Clay mineralogy of the Tertiary onshore and offshore strata of the British Isles

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ABSTRACT: Tertiary sediments are of restricted occurrence in the onshore British Isles but occur extensively offshore, attaining thicknesses of ~4 km in the Faroe–Shetland Basin and ~3 km in the North Sea Basin. Clay mineral stratigraphic studies of the North Sea Paleocene to Lower Miocene successions show a dominance of smectite (and smectite-rich illite-smectite) with minor illite, kaolin and chlorite. Abundant smectite in the Paleocene and Eocene reflects alteration of volcanic ash derived from pyroclastic activity associated with the opening of the North Atlantic between Greenland and Europe. However, the persistence of high smectite into the Oligocene and Middle Miocene indicates that smectite-rich soils on adjacent land areas may also have been an important source of detrital clays. An upwards change to illite-dominated assemblages in the Middle Miocene reflects higher rates of erosion and detrital clay supply, with a subsequent increase in chlorite reflecting climatic cooling. The persistence of smectite-rich assemblages to depths of >3000 m in the offshore indicates little burial-related diagenesis within the mudstone succession, possibly as a consequence of overpressuring. Despite the importance of Paleocene and Eocene sandstones as hydrocarbon reservoirs in the North Sea and Faroe-Shetland basins, there are few published details of the authigenic clays. The principal clay cements in these sandstones are kaolin and chlorite, with only minor illite reported.

The offshore successions provide a valuable background to the interpretation of the more intensively studied, but stratigraphically less complete, onshore Tertiary successions. The most extensive onshore successions occur in the London and Hampshire basins where sediments of Paleocene to earliest Oligocene age are preserved. Here clay assemblages are dominated by illite and smectite with subordinate kaolin and chlorite. The relatively large smectite content of these successions is also attributed primarily to the alteration of volcanic ash. Associated non-smectitic clays are largely detrital in origin and sourced from areas to the west, with reworking of laterites and ‘china clay’ deposits developed over Cornish granites. Authigenic clays include glauconite (sensu lato), early diagenetic kaolin that has replaced muscovite (principally in the London Clay Formation of the London Basin) and smectite that has replaced ash. Pedogenesis has extensively modified the assemblages in the Reading Formation and Solent Group. Tertiary sediments are largely missing from onshore northern and western Britain, but clays and sands of Eocene and Oligocene age are locally preserved in small fault-bounded basins. Here, clay assemblages are dominated by kaolin with minor illite.

KEYWORDS: Tertiary, clay mineralogy, stratigraphy, British Isles.

This review summarizes previous research into the clay mineralogy of the UK Tertiary sediments, integrates it with new data from onshore and offshore sections, and discusses the origins of both the detrital and the authigenic clay minerals. The location of the principal boreholes and sections are shown on a map of the distribution of Tertiary sediments in the British Isles (Fig. 1).

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Although both the North Sea and Faroe–Shetland basins include extremely thick (3–4 km) mudstone-dominated successions, the clay mineral assemblages of the offshore successions have received much less attention than those of the onshore successions. Published accounts are restricted to a few stratigraphic studies and very few, mostly sketchy, accounts of authigenic clays. New information on the clay mineral stratigraphy of the offshore successions provides additional insight into how the clay mineral assemblages reflect the climatic, tectonic and volcanic history of the British Isles. This, in turn, provides an essential foundation for the interpretation of the clay mineral assemblages encountered in the onshore successions.

The most extensive onshore successions occur in southern England, where sediments of Paleocene to earliest Oligocene age are preserved in the London
and Hampshire structural basins. This structural configuration reflects inversion of the Weald Basin during the Miocene (Chadwick, 1993), and sedimentation is believed to have been continuous between the two areas during the Paleocene and Eocene. Tertiary sediments are largely missing from onshore northern and western Britain, but clays and sands of Eocene and Oligocene age are preserved in small fault-bounded basins. Far more extensive and complete stratigraphic successions are found in the offshore basins, attaining thicknesses of ~4 km in the Faroe–Shetland Basin and ~3 km in the North Sea Basin.

Many of the older onshore data are poorly constrained stratigraphically. They are often identified by formation only, which can make comparison difficult where there is considerable bed-scale variation in clay mineral assemblages. A further problem is that the lithostratigraphic terminology and biostratigraphic determinations have changed over time. Where this is the case, both the older and current assignments are given.

METHODS OF ANALYSIS

Sample preparation methods vary between authors, the most important probably being the difference in the size fraction analysed. This varies from <0.2 to <5 μm. Table 1 gives a summary of the methods used, where it has been possible to find this information. Generally it may be assumed that the finer the fraction analysed the more smectite will be recorded, as smectite typically is made up of smaller particles than other clay minerals. Vermiculite may be overlooked, and if so, will be recorded as smectite.

Samples used to obtain the new data presented in this study were mostly taken at 0.1–1 m intervals from the described coastal sections and boreholes. However, for sand-dominated intervals of the London Clay Formation, the spacing was wider. Semi-quantitative percentages should be treated as accurate to no better than ±10%. Computer modelling of X-ray diffraction (XRD) data from clay assemblages in the Solent Group, Whitecliff Bay, shows that the illite and smectite identified includes at least four principal illite-smectite compositions plus 1M4 illite (Huggett & Cuadros, 2005). For the sake of brevity, illite-rich, mixed-layer illite-smectite is generally referred to as ‘illite’, and clay minerals that expand to 17 Å with glycol are referred to as ‘smectite’. However, where detailed investigations have determined the proportion of any interlayers, as in the case of the Solent Group at Whitecliff Bay, specific identifications are provided. Hence, the term ‘smectite’ includes randomly interstratified mixed-layer minerals with <40% illite interlayers. In the figures, illite-smectite denotes a mixed-layer mineral with ~50% of each layer type. The group term kaolin, rather than the specific mineral term kaolinite, is used to describe the 7 Å 1:1 Al-rich clay minerals. This is because although it is likely that most of the kaolin in the sediments described is kaolinite, we have not investigated it in sufficient detail to determine whether or not dickite is present. The term glauconite (i.e. glauconite sensu lato) is used in this account to describe all green clay pellets with a glauconite (sensu stricto) component, either as end-member glauconite or as a glauconite-smectite mixed-layer clay. The XRD data for the Lambeth Group sections were kindly supplied by

Table 1. Methods used by previous workers quoted in the text. Perrin (1971) is not included because the data therein is collated from many other authors whose methods varied.

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* in Ellison and Lake (1986)
Dr Jackie Skipper for small and temporary exposures sampled during her PhD research but not included in her thesis (Skipper, 1999).

