27	41	D	E	−

TABLE 15. Clay mineral analyses (<2 μm) from the Sandringham Sands Formation. Mineral abbreviations and borehole locations are on page 117.

Depth m	K(c)	B	C	M	CM	pd	V	S
			Sandringham Sands Formation					
Hunstanton Borehole								
			Roxham Member (Jurassic) (96.82−102.92 m)					
97.54	33%	−	−	38%	28%	D	−	−
			Mintlyn Member (87.02−96.82 m, includes Runcton Beds)					
89.15	22	−	X	45	33	D	E	−
92.20	29	−	−	62	9	D	E	√
94.95	21	−	B	25	54	D	E	−
			Leziate Member (65.02−87.02 m)					
67.36	72	−	A	14	14	D	−	−
71.32	55	−	−	40	5	D	−	−
73.15	79	−	−	21	−	−	−	−
79.25	53	−	−	38	9	D	E	−
83.36	15	−	−	21	64	D	E	−
85.50	26	−	−	61	12	D	E	−
			Dersingham Formation (53.42−65.02 m)					
54.86	25	−	−	41	34	D	E	−
57.91	26	−	−	51	23	D	F	−
60.96	22	−	−	26	52	D	F	−
64.01	31	−	−	54	15	D	E	−

TABLE 16. Clay mineral analyses (<2 μm) from the Roach Ironstone Formation. Mineral abbreviations and borehole locations are on page 117.

Depth m	K(c)	B	C	M	CM	pd	V	S
			Roach Ironstone Formation					
Alford Borehole (34.14−48.69 m)								
34.17−34.87	−	13%	−	19%	67%	D	−	√
38.71	−	11	−	12	78	D	−	−
40.84−42.67	−	39	−	28	33	D	−	−
44.50−45.11	−	9	−	19	71	D	−	−
45.72−48.46	11%	−	−	29	60	D	−	√
Skegness Borehole (46.56−68.22 m)								
46.94	−	13	−	21	66	D	E	√
51.82	−	20	−	10	70	D	−	−
54.86	−	24	−	16	60	D	E	−
56.39	−	50	−	41	9	D	E	−
57.91	tr.	13	A	11	75	D	E	−
59.44		17	−	19	64	D	F	−
60.96		21	−	21	59	D	E	−
62.64	−	30	−	28	42	D	E	−
64.01	−	41	−	36	23	D	−	−
65.53	10	−	−	38	53	D	−	√
67.06	17	−	−	55	28	D	−	√
Hunstanton Borehole (36.84−53.42 m)								
39.62	17	−	−	46	37	D	E	−
42.67	21	−	−	46	32	D	E	−
45.72	26	−	−	63	11	C	E	−
47.24	37	−	A	39	23	D	E	−
48.77	18	−	A	82	−	−	−	−
51.82	25	−	B	56	19	D	E	−
			Hundleby Clay Formation					
Brickpit, Hundleby, nr Spilsby (Swinnerton, 1941, p. 204)								
	14	−	−	33	53	D	E	−

TABLE 17. Clay mineral analyses (<2 μm) from the Skegness Clay, Sutterby Marl and Carstone Formations. Mineral abbreviations and borehole locations are on page 117.

Depth m. Sample no.	K(c)	B	C	M	CM	pd	V	S
			Skegness Clay Formation					
Skegness Borehole (44.58−46.56 m)								
45.72	25%	−	−	30%	45%	D	E	√
			Sutterby Marl Formation					
Alford Borehole (30.78−34.14 m)								
30.78−32.61	20	7	−	37	36	D	E	√(vs)
32.61−34.14	9	−	−	30	61	D	−	√(vs)
Skegness Borehole (42.60−49.58 m)								
42.67	16	16	−	42	26	D	−	√
44.20	16	16	−	34	34	D	E	√
			Carstone Formation					
Alford Borehole (25.60−30.78 m)								
29.87−30.78	7	−	−	15	78	D	−	√

TABLE 17 (*contd.*).

Depth m. Sample no.	K(c)	B	C	M	CM	pd	V	S
Hunstanton Borehole (17.96−36.86 m)								
36.58	19	−	−	33	48	D	−	√
Red Hill, Goulceby, Lincolnshire (grid ref. TF264806)								
LR164	18	−	−	25	57	D	G	−
LR165	13	−	−	15	72	D	−	√(vs)

TABLE 18. Clay mineral analyses (<2 μm) from the Atherfield Clay Formation. Mineral abbreviations and borehole locations are on page 117.

Depth m/ Sample no.		K(c)	C	M	CM	pd	V	S
			Atherfield Clay Formation					
Warlingham Borehole (311.66−319.13 m)								
312.4		12%	−	44%	44%	C	−	√(vs)
317.9		29	A	28	43	D	E	−
Compton Bay, Isle of Wight (grid ref. SZ 369849)								
1.83*	IOW 66	20	−	45	35	D	E	−
4.88	IOW 65	25	−	54	21	D	E	−
Winchester Borehole No. 1								
188.21		12	A	52	36	D	−	√
188.82		12	−	55	33	D	E	−
Hammer, nr Haslemere, Surrey (grid ref. SU 877325)								
	SuS1	20	−	53	27	D	E	−
	SuS2	9	A	21	70	D	E	−
	SuS3	20	−	52	28	D	−	√
	SuS4	7	−	21	72	D	E	−
Maidstone Prison Borehole no. 6 (Jeans *et al.*, 1982, their fig. 15)								
	KR30	10	−	42	48	D	−	√(vs)
	KR31	16	X	56	28	D	−	√(vs)
	KR32	24	−	48	28	D	F	−
	KR33	18	−	45	37	D	F	−
	KR34	25	−	45	30	D	F	−
	KR36	21	−	50	29	D	E	−
Sandgate Encombe Estate Borehole								
26.67		12	A	55	33	D	F	−
27.43		22	A	59	19	D	E	−
28.88		20	A	53	27	D	F	−

* height above base of Atherfield Clay Formation

TABLE 19. Clay mineral analyses (<2 μm) from the Hythe Beds, Sandgate Beds and Folkestone sand formations. Mineral abbreviations and borehole locations are on page 117.

Depth m/ Sample no.	K(c)	C	M	CM	pd	V	S
				Hythe Formation			
Warlingham Borehole (286.21−311.66 m)							
300.23	3%	−	36%	61%	D	−	√(vs)
301.45	−	−	53	47	C	−	√(vs)
305.10	3	−	36	61	C	F	−
Bletchingley, Surrey (grid ref. TQ 331503)							
SuR10	−	−	61	39	C	−	√(vs)
SuR7	−	−	54	46	C	−	√(vs)
SuR9	−	−	70	30	D	−	−
Otterpool, Kent (grid ref. TR 112366: Jeans *et al.*, 1982, their fig. 9)							
KR53	−	−	52	48	C	−	√(vs)
KR54	−	−	76	24	C	−	√(vs)
KR55	−	−	61	39	C	−	√(vs)
KR56	−	−	49	51	C	−	√(vs)
Maidstone Prison Borehole no. 6 (Jeans *et al.*, 1982, their fig. 15)							
KR23	−	−	32	68	C	−	√(vs)
KR24	−	−	39	61	C	−	√(vs)
KR25	−	−	42	58	C	−	√(vs)
KR27	−	−	33	67	C	−	√(vs)
KR28	2	−	30	68	C	−	√(vs)
KR29	3	−	35	62	C	−	√(vs)
				Sandgate Formation			
Sandgate Encombe Estate Borehole							
26.67	12	A	55	33	D	F	−
27.43	22	A	59	19	D	E	−
28.88	20	A	53	27	D	F	−
Saltwood, Kent (grid ref. TR 159361)							
KR42	11	−	53	36	C	−	√(vs)
Seale, Surrey (grid ref. SU 891472)							
SuR3	20	−	25	55	D	−	√
SuR1	11	−	27	62	D	−	√
SuR2	10	−	33	57	D	−	−
Cliffe Borehole No. 6 (Owen 1971 undifferentiated Lower Greensand; probably Sandgate Formation)							
272.54	5	−	−	95	C	−	√(vs)
272.87	−	−	−	100	C	−	√(vs)
273.00	−	−	−	100	C	−	√(vs)
273.25	5	−	37	58	D	−	√(vs)
				Folkestone Sands Formation			
Sandy Lane, Folkestone (grid ref. TR 190352; Jeans *et al.*, 1982, their fig. 9)							
KR41	2	−	42	56	C	−	√(vs)
KR40	5	−	41	54	C	−	√(vs)
Sandling Junction, Kent (grid ref. TR 147371; Jeans *et al.*, 1982, their fig. 10)							
KR43	−	−	63	37	C	−	√(vs)
KR46	−	−	60	40	C	−	√(vs)
KR45	−	−	42	58	C	−	√(vs)
KR47	−	−	58	42	D	−	−
KR52	−	−	46	54	C	−	√(vs)
KR48	−	−	52	48	D	−	√
KR50	−	−	58	42	D	−	√
KR51	−	−	43	57	C	−	√(vs)

TABLE 19 (*contd.*).

Depth m/ Sample no.	K(c)	C	M	CM	pd	V	S
Pound House, Kent (grid ref. TR 092399; Jeans *et al.*, 1982, their fig. 9)							
KR57	—	—	53	47	C	—	√(vs)
KR58	—	—	44	55	C	—	√(vs)
KR59	—	—	49	51	C	—	√(vs)
KR60	3	—	40	57	C	—	√
KR61	—	—	33	67	C	—	√(vs)
Newlands, Kent (grid ref. TQ 935482; Jeans *et al.*, 1982, their fig. 16)							
SuS13	—	—	35	65	C	—	√(vs)
SuS12	—	—	27	73	C	—	√(vs)
Reigate, Surrey (grid ref. TQ 264505; Jeans *et al.*, 1982, their fig. 16)							
SuS14	46	—	49	5	D	—	√
SuS15	38	—	36	26	D	—	√
SuS16	31	—	40	29	D	—	√
Warlingham Borehole (225.25−284.99 m)							
228.60	—	—	23	77	C	—	√(vs)
242.32	84	—	9	7	—	—	√
247.19	85	—	11	4	—	—	√
Farnham (Coxbridge), Surrey (grid ref. SU 825458; Jeans *et al.*, 1982, their fig. 16)							
SuR5	32	—	28	40	D	F	—
SuR6	37	—	33	30	D	F	—
Wrecclesham, Surrey (grid ref. 827449)							
SuS11	20	—	31	49	D	E	√
SuS10	27	—	34	39	D	E	√
Great Holt, Hampshire (grid ref. SU 821399; Jeans *et al.*, 1982, their fig. 16)							
SuS5	47	—	29	24	D	—	√
SuS6	41	—	32	27	D	—	√
SuS7	19	—	16	65	D	E	—
SuS8	45	—	24	31	D	E	—
SuS9	53	—	31	16	D	E	—

TABLE 20. Clay mineral analyses (<2 μm) of undifferentiated Lower Greensand Group. Mineral abbreviations and borehole locations are on page 117.

Depth m.	K(c)	B	C	M	CM	pd	V	S
			Lower Greensand Formation (undifferentiated)					
Ripe Borehole (1.50−47.79 m)								
5.05	16%	—	—	53%	31%	D	—	√
5.90	21	—	—	49	30	D	—	√
8.65	18	—	—	47	35	D	—	√
9.84	14	—	—	44	42	D	—	√
11.72	18	—	A	51	31	D	—	√
13.00	15	—	—	42	43	D	—	√
14.30	18	—	—	47	35	D	—	√
15.26	6	8%	—	60	26	D	E	—
18.45	16	—	—	29	55	D	E	—
19.04	13	—	—	29	58	D	E	
19.12	16	—	—	37	47	D	—	√
20.50	4	—	—	28	68	D	—	√
23.30	8	—	—	40	52	D	—	√

TABLE 20 (*contd.*).