The preparation and analysis techniques used to obtain the new onshore data are as follows: samples were crushed, mixed with distilled water plus a few drops of ammonia as a dispersant and placed in an ultrasonic bath for 30 min. The clay suspension was decanted off from the >4 μm fraction and centrifuged at 4000 rpm for 20 min to remove all the clay (<4 μm) from suspension. The resulting slurry was filtered onto an unglazed ceramic tile. The tiles were scanned on a Phillips 1820 automated X-ray diffractometer using Ni-filtered Cu-Kα radiation. Scanning was at a rate of 5 s per 0.02°2θ step width, using 0.3 mm slits from 2 to 40°2θ. After spraying with glycol they were re-scanned from 2 to 26°2θ and again after heating at 400°C for 4 h, and after heating at 550°C, also for 4 h.

Most of the new offshore data were obtained from ditch-cuttings samples, for which analysis was restricted to material that passed a 0.5 mm sieve. This procedure minimizes the contaminating effect of cavings (fragments derived from strata exposed on the side of the drill-hole above the actual level of drilling) and provides a sharper definition of downhole compositional change. In all of the wells studied, the drilling mud was of non-oil-based type, and was dispersed easily by gentle agitation in distilled water, leaving a residue of true cuttings material.

The offshore cuttings and core samples were dispersed in distilled water by gentle crushing followed by ultrasonic agitation. The suspended clay was centrifuged to collect the <4 μm fraction, which was used to make oriented smear slides for analysis on a Philips PW1130 X-ray diffractometer under Ni-filtered Co-Kα radiation. Mineral percentages presented here are based on uncorrected peak-area percentages of traces from glycerol-treated samples, calculated by multiplying peak height by peak width at half height. In all samples, glycerolation of the swelling clays resulted in expansion of the peak from ~14 Å to ~17.8 Å, indicating the presence of ‘smectite’, either as a discrete phase or as a component of a randomly interstratified illite-smectite mineral.

The ‘illite’ and ‘smectite’ percentages have been calculated directly from the areas of the glycerolated 10 Å and ~17.8 Å peaks, respectively. Although only semi-quantitative, these estimates served the purposes of the original analysis, which was solely to assess stratigraphic changes in the relative abundance of the clay mineral phases. No further analysis has been carried out on the bulk of these samples, so that there is no direct evidence to say whether the clays are detrital or authigenic.

**NORTH SEA BASIN**

Although Tertiary sediments occur extensively in the offshore areas around the British Isles, clay-mineral stratigraphic data are available only for the North Sea Basin. The most comprehensive stratigraphic coverage has been obtained from sections in the central parts of the North Sea Basin, where the sediments are largely of mudstone facies. Substantial deep-water sandstone units are, however, locally present in the Paleocene and Eocene successions and sandstones of probable shallow-water origin are present in the Miocene and early Plioene successions of the Viking Graben. The North Sea sections provide a valuable background to the interpretation of the more intensively studied, but stratigraphically less complete, onshore Tertiary sections. The stratigraphy of the offshore successions and key elements of the climatic and tectonic evolution of the region are presented in Fig. 2.

Despite the wide extent and substantial thickness of the offshore Tertiary succession, the only published clay mineralogical studies of the full UK succession are those of Pearson and Small (1988) and Pearson (1990). These authors analysed shale cuttings (no sandstones) from six wells (wells 1–6 of Fig. 1) from the Viking Graben and Outer Moray Firth Basin. The Paleocene to Oligocene succession is dominated by smectite-rich illite-smectite with minor illite, kaolin and chlorite, whereas the Miocene to Quaternary succession is dominated by illite and chlorite with minor smectite and kaolin.

A comparable stratigraphic evolution from smectite-dominated to illite-dominated assemblages has been reported from the Tertiary succession of the adjacent Norwegian North Sea (wells N1–N3 of Fig. 1) by Karlsson *et al.* (1979), Berstad & Dypvik (1982) and Huggett (1992). There are, however, differences in the stratigraphic level at which the main upwards decrease in smectite is reported to occur: near the top of the Lower Eocene in the North Viking Graben (Huggett, 1992, her fig. 3), in the uppermost Oligocene in the South
Viking Graben (Berdast and Dypvik, 1982, their fig. 4) and within the Miocene section in the Central Graben (Karlsson et al., 1979, their fig. 5). Both Karlsson et al. (1979, their fig. 5) and Berdast & Dypvik (1982, their fig. 4) identified a reappearance of chlorite in the upper part of the Miocene section, similar to that reported (with less stratigraphic precision) by Pearson & Small (1988) and Pearson (1990). The clay mineral stratigraphy of a well in the Danish central North Sea was described by Nielsen (1979), but the data set is too sparse to establish detailed stratigraphic trends.

Since most of the published data are derived from wells drilled at an early stage in North Sea oil exploration, the chronostratigraphic assignments based on the original completion logs are open to question. Of particular significance in this context is the identification of the base of the Oligocene. Sediments that were assigned to the Middle and Upper Eocene in many early Viking Graben well completion logs are now known to belong to the Oligocene Lark Formation (C. King, pers. comm., 2005). This is believed to be the case for the well studied by Berdast & Dypvik (1982), reported to be
Norwegian well 15/12-1 (H. Berstad, pers. comm., 2005). Published data available for the nearby wells 15/12-4 (Norwegian Petroleum Directorate, 1990) and 15/12-5 (Norwegian Petroleum Directorate, 1992) show a sharp upwards increase in gamma-ray values in the middle of the 'Eocene' section, accompanied by a downwards change from brown-grey to green-grey mudstone. According to present-day stratigraphic usage, these criteria define the base of the Lark Formation (base Oligocene) (Knox & Holloway, 1992). By analogy, the sharp reduction in smectite values reported by Berstad & Dypvik (1982) as occurring in the middle of the Eocene section (base Unit 2) in Norwegian well 15/12-1 is actually associated with the base of the Lark Formation. The base of the Nordland Group, which probably lies at the base of the sandstone section at ~1350 m, would now be assigned to the late Mid-Miocene.

The identity of the well described by Huggett (1992) remains unknown, but it is believed to be within the Gullfaks Field (Norwegian block 34/10). Published data for 34/10-13 and 34/10-14 (Norwegian Petroleum Directorate, 1988) show the characteristic downwards appearance of grey-green mudstones at the top of the 'early Eocene' section. In 34/10-13, the base of the Lark Formation can be picked at 1340 m on the gamma-ray trace, 15 m below the top of the 'early Eocene' section. There can be little doubt, therefore, that the marked upwards reduction in smectite values recorded by Huggett (1992) shortly below the top of the 'early Eocene' section is in fact located at the base of the Lark Formation (base Oligocene). The base of the Nordland Group (late Mid-Miocene or younger) probably equates with the base of the 'Miocene' section.