Depth m.	K(c)	B	C	M	CM	pd	V	S
25.37	12	–	–	30	58	D	–	√
27.50	9	–	–	39	52	D	–	√
30.50	3	–	–	29	68	D	–	√
31.50	1	–	–	16	83	D	–	√
33.05	2	–	–	29	69	D	–	√
33.58	1	–	–	18	81	D	–	√
40.20	2	–	–	36	62	D	–	√
42.22	2	–	–	26	72	D	–	√
43.10	1	–	–	21	78	D	–	–
~43−47.79	2	–	A	59	39	D	–	–
~43−47.79	2	–	A	49	49	D	–	–
Lower Greensand Formation (undifferentiated)								
Hampden Park Borehole (18.82−39.57 m)								
25.70	9	–	–	40	51	D	–	√
29.63	5	–	–	39	56	D	–	√
31.96	6	–	A	77	17	D	E	√
34.26	2	–	–	32	66	D	–	√
37.63	6	–	–	85	10	D	–	√

TABLE 21. Clay mineral analyses (<2 μm) from the Ferrugenious Sand and Sandrock Formations. Mineral abbreviations and borehole locations are on page 117. Depths are from the top of the formations.

Depth m. Sample no.	K(c)	C	M	CM	pd	V	S
Ferruginous Sand Formation							
Worbarrow Bay, Dorset (see Fig. 30)							
W64	21%	–	49%	30%	D	–	–
W63	27	–	59	14	D	–	–
W62	28	–	52	20	D	–	–
W61	25	–	66	9	D	–	–
W60	30	–	61	9	D	–	–
W59	29	–	47	24	D	–	–
W58	28	–	41	31	D	–	–
W57	86	–	9	5	D	?	–
W56	100	–	–	–	–	?	–
Compton Bay, Isle of Wight (grid ref. SZ 368851)							
9.83 (IOW24)	29	–	49	22	D	–	–
14.91 (IOW25)	14	–	51	35	D	E	–
19.19 (IOW21)	17	–	36	47	D	E	–
19.94 (IOW22)	4	–	49	47	D	E	–
24.69 (IOW23)	13	–	56	31	D	E	–
38.40 (IOW20)	25	–	76	–	D	E	–
40.69 (IOW69)	23	–	31	46	D	E	–
70.26 (IOW67)	20	–	37	43	D	E	–
Sandrock Formation							
Compton Bay, Isle of Wight (grid reg. SZ 368851)							
3.68 (IOW31)	32	–	34	34	D	E	–
16.31 (IOW30)	30	–	33	37	D	E	–
20.57 (IOW29)	26	–	30	44	D	E	–
23.01 (IOW27)	10	–	38	41	D	?	–
23.62 (IOW28)	27	–	32	52	D	E	–
24.00 (IOW26)	18	–	48	34	D	E	–

TABLE 22. Clay mineral analyses (<2 μm) from the Woburn Sands Formation. Mineral abbreviations and borehole locations are on page 117.

	Sample no.	K(c)	C	M	CM	pd	V	S
				Woburn Sands Formation				
Mundays Hill Pit, Leighton Buzzard (grid ref. SP 939280; Jeans *et al*., 1982, their fig. 20)								
Silver Sands	Beds 55	22%	—	42%	36%	D	E	√
Brown Sands	Beds 32	20	—	52	28	C	—	√(vs)
Brown Sands	Beds 31	16	—	47	37	C	—	√
Brown Sands	Beds 30	16	—	52	32	D	—	√
New Trees Pit, Leighton Buzzard (grid ref. SP 931276; Jeans *et al*. ,1982, their fig. 22)								
Red Sands	Beds 58	5	—	36	59	C	—	√(vs)
Silver Sands	Beds 68	17	—	59	24	D	—	√
Silver Sands	Beds 69	16	—	40	44	C	—	√(vs)
East of Clophill, Bedfordshire (12 m of ferruginous sands and black clay with sand seams: grid ref. TL 378105)								
	Beds 105	16	—	37	47	D	—	√
	Beds 104	11	—	25	64	D	E	√
	Beds 103	15	—	40	45	D	—	√
	Beds 102	12	—	34	54	D	E	—
	Beds 101	13	—	37	50	D	E	√

TABLE 23 (a−r). Clay mineral analyses (<2 μm) of the Selborne Group (Gault Clay Formation, Upper Greensand Formation) from various locations in southern and eastern England. Mineral abbreviations and borehole locations are on page 117. Zone/Subzone abbreviations are given in Fig. 31.

TABLE 23a

Sample no.	Bed no.	Zone/ Subzone	K(c)	C	M	CM	pd	V	S
		Folkestone, Kent (grid ref. TR242365−263384): Gault Clay Formation							
FOW 43	XIII	Mp?	—	—	18%	82%	C	—	√(vs)
FOW 40	XI	Ca	—	—	15	85	C	—	√(vs)
FOW 39	XI	Ca	—	—	14	86	C	—	√(vs)
FOW 36	XI	Ca	26%	—	49	25	D	E	√
FOW 33	X	Hv	32	—	37	31	D	E	—
FOW 30	IX	Ho	24	A	49	27	D	E	—
FOW 27	IX	Ho	22	A	50	28	D	E	—
FOW 22	VII	Ad	24	A	59	17	D	E	—
FOW 19	V	Em	22	—	50	28	D	E	√
FOW 15	III	Dn	20	A	55	24	D	E	√
FOW 11	II	Hs/Ll	15	—	65	20	D	—	√(vs)
FOW 6	I	Hs/Ll	2	—	52	46	C	—	√(vs)
FOW 4	I	Hs/Ll	—	—	26	74	C	—	√(vs)
FOW 2	I	Hs/Ll	—	—	10	90	C	—	√(vs)

Bed numbering is after Jukes−Browne (1900): additional stratigraphical details are given in Owen (1971, 1975). Samples donated by Dr D.B. Willliams