The major upwards decrease recorded in the Viking Graben successions thus appears to coincide with the base of the Lark Formation (base Oligocene) in the two sections for which the most detailed data are available (Berstad & Dypvik, 1982; Huggett, 1992).

The stratigraphic interpretation of the older wells in the expanded succession of the central North Sea remains little changed. Comparison with published data for Norwegian well 2/11-7 (Norwegian Petroleum Directorate, 1992), indicates that the base of the Lark Formation in well 2/11-1 lies close to the base of the Oligocene as shown by Karlsson et al. (1979, their fig. 5). No significant upwards increase in smectite is apparent at this level, however. The base of the Nordland Group probably corresponds to the base of the Middle Miocene as shown in Karlsson et al. (1979, their fig. 5).

Huggett (1996) analysed clay and bulk-rock mineralogy for a ~100 m thick cored Palaeocene succession from a single well in the central North Sea. This study differed from other published clay mineral studies in the offshore in that sandstones were included and the textural relationships of the constituent minerals of both shale and sandstones were observed by back-scattered electron microscopy. The <4 µm fraction in this well is dominated by illite and illite-smectite (with 40–60% smectite), plus minor kaolin and chlorite.

Previously unpublished data acquired by the British Geological Survey in the 1980s are presented here from well sections in the UK sector (Figs 3–5). These confirm the stratigraphic trends established for the Norwegian North Sea. These sections are all from the central and southern areas of the North Sea Basin, where the succession consists almost entirely of deep-water, clay-dominated facies. Stratigraphic nomenclature is taken from Knox & Holloway (1992).

The most complete clay mineral record was obtained from well 30/1-1 (Fig. 3) and displays stratigraphic clay mineral trends very similar to those recorded by Berstad & Dypvik (1982, their fig. 4) from the Norwegian central North Sea. Although differences in the relative proportions of clay minerals are apparent, probably reflecting differences in analytical technique, both successions clearly show the same gross upwards increase in illite at the expense of smectite. The timing of major changes in the composition of the clay mineral assemblages is also similar in the two wells, when the chronostratigraphic assignments for the well studied by Berstad & Dypvik (1982) are updated (see above).

The earliest Tertiary sediments (Chalk Group: Ekofisk Formation) are in limestone facies and were not analysed. The clastic sediments of the overlying Upper Palaeocene sediments (Cycle 2: Maureen and Lista formations) display somewhat variable clay assemblages, with smectite, illite, chlorite and kaolin present in broadly equal proportions (Fig. 3). The unusually high proportion of chlorite is a distinctive feature, reported also by Berstad & Dypvik (1982, fig. 4) from the Norwegian sector. The base of the Sele Formation (early Eocene) is marked by a sharp increase in kaolin relative to the other clays, while smectite
disappears. Higher in the Sele Formation, smectite reappears and increases upwards at the expense of the other clay minerals.

Clay mineral trends in the Balder Formation and the lower part of the Horda Formation (Eocene) are obscured in the 30/1-1 section because of stratigraphic condensation, but a detailed picture is provided by a cored section from borehole 81/46A to the west, also shown in Fig. 3. A slight upwards decrease in smectite in the upper part of the Sele
Formation is followed by very high values in the lower, tephra-rich part of the Balder Formation. Kaolinite begins to increase in the upper part of the Balder Formation, reaching a peak shortly above the base of the Horda Formation. The remainder of the Horda Formation shows an upwards increase in smectite at the expense of kaolinite. In well 30/1-1, the smectite increase is more sharply defined, probably because of stratigraphic condensation.

The base of the Lark Formation in well 30/1-1 is marked by a sharp decrease in smectite, with a further sharp decrease taking place some 120 m higher in the section. This reduced proportion of smectite is maintained through much of the Lark Formation, but a return to higher smectite proportions takes place towards the top. The base of the Nordland Group (Late Miocene to Recent) is marked by an initial increase in illite and kaolinite at the expense of smectite. A subsequent return to higher smectite proportions is followed by an upwards increase in illite and chlorite at the expense of smectite.

When traced to the south into wells 38/25-1 and 53/5-1 (Fig. 4), the succession undergoes considerable thinning but displays the same gross pattern of clay mineral distribution. The most striking difference is the dominance of smectite in the basal part of the section (Maureen, Lista and lower Sele formations), chlorite being a very minor constituent. The kaolinite influx in the lower part of the Horda Formation is present in both sections, becoming the dominant feature in the Horda Formation of 53/5-1. The clay mineral pattern in the Lark Formation is less consistent, possibly reflecting preservation of different parts of the section in these relatively condensed and truncated sections. The Nordland Group in 38/25-1 shows a pattern similar to that of 30/1-1, although the relatively smectite-rich sediments of Cycle 7 are considerably thinner. In 53/5-1, the low-smectite sediments of Cycle 8 appear to rest directly on the Westray Group.

The principal differences between the clay mineral succession of well 30/1-1 (Fig. 3) and that reported from the Norwegian sector occur in the Paleocene and early Eocene interval. The most pronounced difference concerns the relatively low smectite content in the Maureen and Lista formations (Paleocene: Montrose Group) and in the lower part of the Sele Formation (earliest Eocene: Moray Group). Comparable features are displayed by data from wells 22/10a-4 and 22/17-A12 (Fig. 5), which were obtained from mudstone samples within cored sections. Unlike the Norwegian sections, those of 30/1-1, 22/10a-4 and 22/17-A12 are located at the distal end of

![Clay mineral stratigraphy of UK North Sea wells 38/25-1 and 53/5-1.](image-url)
successive major submarine fan systems that extended into the Central North Sea from the northwest. Smectite content is particularly low in 22/17-A12, which is located on the axis of sand fan deposition. Here illite is the dominant mineral and kaolin is more abundant than in 30/1-1.

The upper part of the Lista Formation, which is missing in the 22/17-A12 section, is fully represented in 22/10a-4, where it consists of extremely fine-grained, pale green, cream and red-brown claystones. Clay mineral assemblages are characterized by small illite and extremely small kaolin proportions, coupled with an alternation of smectite and chlorite as the dominant mineral. As discussed above, Berstad & Dypvik (1982) recorded comparably large chlorite contents in the Paleocene to early Eocene succession of the south Viking Graben.