T<small>ABLE</small> 23b

Sample no.	Bed no.	Zone/Subzone	K(c)	C	M	CM	pd	V	S
		Wrotham (Ford Place), Kent (grid ref. TQ 636591): Gault Clay Formation							
WWR 42	80 (0.61 m*)	Hv(U)	27%	A	45%	28%	D	G	−
WWR 39	76 (middle)	Hv(M)	26	A	40	34	D	F	−
WWR 37	71	Hv(L)	9	−	17	74	D	E	√
WWR 33	65	Ho(U)	26	−	50	24	D	F	−
WWR 28	49	Ho(L)	25	A	46	29	D	F	−
WWR 27	45	Dc(U)	22	A	41	37	D	E	√
WWR 21	35	Ad/En	17	A	34	49	D	G	−
WWR 16	25	Dn	8	A	15	77	D	F	−
WWR 10	19	Ai(U)	19	−	45	36	D	F	√
WWR 5	13 (middle)	Ai(L)	11	A	32	57	D	F	√
WWR 2	9 (top)	Hb/He	14	−	33	53	D	E	√

Stratigraphy based on Milbourne (1963)
*Height above base of bed. L = lower, M = middle, U = upper. Samples donated by Dr D.B. Williams

T<small>ABLE</small> 23c

Depth	Zone/Subzone	K(c)	C	M	CM	pd	V	S
	Cliffe No. 6 Borehole, Kent (grid ref. TQ 68907715): Gault Clay Formation and Lower Greensand Group							
Gault Clay Formation (209.39−269.23 m)								
256.39m	Hv	~20%	X	~40%	~40%	C	F	−
257.84	Ho	20	A	41	39	C	F	−
259.23	Dc	~20	X	~40	~40	C	E	−
259.99	Dc	24	−	55	21	C	F	−
261.90	not known	20	A	44	36	C	F	−
263.17	Ms/Dn	11	A	32	57	C	F	√
265.08	Ai	5	−	23	72	D	−	√(vs)
266.55	Ai	7	−	34	59	D*	−	−
268.23	Hs/Ll	5	−	49	46	D*	−	−
Lower Greensand (269.23−274.09 m)								
272.54		5	−	−	95	D	−	√(vs)
272.87		−	−	−	100	D	−	√(vs)
273.00		−	−	−	100	D	−	√(vs)
273.25		5	−	37	58	D	−	√(vs)

Stratigraphy based on Owen (1971)

T<small>ABLE</small> 23d

Sample no.	Bed no.	Zone/Subzone	K(c)	C	M	CM	pd	V	S
		Rockshaw Road, Merstham, Surrey (TQ30305387−TQ31045354): Upper Greensand Formation							
RSM 16	B(j)	Mp?	−	−	42%	58%	D	−	√(vs)
RSM 14	B(f)	Mp	−	−	43	57	D	−	√(vs)
RSM 15	B(d)	Mp	−	−	44	56	D	−	√(vs)
RSM 13	B(c)	Mp	−	−	29	71	D	−	√(vs)
RSM 10	B(a)	Mp	−	−	63	37	D	−	√(vs)
RSM 9	A(e)	Mr	−	−	77	23	D	−	√(vs)
RSM 11	A(d)	Mr	−	−	46	54	D	−	√(vs)

Stratigraphy based on Owen (1975). Samples donated by Dr H.G. Owen

TABLE 23e

Depth m	Zone/Sub-zone	K(c)	C	M	CM	pd	V	S	mQ	Z
			Warlingham Borehole, Surrey: Selborne Group							
Upper Greensand Formation (120.40−137.16 m)										
126.49	not known	−	−	49%	51%	D	−	√	opal−CT	−
128.02	" "	−	−	43	57	D	−	√(vs)	opal−CT	−
132.59	" "	−	−	68	32	D	−	√	opal−CT	
137.16	" "	−	−	36	64	D	−	√	−	√
Gault Clay Formation (137.16−225.25 m)										
139.60	not known	trace	−	36	64	D	−	√(vs)	−	−
140.21	" "	2%	−	45	53	D	−	√(vs)	√	−
147.83	" "	−	−	30	70	D	−	√(vs)	−	−
155.45	" "	−	−	40	60	D	−	√(vs)	−	−
159.72	" "	−	−	34	66	D	−	√(vs)	−	
167.94	" "	−	−	25	75	D	−	√(vs)	−	
175.56	" "	trace	−	33	67	D	−	√(vs)	−	−
181.36	" "	4	−	33	63	D	−	√(vs)	−	−
189.59	" "	27	−	42	31	D	E	−	−	−
191.11	" "	trace	−	40	60	D	−	√(vs)	−	−
195.07	" "	26	−	42	32	C	F	−	−	−
201.17	" "	trace	−	31	69	D	−	√(vs)	−	−
202.69	" "	−	−	35	65	D	−	√(vs)	−	−
209.70	" "	5	−	41	54	D	−	√(vs)	−	−
217.32	" "	5	−	33	62	D	−	√(vs)	−	−

Stratigraphy based on Worssam & Ivimey-Cook (1971)

TABLE 23f

Sample no.	Height above base of Gault[+]	Zone/Subzone	K(c)	C	M	CM	pd	V	S
		Buckland, Surrey (grid ref. TQ232512): Gault Clay Formation							
SUR 42	9.43 m	not known	25%	−	67%	8%	D	F	√
SUR 41	8.59	" "'	20	−	43	37	D	F	√
SUR 40	7.76	" "	23	−	48	29	D	E	√(vs)
SUR 39	6.92	En (bed 13)	22	−	51	27	D	E	√
SUR 38	6.09	Ms (?bed 12)	24	−	56	20	C	E	−
SUR 37	5.25	Ai/En	21	−	56	23	D	F	√
SUR 36	4.42	Ai	21	−	52	27	C	F	−
SUR 35	3.58	Ai	18	−	59	23	C	E	√
SUR 34	2.75	Ai(?bed 10)	20	−	55	25	C	E	−
SUR 33	1.91	Ai(bed 9)	18	A	47	35	C	F	−
SUR 32	1.07	Hs(bed 4)	22	A	48	30	C	F	−
SUR 31	0.53	Hs(bed 3)	27	−	49	24	C	F	−
SUR 30	0.00	Ll (bed 1)	23	−	55	22	C	E	−
SUR 43	−1.00	Junction beds with	28	−	57	15	C	E	−
SUR 44	−2.00	Lower Greensand (Folkestone Sands)	~35	−	~55	~10	C	E	−

[+] base of Gault at base of Bed 1; samples SUR 43 and 44 are from below the base.
Stratigraphy based on Owen (1971, his fig. 13) as far as possible although the lithological section recorded in 1975 during sample collection does not agree in detail and thickness with Owen's.