The base of the Sele Formation (Moray Group) is marked in the UK central North Sea by a return to sand-dominated facies (Forties Sandstone Member). In terms of clay mineralogy this is characterized by a sharp increase in kaolin and illite at the expense of smectite. The most detailed clay mineral record across the Lista/Sele formation (Paleocene/Eocene) boundary has been obtained from well 22/10a-4 (Fig. 5), where the boundary is transitional and in mudstone facies (Knox 1996). Here, the basal Sele Formation mudstones (Sele unit 1a of Knox & Holloway, 1992) display a progressive increase in kaolin at the expense of chlorite, while the overlying sand-dominated section (Sele unit 1b) shows an increase in kaolin at the expense of smectite and illite. A smectite peak near the middle of the section represents a thin bed of hemipelagic mudstone.
In the highly condensed sections of 38/5-1 and 53/5-1 (Fig. 4), the entire Montrose Group and basal Moray Group succession is represented by extremely smectite-rich claystones. Comparable smectite-rich claystones extend into southeast England (Ormesby Clay: see above) and Denmark (Holmehus Clay: Hellemann-Clausen et al., 1985; Deyu, 1987).

The remainder of the Eocene succession, including the tephra-rich sediments of the Balder Formation, is dominated by mudstone facies and by clay mineral assemblages rich in smectite. The lower part of the Horda Formation includes an interval of relatively high kaolin values. This is poorly defined in the condensed succession of 30/1-1 (Fig. 3) but is more clearly defined in 38/25-1 and especially in 81/46A and 53/5-1 (Figs 3, 4). The same feature is found in the Danish succession, where a kaolin influx occurs at the base of the Røsnæs Clay and persists into the Lillebælt Clay (Hellemann-Clausen et al., 1985; Deyu, 1987, his fig. 3.). The largest proportions of kaolin are associated with a condensed interval of red and variegated claystone, which is interpreted as representing the maximum extent of the Eocene transgression. Unlike the kaolin influxes of the late Paleocene, this influx is not associated with the introduction of deep-water sands and is not accompanied by an increase in illite. It is, however, associated with an increase in chlorite, both in the North Sea sections (Figs 3, 4) and in Denmark (Deyu, 1987).

From the base of the Nordland Group upwards, the UK central and southern North Sea succession displays similar clay minerals trends to those reported from the Norwegian central and northern North Sea successions, with a progressive increase in illite at the expense of smectite. A marked upwards increase in chlorite, accompanied by a

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Fig. 6. Chronostratigraphic correlation of Paleocene to Oligocene outcrop and borehole sections in south-eastern and central southern England (adapted from Ali & Hailwood, 1995). Lambeth (Lamb) Group nomenclature after Ellison et al. (1994); Montrose (Montr) Group after C. King (pers. comm., 2005).
further reduction in smectite content, takes place close to the base of Cycle 8.

EAST ANGLIA AND THE LONDON AND HAMPSHIRE BASINS

The Tertiary succession of southeast England provides the thickest and most complete onshore record of Tertiary sedimentation. The present structural configuration results from a period of basin inversion that took place in Mid-Miocene times, and sedimentation is believed to have been continuous between the London and Hampshire basins during Paleocene, Eocene and Oligocene sedimentation. Most of the principal formations encountered in these basins can be traced into the offshore, and it is clear that sedimentation took place in an embayment of the North Sea Basin. This embayment extended southwards into the areas currently occupied by the English Channel and northern France and at times of high sea level connected with the Atlantic Ocean via the Western Approaches. Many of the mineralogical features of the adjacent southern North Sea succession can therefore be recognized in the onshore successions, especially those of East Anglia and the London Basin.

The stratigraphic intervals encountered in each of the principal outcrops and onshore boreholes described below are shown in Fig. 6. The clay mineral assemblages are described on a formation-by-formation basis in ascending stratigraphic order.

Montrose Group

Ormesby Clay Formation. The Ormesby Clay Formation (1–27 m) is a sequence of glauconitic, calcareous and non-calcareous marine mudstones with a few tuff horizons. The base is sandy with glauconitic clay-coated flints. The formation is known only in the sub-surface of East Anglia (Ormesby borehole: Cox et al., 1985; Hales borehole: Knox et al., 1990; Halesworth borehole: Moorlock et al., 2000, p. 108; Shotley borehole: Ellison & Knox, 1978). A reddish brown mudstone unit is present in the middle of the formation in both the Ormesby and Hales boreholes. Glauconite is very abundant, occurring as grains, as fragments of grains and as green smectite-rich layers. Knox et al. (1990) suggested that these green smectite clays represent argillized and glauconitized ash. The clay mineralogy has been determined from boreholes at Ormesby (Fig. 7: 27.35 m, 57 analyses), Shotley (Fig. 8: 0.7 m, 4 analyses) and Halesworth (Fig. 9: only the very top cored, 1 sample). It is dominated by smectite (45–99%) with lesser illite (0–47%), chlorite (0–13%) and kaolin (0–13%).

![Fig. 7. Clay mineral stratigraphy of the Paleocene and Eocene succession of the Ormesby borehole.](image-url)
Representative XRD traces are presented in Fig. 10a. The Ormesby borehole sequence shows stratigraphic variation in the clay assemblage similar to that reported by Arthurton et al. (1994, p. 29). The lower half (123.5–139.85 m) has an assemblage of almost pure smectite with small amounts of illite and chlorite. Heulandite-clinoptylomite (Fig. 11a) is associated with this assemblage, forming up to 40% of the clay fraction. The middle part (118–123.5 m) has an assemblage of smectite plus illite and minor chlorite. The upper part (112.5–118 m) has an assemblage dominated by smectite with minor illite and kaolin, plus rare chlorite.

Thanet Sand Formation. The Thanet Sand Formation is the stratigraphic equivalent of the Ormesby Clay Formation, and occurs only in the London Basin. It is up to ~33 m thick and comprises marine glauconitic fine sands, silty sands, silty clays, clays and marls. The basal bed (0.75 m), the Bullhead Pebble Bed, is particularly rich in volcanic grains and glauconite grains (≤40%), together with the characteristic glauconite-coated flint pebbles.