TABLE 23g

Depth m	Zone/ Subzone	K(c)	C	M	CM	pd	V	S	mQ

<div align="center">Fetcham Mill Borehole, Surrey</div>

Upper Greensand Formation

Depth m	Zone/ Subzone	K(c)	C	M	CM	pd	V	S	mQ
256.79	not known	−	−	38%	62%	D	−	√(vs)	√
258.93	" "	−	−	23	77	D	−	√(vs)	√
261.98	" "	−	−	44	56	D	−	√	√
262.59	" "	−	−	36	64	D	−	√(vs)	√
265.02	" "	−	−	41	59	D	−	√(vs)	√
268.07	Mp	−	−	27	73	D	−	√(vs)	√
271.42	Mr	−	−	20	80	D	−	√(vs)	√
274.17	Mr	−	−	35	65	D	−	√(vs)	√
275.08	Mr	−	−	42	58	D	−	√(vs)	√
277.22	Mr	−	−	35	65	D	−	√(vs)	√

Gault Clay Formation

Depth m	Zone/ Subzone	K(c)	C	M	CM	pd	V	S	mQ
280.26	Mr	−	−	24	76	D	−	√(vs)	−
282.09	Mr	−	−	26	74	D	−	√(vs)	−
283.312	Mr	−	−	26	74	D	−	√(vs)	−

Stratigraphy based on Gray (1965) and Owen (1975, his fig. 8)

TABLE 23h

Depth m	Zone/ Subzone	K(c)	C	M	CM	pd	V	S	mQ

<div align="center">Glyndebourne Borehole, Sussex: Gault Clay Formation</div>

Depth m	Zone/ Subzone	K(c)	C	M	CM	pd	V	S	mQ
48.50	SD(U*)	−	−	25%	75%	D	−	√(vs)	√
48.68	SD(U)	2%	−	32	66	D	−	√(vs)	√
49.33	SD(U)	−	−	28	72	D	−	√(vs)	√
49.61	SD(U)	−	−	36	64	D	−	√(vs)	−
53.80	SD(U)	−	−	49	51	D	−	√(vs)	−
56.75	SD(U)	−		44	56	D	−	√	−
58.34	Mr	−		25	75	D	−	√	√
59.94	Mr	−	−	60	40	D	−	√	√
61.24	Mr	−	−	49	51	D	−	√	√
62.71	Mr	−	−	37	63	D	−	√	√
65.41	Mr	−	−	54	46	D	−	√(vs)	√
68.43	Ca	1	−	35	64	D	−	√(vs)	√
69.90	Ca	1	−	29	70	D	−	√(vs)	√
71.37	Ca	−	A	63	37	D	−	√(vs)	√
72.97	Ca	−	−	28	72	D	−	√(vs)	√
74.57	Ca	−	−	28	72	D	−	√(vs)	√
75.64	Ca	2	−	48	50	D	−	√(vs)	√
77.10	Ca	−	−	59	41	D	−	√	−
78.71	Ca	−		27	73	D	−	√(vs)	−
80.31	Ca	2	−	35	63	D	−	√	−
83.46	Ca	2	−	49	49	D	−	√(vs)	−
85.06	Ca	−	−	42	58	D	−	√(vs)	−
86.66	Ca	−	−	53	47	D	−	√(vs)	−
88.24	Ca	2	−	38	60	D	−	√	−
89.81	Ca	11	−	42	47	D	−	√(vs)	−
91.39	Ca	14	−	52	34	D	E	−	−
92.84	Ca	22	A	43	35	D	E	−	−
94.44	Ca	20	A	45	35	D	−	−	−

TABLE 23h (*contd.*).

Depth m	Zone/ Subzone	K(c)	C	M	CM	pd	V	S	mQ
95.97	Ca	35%	A	58%	6%	D	F	—	—
97.46	Hv(U)	35	A	58	7	D	F	—	—
98.88	Hv(U)	30	—	47	23	D	F	—	—
100.56	Hv(U)	25	—	38	37	D	E	—	—
102.16	Hv(U)	20	—	24	56	D	F	—	—
103.45	Hv(U)	23		34	43	C	F	—	—
105.05	Hv(U)	31	—	40	29	C	F	—	—
107.92	Hv(L)*	33	A	45	22	C	F	—	—
109.51	Hv(L)	31	—	51	18	D	F	—	—
111.06	Hv(L)	211	A	32	47	D	F	—	—
112.37	Hv(L)	30	A	51	19	C	F	—	—
114.61	Ho	31	A	51	18	C	F	—	—
115.30	Ho	31	—	38	31	C	F	—	—
116.97	Ho	28	—	42	30	C	F	—	—
118.49	Dc	27	—	48	25	C	F	—	—
119.91	Dc	24	A	39	37	D	F	—	—
121.44	Dc	25	A	42	33	D	F	—	—
122.33	Dc	27	A	49	24	C	F	—	—
123.93	Dc	20	X	37	43	C	F	—	—
125.30	En	20	X	37	43	D	F	—	—
126.50	En	21	—	44	35	D	F	—	—
127.89	En	15	—	30	55	C	F	—	—
128.93	Em	17	—	40	43	D	F	—	—
130.53	Em	21	—	43	36	C	F	—	—
132.00	Dn	22		47	31	C	F	—	—
133.65	Ai	18	—	45	37	C	F	—	—
135.20	Ai	16	—	34	50	D	F	—	—
136.68	Ai	18	—	38	44	C	F	—	—
138.05	Ai	18	A	42	40	D	E	—	—
139.60	Ai	19	—	36	45	D	F	—	—
141.20	Ai	21	—	35	44	D	F	—	—
142.72	Ai	26	A	45	29	D	E	—	—
145.47	Ai	21	—	41	38	C	F	—	—
147.02	Ai	23	√	46	31	C	F	—	—
148.36	Hs	24	√	58	18	C	F	—	—
149.87	L1/Hb	19	—	39	42	D	—	—	—
151.07	Ll/Hb	—	—	57	43	D*	—	—	—
151.85	Ll/Hb	16	—	40	44	D	E	√	—
152.60	L1/Hb	7	—	44	49	D	F	—	—

* U = upper part of Zone
L = lower part of Zone
Stratigraphy based on Lake *et al*. (1987, Appendix 3)

TABLE 23i

Depth m	Zone/Sub-zone	K(c)	C	M	CM	pd	V	S
	Winchester Borehole No. 1, Hampshire: Gault Clay Formation/Lower Greensand Group							
130.00	not known	19%	−	47%	34%	D*	F	−
132.06	" "	17	A	44	39	D*	−	−
146.30	" "	11	−	49	40	D	−	√
149.81	" "	16	−	52	32	D	F	−
152.75	" "	21	X	47	32	D*	F	−
154.46	" "	20	−	42	38	D	F	−
156.82	" "	24	−	55	21	D	F	−
160.38	" "	26	−	55	19	D	E	−
166.12	" "	23	−	53	24	D	F	−
168.17	" "	22	−	41	37	D	F	−

Owen (1971) places the base of the Gault at 160.68 m depth.

TABLE 23j

Sample no.	Depth below base of Lower Chalk	K(c)	C	M	CM	pd	V	S	mQ
	Compton Bay, Isle of Wight (grid. ref. SZ366853)								
Upper Greensand Formation									
IOW32	3.0 m	−	−	50%	50%	D	−	√	√
IOW33	6.1	−	−	43	57	D	−	√	√
IOW34	8.9	−	−	83	17	D	−	√(vs)	√
IOW35	12.2	−	−	61	39	D	−	√	√
IOW36	15.2	−	−	18	82	D	−	√	√
IOW37	18.3	−	−	32	68	D	−	√	√
IOW38	21.3	−	−	37	63	D	−	√(vs)	√
IOW39	24.4	−	−	41	59	D	−	√(vs)	√
IOW40	27.4	−	−	39	61	D	−	√(vs)	√
IOW41	30.5	−	−	29	71	D	−	√(vs)	√
Passage Beds									
IOW42	33.5 m	−	−	37	63	D	−	√(vs)	√
IOW43	36.6	−	−	42	58	D	−	√(vs)	√
IOW44	39.6	1%	−	33	64	D	−	√(vs)	√
IOW45	42.7	1	−	37	62	D	−	√(vs)	−
Gault Clay Formation									
IOW46	45.7 m	6%	−	28%	66%	D	−	√(vs)	−
IOW47	48.8	3	−	32	65	D	−	√(vs)	−
IOW56	53.3	13	−	38	49	D	−	√(vs)	−
IOW55	56.4	12	−	30	58	D	−	√(vs)	−
IOW54	59.4	11	−	38	51	D	−	√(vs)	−
IOW53	62.5	14	−	48	38	D	G	−	−
IOW52	65.5	24	A	39	37	D	G	−	−
IOW50	71.6	23	−	38	39	D	G	−	−
IOW49	72.9	24	−	33	43	D	G	−	−

TABLE 23k

Sample no.	Depth below base of Lower Chalk	K(c)	C	M	CM	pd	V	S	mQ
	Worbarrow Bay, Dorset (grid ref. SY862804): Upper Greensand and Gault Clay Formations								
Do60	0.8 m	—	—	62%	38%	D	—	√(vs)	√
Do62	6.3	2%	—	41	57	D	—	√(vs)	√
Do63	10.1	2	—	49	49	D	—	√(vs)	—
Do64	12.8	5	—	51	44	D*	—	√	—
Do65	15.6	22	—	41	37	D	—	√	—
	Hooken Cliff, Devon (grid ref. SY216879): Upper Greensand Formation (a) above or (b) below base of a serpulid-rich bed*								
De250	5.54(a)m	—	A	24	76	D*	—	√	√
De252	0.91(b)	3	—	78	19	D	—	√	√
De253	2.13(b)	3	A	58	39	D	—	√	√
De254	5.18(b)	—	—	49	51	D	—	√(vs)	√
De255	8.23(b)	4	A	25	71	D	—	√(vs)	√

* This bed is ~ 7.5 m below the base of the Chert Beds (Jukes−Browne, 1900).

TABLE 23l

Sample no.	Bed no.	Zone/Subzone	K(c)	C	M	CM	pd	V	S
	Caen Hill Brickyard, Rowde, Wiltshire (ST98246135): Gault Clay Formation								
CB 58	7(2.13*)	Ai	13%	A	35%	52%	D	F	—
CB 64	7(1.22)	Ai	16	—	42	42	D	F	—
CB 57	7(0.48)	Ai	10	—	40	50	D	E	√
CB 62	7(0.38)	Ai	14	A	41	45	D	E	—
CB 61	7(0.91)	Ai	22	B	55	23	C	G	—
CB 60	4(upper)	Hs	26	—	48	26	C	F	—
CB 56	4(upper)	Hs	27	—	40	33	C	F	—
CB 59	3	Hs	30	B	48	22	C	F	—

* Height (m) of sample horizon above base of bed. Stratigraphy based on Owen (1975, his fig. 26). Samples donated by Dr H.G. Owen.