The clay mineralogy is known from Weir & Catt (1969) and Perrin (1971, seven analyses from various authors), who give data for various localities in Kent. New data are presented here (Fig. 12) for the Staines borehole (3.7 m, eight analyses). Representative XRD traces are presented in Fig. 10b. The clay mineral assemblages are dominated by smectite with minor illite, plus rare or trace kaolin, vermiculite, chlorite and illite-chlorite. Transmission electron microscope (TEM) analyses by Weir & Catt (1969) using samples from northeast Kent show euhedral lath-shaped crystal morphologies of smectite and much of the illite, the latter occurring as overgrowths on clay platelets. This morphology indicates that the clay assemblage is largely authigenic, although Weir & Catt (1969) suggested that a small proportion could be reworked from similar clay mineral assemblages in the Chalk.
Abundant silt-sized, smectite-rich clay aggregates in the Thanet Sand sediments have been interpreted as argillized particles of volcanic ash (Merriman in Ellison & Lake, 1986). Authigenic zeolite belonging to the heulandite-clinoptilolite series has been reported from the Thanet Sand Formation of
Mockbeggar, Pegwell Bay and Herne Bay in Kent (Weir & Catt, 1969; Knox, 1979), from the Great Bardfield and Wormingford boreholes in Essex (Ellison et al., 1978; Ellison & Lake, 1986) and from the Bures and Great Cornard boreholes in Suffolk (Ellison et al., 1978; Ellison & Lake, 1986). The zeolite is more abundant in the 5–20 μm silt fraction (<90%) than in the clay fraction (Weir & Catt, 1969). R. Merriman, in Ellison & Lake (1986), recognized three varieties of glauconite in the basal beds of the Thanet Sand Formation in the Wormingford borehole: clasts, lobate grains and matrix. The majority of sand-grade glauconite grains were fragments of volcanic rock often retaining clay ‘ghosts’ of phenocrysts and igneous groundmass textures.

**Lambeth Group**

*Upnor Formation.* The Upnor Formation (≤8 m) is a sequence of marine, glauconitic silty sands, with a locally developed basal pebble bed (e.g. Harefield, Middlesex: Daley & Balson, 1999, and references therein) that is restricted to the London Basin. It is referred to by Perrin (1971) as the Woolwich Bottom Bed. The Upnor Formation is not present in the Isle of Wight but reworked or pedogenically modified sediments of Upnor age are present (J.A. Skipper, pers. comm., 2005).

The clay mineralogy is known from Weir & Catt (1969), Perrin (1971; six analyses) and Skipper (1999; five analyses) and Hight et al. (2004). New data are presented here for the Shotley borehole (Fig. 8: 2.4 m, five analyses), the Staines borehole...
(Fig. 12: <1 m thick, one analysis) and a temporary exposure in the Newbury bypass (Fig. 13: ~18 m thick, two analyses). Representative XRD traces are presented in Fig. 10c. There is considerable variation in the clay assemblages. The lower part of the formation exposed at Bishopstone Point (north Kent coast), is dominated by smectite with minor illite (Weir & Catt, 1969: two analyses). Higher up in the formation, at Lower Upnor (north Kent coast) and at Swanscombe, the clay assemblage contains appreciable kaolin in addition to smectite and illite (Perrin, 1971; Skipper, 1999).

The top of the formation at Swanscombe consists of a bed of lignite overlying a kaolin-rich bed that is possibly a scat-earth (see later sections on palaeosols). In the Shotley borehole (Fig. 8), the Upnor Formation (3.45 m thick) is dominated by smectite, with lesser illite; kaolin and chlorite increase up the section at the expense of illite. The Newbury bypass section is dominated by

Fig. 12. Clay mineral stratigraphy of the Paleocene and Eocene succession in the Staines borehole. A2—D are the stratigraphic divisions of King (1981).

Fig. 13. Clay mineral stratigraphy of the Paleocene and Eocene succession at the Newbury bypass.
smectite with minor illite and rare chlorite. The very thin (1 m) section of the Upnor Formation in the Staines borehole displays a marked upwards change in the clay assemblage from one dominated by smectite with minor illite and traces of chlorite and kaolin to one dominated by illite with appreciable amounts of smectite and kaolin, plus minor chlorite (Fig. 12).

**Woolwich Formation.** The Woolwich Formation (10–15 m) is composed of marginal marine to freshwater, interlaminated sands, silts and clays with lignites (up to 4 m). It is restricted to the eastern half of the London Basin. The Woolwich Formation interdigitates with the Reading Formation in the London area (Ellison, 2004).

The clay mineralogy of the Woolwich Formation is known from Weir & Catt (1969: three analyses) and Perrin (1971: six analyses from various authors). New data are presented here for the Halesworth borehole (Fig. 9: 5 m, ten analyses) and Swanscombe (Fig. 14: ~16 m, 13 analyses). Representative XRD traces are presented in Fig. 10d. The clay assemblage varies considerably, showing no consistent regional or stratigraphic variation. At Bishopstone Point (north Kent coast), two analyses by Weir & Catt (1969) show that assemblages are dominated by smectite with lesser illite. Similar assemblages, but with minor chlorite and kaolin, are reported from Lower Upnor, Herne Bay and Shelford (north Kent) (Weir and Catt, 1969), Swanscombe (J.A. Skipper, unpublished data) and the Halesworth borehole (Moorlock et al., 2000). Smectite shows an overall decrease towards the top of the formation. Weir & Catt (1969) show a TEM image of euhedral and subhedral kaolin crystals from the Woolwich Formation at Lower Upnor.

**Reading Formation.** The Reading Formation (25–47 m) occurs in the western part of the London Basin, in parts of East Anglia and in the Hampshire Basin Basin. It consists of non-marine, red/purple mottled clays and thin sandy units. Typically, the base is transitional with the underlying Upnor Formation, where present; elsewhere it rests unconformably on the Chalk or the Thanet Sand Formation. In the London area, interdigitation with the Woolwich Formation splits the formation into upper and lower mottled clay units (Ellison, 2004), which elsewhere are often separated by a lignitic bed. There is evidence of extensive penecontemporaneous pedogenesis in the mottled clay, particularly in the upper part of the formation (Buurman 1980; Page & Skipper 2000).

The clay mineralogy of the Reading Formation is known from Weir & Catt (1969), Gilkes (1968), Perrin (1971: 23 analyses from various authors), Edwards & Freshney (1987) and Hight et al. (2004). New data are presented here for the Shotley borehole (Fig. 8: 11.7 m, 26 analyses), the Staines borehole (Fig. 12: 21 m, 45 analyses) and temporary exposures in the Newbury bypass (Fig. 13: 14.3 m, ten analyses), Alum Bay (Fig. 15: 34 m, eight analyses) and Whitecliff Bay (Fig. 16: 34.5 m, 14 analyses, Table 2). Representative XRD traces are presented in Fig. 10e. The clay mineral assemblage shows a great deal of variation that may reflect variable contributions made by the argillized volcanic detritus and by pedogenic modification. The most complete section in the London Basin is in the Staines borehole (Fig. 12). Here the assemblage is illite-dominated, with minor smectite, kaolin and

![Fig. 14. Clay mineral stratigraphy of the Eocene succession at Swanscombe.](image-url)
chlorite. A smectite-dominated horizon near the top of the borehole may be altered ash. Similar smectite-rich horizons are known from Harefield, Middlesex (Gilkes, 1968) and the basal bed at Whitecliff Bay (Fig. 16). The Reading Formation in the Shotley borehole is predominantly clay, variably silty and partly mottled with abundant pedogenic features. The clay mineral assemblage is illite, with minor smectite, kaolin and chlorite. There is an overall decrease in smectite from the base of the formation to the base of the upper sand.

There is an overall increase in smectite towards the north of the Hampshire Basin and a decrease towards the west (Gilkes, 1966). However, there is a great deal of fine-scale variation in the clay assemblage that may reflect variable pedogenic modification. Gilkes (1968) reported that at Bishops Waltham and Otterbourne in the northeast of the Hampshire Basin the <5 µm fraction is illite- and smectite-dominated, with minor kaolin. By contrast, in the south of the basin (Whitecliff Bay and Alum Bay) he reported it to be illite- and kaolin-dominated with subordinate smectite, which decreased towards the west (Studland Bay, Dorset). New data indicate that the <4 µm fraction of the Reading Beds of the Isle of Wight (Whitecliff Bay and Alum Bay) is generally dominated by illite with moderate amounts of smectite and kaolin, plus rare chlorite (Fig. 10c). Gilkes (1966) and new data for Whitecliff Bay and the Isle of Dogs (east London) show an unusual illite-smectite mineral in the upper part of the Reading Formation. This mineral does not fully collapse on heating at 400°C, possibly due to intercalation of Al(OH)₃ or organic compounds.

The Alum Bay section includes a bed exceptionally rich in kaolin within the upper mottled beds, immediately below a reworked lignite horizon that is interpreted as pedogenic in origin, possibly a seat-earth. The Isle of Wight data show slightly more smectite at the base than through the rest of the formation. There is also a smectite-rich assemblage at the base of the Reading Formation in the Bunker’s Hill and Shamblehurst boreholes (Edwards & Freshney, 1987). The Bunker’s Hill borehole assemblage is unusual in containing a narrow zone 3 m above the smectite-rich clay in a narrow zone that possesses a clay assemblage dominated by halloysite with minor mixed-layer vermiculite-chlorite and chlorite-smectite. This assemblage is thought to have formed by in situ subaerial weathering of the underlying volcanogenic clay (Edwards & Freshney, 1987). The remainder of the formation is illite-rich as elsewhere in the Hampshire Basin.

The Tower Wood Gravel of Devon was correlated by Daley & Balson (1999) with the
Fig. 16. Clay mineral stratigraphy of the Eocene succession at Whitecliff Bay. For reasons of clarity, not all the data are included in the stratigraphic clay mineral plots. A2–E are the stratigraphic divisions of King (1981).
Table 2. Ranges and means for semi-quantitative XRD estimates of clay minerals present in the <2 µm onshore Tertiary sections described in the text.

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<th>Location</th>
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<th>Smectite</th>
<th>Illite</th>
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<th>Kaolinite</th>
<th>Illite-smectite</th>
<th>Heulandite/clinoptilolite</th>
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* clinoptilolite is only present in 8 m of the Wittering Formation
Reading Formation, although Sellwood *et al.* (1984) considered it to be younger. This gravel has a white (locally brown) clay matrix that typically consists of well ordered ‘china clay-type’ kaolin, with a little disordered ‘ball clay-type’ and illite (Hamblin, 1973). The overlying Buller’s Hill Gravel is identified as the same age as the Reading Formation by Daley & Balson (1999) but Hamblin (1973) considered that it could be the stratigraphic equivalent of the Barton Formation. The Buller’s Hill Gravel includes lenses of white clay that are mainly disordered kaolin with a large and variable content of illite (Sellwood *et al.*, 1984).

**Thames Group**

**Harwich Formation.** The Harwich Formation consists of marine sandstones, siltstones and mudstones, up to ~30 m thick; it contains abundant glauconite. In north Essex and Suffolk it is represented by mudstones and siltstones, whereas in the London and Hampshire basins, sandstones are dominant. In northern Kent the Harwich Formation is represented by the Oldhaven Member, which consists of a basal conglomerate overlain by laminated fine sands with occasional thin clay lenses. In the London and Hampshire basins it is represented by cross-bedded muddy sands (King, 1981; Huggett & Gale, 1997) and in East Anglia by mudstones formerly known as the London Clay Basement Bed (King, 1981). In the Isle of Wight and the western part of the London Basin, it is rich in glauconitized faecal pellets. The Harwich Formation is characterized in East Anglia by the presence of volcanic ash beds (10–80 mm) in the upper part (Wrabness Member) and numerous sand-size volcanic grains throughout. The degree of preservation of the ash layers is variable; many, but not all, are replaced by smectite, while many volcanic particles have been replaced by glauconite (Knox, 1983). In the Oldhaven Beds and the London Clay Basement beds of the London Basin, ash layers are no longer evident, but glauconitized and unaltered ash particles are present (Knox, 1983). The Harwich Formation on the Isle of Wight (Whitecliff Bay and Alum Bay) consists of fine-grained, cross-bedded glauconitic sands (the glauconite has replaced faecal pellets, not altered ash) sands, silts and clays with a thickness of 3–4 m.

The clay mineralogy of the Harwich Formation is known from the work of Weir & Catt (1969) on the Oldhaven Beds and London Clay Basement Beds and Perrin (1971) on the Oldhaven Beds and London Clay Basement Beds, including two analyses from Weir and Catt (1969). New data are presented here for the Ormesby borehole (Fig. 7: 42.2 m, 70 analyses), Shotley borehole (Fig. 8: only the basal 1 m cored, 2 analyses), Halesworth borehole (Fig. 9: 17.2 m, 37 analyses) and Staines borehole (Fig. 12: <1 m, one sample), together with cliff sections at Alum Bay (Fig. 15: 4.3 m, 4 analyses) and Whitecliff Bay (Fig. 16: 3 m, two analyses). Representative XRD traces are presented in Fig. 10f. The clay assemblages from East Anglia (Ormesby and Halesworth boreholes) are dominated by smectite, with lesser illite, plus variable kaolin and chlorite (Figs 7, 9, 10f). A pure smectite assemblage in the basal bed of the Harwich Formation in the Halesworth borehole may represent altered volcanic ash. Clay assemblages from Shelford (northeast Kent) and Herne Bay (Weir & Catt, 1969) are dominated by smectite with minor illite and kaolin; illite particles show lath-shaped overgrowths similar to those in the Thanet Sand Formation (Weir & Catt, 1969). The clay assemblages from the Shotley and Staines boreholes, and those from the Isle of Wight comprise smectite and illite, with minor kaolin and variable chlorite.