TABLE 23m

Depth	Zone/Subzone	K(c)	C	M	CM	pd	V	S	Z
				Kingston Lisle Borehole, Berkshire: Selborne Group					
Upper Greensand Formation									
5.18 m	Mr	–	–	47%	53%	D*	–	–	√
7.87	Mr	–	–	30	70	D*	–	–	√
9.96	Mr	–	–	45	55	D*	–	√(vs)	√
Gault Clay Formation									
12.65	Mr	–	–	54	46	D*	–	–	√
16.10	Mr	2%	–	42	56	D*	–	–	√
18.75	Mr	1	–	37	62	D*	–	√	√
21.21	Mr	2	–	60	38	D	–	√(vs)	√
21.79	Mr	2	X	62	36	D*	–	–	√
25.40	Ca(U)	1	–	40	59	D*	–	√	√
27.89	Ca(U)	2	–	41	57	D*	–	√(vs)	√
31.65	Ca(L)	2	–	33	65	D*	–	√(vs)	–
34.11	Ca(L)	1	–	24	75	D	–	√(vs)	–
37.85	Ca(L)	5	–	35	60	D*	–	√	–
40.72	Ca(L)	9	–	44	47	D*	E	√	–
43.59	Ca(L)	19	A	38	43	D	–	√	–
46.51	Ho	23	A	54	23	D*	E	√	–
48.21	Dc	17	A	46	37	D	F	–	–
52.88	Em/Dn	17	A	48	35	D	E	√	–
56.31	Dn	14	X	52	34	D	–	√	–
59.31	Ai	19	A	46	35	D	F	√	–
62.28	Hs(U)	22	X	53	25	D*	F	–	–
64.95	Hs(L)	22	X	41	37	C	E	–	–
67.67	Hs(L)	25	–	63	12	C	E	–	–
70.26	Ll	23	X	50	27	D*	F	–	–
74.24	Ll	26	–	50	24	C	F	–	–
77.45	L1	22	–	48	30	D*	F	√	–

Stratigraphy based on Mr Adrian Morter's (British Geological Survey) manuscript log of the borehole.
L = lower, U = upper

TABLE 23n

Sample no.	Height above base of Gault*	Zone/Subzone	K(c)	C	M	CP	pd	V	S
		New Trees Pit, Leighton Buzzard (grid ref. SP930275): Gault Clay Formation							
Beds 67	5.94 m	Ai	11%	–	65%	24%	D*	–	√
Beds 66	5.03	Ai	7	–	66	27	D	–	√
Beds 65	4.19	Ai	5	–	56	39	D	–	√(vs)
Beds 64	3.35	Ai	4	–	45	51	D	E	√
Beds 63	2.52	Ai	7	–	29	64	D	–	√(vs)
Beds 62	1.68	Ai	3	–	41	56	D	–	√(vs)
Beds 61	0.84	Ai	3	–	36	61	D	–	√(vs)
Beds 60	0.0	Hs	3	–	37	60	D	–	√(vs)
Beds 59	Gault/Woburn Sands	not known	–		33	67	D	–	√
Beds 58	junction bed	not known	5	–	36	59	D	–	√(vs)

* Stratigraphy based on Owen (1972, pp. 295–296), the base of the Gault taken as top of Owen's bed 1 (Gault/Woburn Sands junction bed).

TABLE 23o

Sample no.	Height above base of Gault	Zone/Subzone	K(c)	C	M	CM	pd	V	S
Mundays Hill Pit, Leighton Buzzard, Bedfordshire (grid ref. SP939280): Gault Clay Formation									
Beds 53	16.76 m	not known	16%	—	42%	42%	D	—	√
Beds 52	15.93	" "	19	—	41	40	D	—	√
Beds 51	15.09	" "	21	—	42	37	D	E	√
Beds 49	13.41	Hv?	19	—	38	43	D	E	√
Beds 48	12.57	Hv?	24	—	50	26	D	E	√
Beds 47	11.73	Hv?	25	—	50	25	D	—	—
Beds 46	10.90	Hv?	23	—	46	31	D	E	—
Beds 45	10.06	Hv?	27	—	55	18	D	E	√
Beds 44	9.22	Hv?	24	—	41	35	D	E	√
Beds 43	8.38	Hv?	24	—	41	35	D	F	—
Beds 42	7.54	Hv?	17	—	30	53	D	E	√
Beds 41	6.71	Hv	22	—	38	40	D	E	√
Beds 40	5.87	Ho	24	—	41	35	D	F	√
Beds 39	5.03	Ho	20	—	37	43	D	E	√
Beds 38	4.19	Dc	20	—	41	39	D	E	√
Beds 37	3.35	Dn	16	—	48	36	D	E	√
Beds 36	2.51	Ai	14	—	49	37	D	E	√
Beds 35	1.68	Ai	9	—	40	51	D	—	√(vs)
Beds 34	0.84	Ai	11	—	45	44	D	E	√(vs)
Beds 33	0.23	Hs	15	—	41	44	D	E	√(vs)

Stratigraphy based on Owen (1972, pp. 297−301)