**London Clay Formation.** The London Clay Formation is dominated by siltstones and claystones with locally thick shallow marine or estuarine sandstones; it becomes sandier towards the western palaeo-shoreline (King, 1981). Glauconite occurs throughout in minor amounts (~1%), although at some burrowed horizons it forms up to 10% of the bulk sediment (Huggett & Gale, 1997, 1998). The formation occurs in the London Basin, the Hampshire Basin, where it reaches its maximum recorded thickness of ~135 m at Whitecliff Bay, and in East Anglia. It also extends beneath the North Sea, where it is continuous with the upper part of the Balder and the lower part of the Horda Formation in the southern North Sea Basin. It should be noted that the lower part of what were formerly called the Bagshot Beds is now included within the London Clay Formation; these are the estuarine sands named the Nursling, Portsmouth, Whitecliff, Claygate and Bracknell Beds of King (1981). In discussing older studies (e.g. Gilkes, 1966, 1968; Weir & Catt, 1969) the data have been dealt with in accordance with the new stratigraphy.
The clay mineralogy is known from many investigations including those of Gilkes (1966, 1968), Weir & Catt (1969), Perrin (1971: 41 analyses from various authors), Burnett & Fookes (1974), Merriman (in Lake et al., 1986) and Huggett & Gale (1998: 33 analyses). New data are here presented for the Staines borehole (Fig. 12: 95.4 m, 114 analyses) and Hampstead Heath borehole (Fig. 17: 57.2 m, 69 analyses) and for the cliff sections at Alum Bay (Fig. 15: ~80 m, 26 analyses) and Whitecliff Bay (Fig. 16: 130 m, 60 analyses shown).

Representative XRD traces are presented in Fig. 19a. In the London Basin the clay mineral assemblage is uniformly dominated by smectite and illite with minor chlorite and kaolin (Figs 12 & 17). In the Hampstead Heath borehole chlorite increases upwards to the top of the London Clay Formation. The Hadleigh borehole in Essex includes 132.2 m of London Clay with a clay assemblage dominated by smectite and illite with minor kaolin and rare chlorite (Merriman in Lake et al., 1986). In this borehole, an upwards increase in the proportion of kaolin increases was reported, with a maximum of 15% quoted for the Claygate Beds (now the Virginia Water Formation). This trend is associated with an overall upwards increase in grain size (Merriman in Lake et al., 1986). Interstratified illite-smectite was recorded in the lower part of the London Clay (Divisions B/C of King, 1981).

Gilkes (1966,1968) found that the <5 μm fraction at Whitecliff Bay has a wide range of compositions from illite-rich with minor smectite and kaolin, to smectite-rich with minor illite and kaolin. In contrast, at Alum Bay he found the <5 μm fraction to be dominated by illite and kaolin with no smectite (these analyses were from above the interval sampled for the new data in Fig. 15). Overall, there is a lateral increase in kaolin, and a decrease in smectite from east to west across the Hampshire Basin in both the clay fraction (Gilkes, 1966, 1968), and in the bulk rock (Burnett & Fookes, 1974). There are no trends apparent between the Hampshire Basin and the London Basin (Table 3). However, the new data (<4 μm, Figs 15 & 16) suggest that at both Alum Bay and Whitecliff Bay, the clay mineral assemblage of the London Clay Formation displays much more vertical variability than in the London Basin, with notably kaolin-rich assemblages in some sand units (Fig. 16). These kaolin-rich assemblages

![Diagram of clay mineral stratigraphy](image)

**Fig. 17.** Clay mineral stratigraphy of the Eocene succession in the Hamstead Heath borehole. D—Claygate Mbr are the stratigraphic divisions of King (1981).

<table>
<thead>
<tr>
<th></th>
<th>Illite</th>
<th>Kaolinite</th>
<th>Chlorite</th>
<th>Smectite</th>
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</thead>
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<tr>
<td>Alum Bay</td>
<td>41</td>
<td>13</td>
<td>2</td>
<td>44</td>
</tr>
<tr>
<td>Whitecliff Bay</td>
<td>40</td>
<td>15</td>
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<tr>
<td>Staines</td>
<td>40</td>
<td>11</td>
<td>5</td>
<td>44</td>
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<td>Hampstead Heath</td>
<td>35</td>
<td>12</td>
<td>7</td>
<td>46</td>
</tr>
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</table>

**Table 3.** Means for semi-quantitative XRD estimates of clay minerals present in the <2 μm fraction of the London Clay Formation. Intervals where glauconite has weathered to kaolin are excluded.
are due mostly to replacement of glauconite by kaolin at, or soon after, deposition (Huggett & Gale, 1997, 1998). In the Hampshire Basin, replacement of detrital mica grains by kaolin is extremely rare, whereas in the London Basin it is widespread (Fig. 18).

The clay mineral assemblage (<2 μm) of the London Clay Formation from the Bunker’s Hill

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Fig. 18. Back-scattered SEM images of polished surfaces of the London Clay Formation: (a) Division A2, 51 m, Whitecliff Bay, Isle of Wight; (b) Division A2, South Ockendon Clay pit, Essex.
borehole is illite > smectite > kaolin, while further
cast in the Shamblehurst borehole it is smectite >
illite > kaolin (Edwards & Freshney, 1987). In both
boreholes, there is a gradual upwards increase in
smectite to the top of Division B (also shown at
Alum Bay, Fig. 15).
The smectite in the London Clay Formation of
north-east Kent is a mixture of lath-shaped and
rounded particles at the base, with the proportion of rounded particles increasing up the sequence (Weir & Catt, 1969; 4 analyses). Using TEM analysis, Gilkes (1966) found that the majority of particles in smectite-dominated samples from Whitecliff Bay are 0.1–0.3 μm in size and consist of anhedral ‘fluffy’ aggregates and very thin lath-shaped particles, whereas samples from Alum Bay include a much higher proportion of thick lath-shaped euhedral particles ~0.3 x 0.6 μm. Gilkes noted that these laths resemble the laths identified by Weir & Catt (1969) as smectite. However, he suggested that the larger laths found in the kaolin and illite rich clay mineral assemblage of western localities are either kaolin or illite, with the smaller ones being smectite.