TABLE 23p

Sample no.	Depth below base of Lower Chalk	Zone/ Subzone	K(c)	C	M	CM	pd	V	S
Arlesey Brickworks and Borehole, Arlesey, Bedfordshire (grid ref. TL186351): Gault Clay Formation									
Beds 88	0.15 m	Mr(G18)	10%	A	41%	49%	D	E	√(vs)
Beds 89	1.83	Mr(G18)	12	A	46	42	D	E	√
Beds 90	3.51	Mr(G17)	17	−	56	27	D	E	√
Beds 91	5.18	Mr(G17)	13	−	30	57	D	−	√
Beds 92	6.86	Mr(G17)	17	A	52	31	D	−	√
Beds 93	8.53	Mr(G17)	20	A	44	36	D	−	√
	10.10	Mr(G17)	23	A	40	37	D	F	−
Beds 94	10.21	Mr(G17)	20	−	45	35	D	−	√
	11.63	Mr(G17)	19	−	36	45	D	E	√
Beds 95	11.89	Mr(G17)	22	A	46	32	D	E	√
	13.15	Mr(G17)	24	−	51	25	D*	E	−
Beds 96	13.56	Mr(G17)	22	A	51	27	D	E	√
	14.67	Mr(G17)	19	−	37	44	D	E	√
Beds 97	15.24	Mr(G17)	23	−	57	20	D	E	√
	16.20	Mr(G17)	19	−	40	41	D	−	√
Beds 98	16.92	Mr(G17)	23	−	54	23	D	E	−
	17.72	Mr(G17)	17	−	43	40	C	E	−
Beds 99	18.59	Mr(G17)	24	−	41	35	D*	−	√
	19.25	Mr(G17)	19	−	43	38	D	E	√
Beds 100	20.12	Mr(G17)	26	−	42	32	D	E	√
	20.77	Mr(G17)	17	−	40	43	D	E	√
	22.29	Ca(G16)	18	A	42	40	D	E	−
	23.81	Ca(G16)	21	A	42	37	D*	F	−
	25.34	Ca(G16)	24	−	50	26	D	F	−
	26.86	Ca(G16)	19	−	41	40	D*	F	−
	29.91	Ca(G16)	25	−	44	31	C	E	−
	31.43	Ca(G16)	28	X	47	25	D	F	√
	32.96	Ca(G16)	23	−	36	41	D	E	−
	34.48	Ca(G16)	27	−	52	21	D*	F	√
	36.01	Ca(G16)	24	A	42	34	D	F	√
	37.53	Ca(G15)	26	−	40	34	D	F	−
	39.36	Ca(G15)	23	−	44	33	D	F	−
	40.58	Ca(G15)	23	−	47	30	D	F	√
	42.10	Ca(G15)	20	−	41	39	D	F	√
	43.63	Hv(G14)	17	−	52	31	D	F	√

Stratigraphy based upon the British Geological Survey Arlesey Borehole (Woods *et al*., 1995)
G14−G16 refers to the bed numbers used by Gallois & Morter (1982) in describing the Gault Clay Formation of East Anglia
Borehole samples donated by the London Brick Company Limited

Table 23q

Depth	Zone/Subzone	K(c)	C	M	CM	pd	V	S
	Ely−Ouse Borehole No. 4, Suffolk (grid ref. TL 70127169): Gault Clay Formation							
58.80 m	Mr	27%	A	40%	33%	D	F	−
60.20	Mr	26	−	39	35	D	E	√
60.55	Ca	28	A	38	34	D	E	√
62.08	Ca	26	A	46	28	D	E	√
63.55	Ca	24	−	43	33	D	G	−
63.55	Ca	26	A	39	35	D	E	√
65.00	Hv	27	−	42	31	D	E	√
66.52	Hv	27	−	41	32	D	F	−
66.52	Hv	28	A	40	32	D	F	−
68.05	Ho	26	−	45	29	D	F	−
69.14	Ho	23	−	46	31	D	F	−
69.88	Ho	25	A	37	38	D	G	−
72.47	En	25	−	48	27	D	E	√
72.47	En	25	−	46	29	D	F	−
73.99	Em	23	A	45	32	D	F	−
74.73	Em	23	A	41	36	D	G	−
76.96	Em/Ms	23	−	49	28	D	F	√
78.46	Ai	17	−	42	41	D	E	√

Table 23r

Depth m	Zone/Sub-zone	K(c)	C	M	CM	pd	V	S
	Ely−Ouse Borehole No. 23, Suffolk (grid ref. TL69168817): Gault Clay Formation							
22.11	Mr	21%	A	44%	35%	D	E	−
23.64	Mr	30	A	44	26	D	F	−
23.60	Mr	30	−	46	24	D	F	√
23.84	Ca	24	−	37	39	D	E	√
25.37	Ca	29	A	41	30	D	F	−
26.75	Ca	31	A	47	22	D	E	√
26.79	Ca	27	−	43	30	D	E	√
28.17	Hv	29	A	44	27	D	F	−
29.36	Hv	29	−	40	31	D	G	−
29.41	Hv	31	−	41	28	D	F	−
30.73	Hv	28	−	48	24	D	F	−
30.86	Hv	25	A	50	25	D	F	−
32.08	Hv	25	A	50	25	D	F	−
32.64	Hv	26	A	53	21	D	F	−
34.57	Dc	29	A	46	25	D	E	−
35.08	?	24	−	42	34	D	E	√
35.20	?	26	A	56	18	D	F	−
36.55	?	28	−	53	19	D	G	−
38.10	?	28	−	46	26	D	F	−
38.20	Em	26	A	45	29	D	G	−

TABLE 24. Clay mineral analyses (<2 μm) from the Red Chalk Formation. Mineral abbreviations and borehole locations are on page 117. Zone/Subzone abbreviations are given in Fig. 31.

Sample no./ Depth	Zone/ Subzone	K(c)	C	M	CM	pd	V	S
Red Chalk Formation (Cromer Knoll Group)								
Speeton, Yorkshire (Fig. 35a; grid ref. TA155754−TA1809748)								
Ysa 141	SD	26%	A	45%	29%	D	G	√
Ysa 136	SD	32	A	33	35	D	G	−
Ysa 63	SD	32	A	40	28	D	G	−
Ysa 135	SD	29	A	36	35	D	G	−
Ysa 64	MI(Ca?)	29	A	27	44	D	E	√
Ysa 138	MI(Ca?)	30	A	28	42	D	F	−
H 713	HD	14	−	32	54	D	E	√
Red Hill, Goulceby, Lincolnshire (grid ref. TF2643806)								
0.25 m below top[+] (LR161)	not known	19	−	24	57	D	−	√(vs)
0.84 m below top (LR162)	not known	23	−	20	57	D	−	√(vs)
1.27 m below top (LR163)	not known	20	−	22	58	D	−	√(vs)
Skegness Borehole (34.93−40.41 m)								
35.20 m	not known	20	−	27	53	D	−	√
36.58	not known	21	−	27	52	D	−	√
38.10	not known	24	−	28	48	D	−	√
39.62	not known	20	−	25	55	D	−	√

[+] top of Red Chalk taken at bored surface at top of Brinkhill Member (Jeans, 1980)
Stratigraphy of the Red Chalk Formation at Speeton is based on Mitchell (1995, his fig. 12)