No data are available on the clay assemblage of the Aller Gravel of Devon (correlated with the London Clay Formation by Daley & Balson, 1999).

**Bagshot Formation.** The Bagshot Formation (0.35–27 m) comprises shallow marine to estuarine sands overlying the Virginia Water Formation in the London Basin. These sand-rich beds were formerly termed the Middle-Upper Bagshot Beds.

The clay mineralogy is known from Weir & Catt (1969: 1 sample). New data are here presented for the Hampstead Heath borehole (Fig. 17: 11 m, 2 analyses). Representative XRD traces are presented in Fig. 19b. The clay mineral assemblages display a slight increase in illite, and a decrease in smectite in the Bagshot Formation compared with the underlying London Clay Formation. This change corresponds with an increase in grain size of the bulk sediment (Fig. 17). In contrast, Weir & Catt (1969) found that on the Isle of Sheppey the <2 μm fraction of the Bagshot Formation (now the Virginia Water Formation) is dominated by smectite, with minor illite and kaolin. They describe the smectite as having a lath-shaped morphology, while the illite exhibits what appear to be lath-shaped overgrowths.

**Bracklesham Group**

The Bracklesham Group, present only in the Hampshire Basin, was first sub-divided by Fisher (1862) and his classification was used for ~100 y. Fisher’s bed numbers are widely referred to in the literature and are given below with their current formation names. In the Hampshire Basin the upper part of what was formerly termed the Bagshot Beds, and in the London Basin the whole of the Bagshot Beds, is biostratigraphically equivalent to the glauconitic Wittering and Earnley formations of the Bracklesham Group. Gilkes (1966, 1968) groups data for the <5 μm clay assemblages of the entire Bracklesham Group together. He found a sharp transition from a smectite and illite-dominated assemblages in the east (Whitecliff Bay) to an illite- and kaolin-dominated assemblage at Alum Bay and localities further to the west. A predominance of anhedral clay platelets and a wide range of particle sizes (~0.1–2.5 μm) were reported in both eastern and western localities.

**Poole Formation.** In Dorset, the lower part of the Bracklesham Group is named the Poole Formation. It consists of interbedded sands, silts and clays with a few lignites, deposited mainly in fluvial and alluvial environments with a thickness of 30–160 m (Bristol et al., 1991). In what he referred to as Bagshot Beds (now the Poole Formation) at Studland Bay and Bournemouth (Freshwater Beds) and in the Dorset Ball Clays around Wareham, Dorset, Gilkes (1966) found that the <4 μm clay mineral assemblage consists only of kaolin (minor to major) and illite (minor to major). Analyses provided in Perrin (1971) are from Gilkes (1966, 1968).

**Wittering Formation (Fisher Beds I–V).** The Wittering Formation (23–57 m) is made up of shallow marine, glauconitic sand, plus lacustrine and estuarine silts and clays (Edwards & Freshney, 1987; Huggett & Gale, 1997). At Whitecliff Bay, a rooted lignite bed (the Whitecliff Bay Bed) is present. The clay mineralogy of the Wittering Formation is known from Gilkes (1966, 1968, 1978) and Edwards & Freshney (1987). New data are presented here for Whitecliff Bay (Fig. 16: 51 m, 14 analyses). Perrin (1971) includes seven of Gilkes’ numerous analyses in his compilation. Representative XRD traces are presented in Fig. 19c. There is considerable variation in the clay assemblage, both laterally and stratigraphically. At Whitecliff Bay, the clay mineral assemblage is dominated by illite and smectite, with minor kaolin and chlorite. Gilkes (1968) noted a smectite-dominated (80%) horizon within the Whitecliff Bay Bed, the presence of which has since been confirmed by Huggett et al. (2005). Lenses of pink clay within the Whitecliff Bay Bed are pure kaolin and comprise euhedral vermicular and tabular kaolin crystals in a matrix of cryptocrystalline kaolin and organic matter (Gilkes, 1966). Cristobalite and clinoptilolite occur as cements in smectite-rich sands immediately beneath the Whitecliff Bay Bed (Fisher Beds IV–V) (Gilkes, 1968; Huggett et al., 2005). At
Whitecliff Bay the proportion of smectite increases upwards towards the middle of the formation and then decreases to the top. Kaolin is absent from the middle of the formation. There is no obvious increase in the proportion of illite in the sandy intervals containing abundant glauconite pellets compared with those without pellets. This may be because the glauconite in the Wittering Formation consists mostly of mature, indurated pellets that are not readily disaggregated into clay-size particles during sample preparation, and are consequently not recorded by the clay fraction XRD data. The clay mineralogy (<2 μm) of the Wittering Formation from the Bunker’s Hill, Ramnor Inclosure and Shamblehurst boreholes is reported summarily in Edwards & Freshney (1987). At Bunker’s Hill, the clay mineral assemblage is given as illite (50%), kaolin (25%) and smectite plus vermiculite (25%); vermiculite is particularly abundant below the Whitecliff Bay Bed. In the Shamblehurst borehole, the smectite-dominated clay assemblage of the London Clay Formation extends 3–4 m upwards into the Wittering Formation, and then passes into an illite-dominated assemblage with smectite more abundant than kaolin. The proportion of illite is greater than at Bunker’s Hill. The Ramnor Inclosure clay assemblage is similar to that at Shamblehurst, except that kaolin is more abundant than smectite. In all three boreholes, minor chlorite and vermiculite are present throughout, and kaolin is most abundant in the Whitecliff Bay Bed. Westwards, the Wittering Formation passes into the Agglestone Member of the Poole Formation, for which no clay data are available.

**Earnley Formation (Fisher Beds VI–VII).** The Earnley Formation (4–24 m) comprises marine, highly glauconitic, clayey sandstones and siltstones. The clay mineralogy is known from Gilkes (1966, 1968, 1978) and Edwards & Freshney (1987). Perrin (1971) includes representative analyses from Whitecliff Bay (mostly from Gilkes, 1966, 1968). New data are presented here for Whitecliff Bay (Fig. 16: 25 m, 9 analyses). Representative XRD traces are presented in Fig. 19f. At Whitecliff Bay, the clay assemblage is dominated by illite and smectite and shows an upwards decrease in the smectite:illite ratio; minor kaolin and chlorite are also present (Fig. 16). Chlorite is less abundant than in the Wittering Formation. Glaucnite is present as indurated sand-grade pellets. In the Ramnor Inclosure, Bunker’s Hill and Shamblehurst boreholes, smectite is less abundant than at Whitecliff Bay, whereas kaolin is more abundant, forming up to 30% of the assemblages (Edwards & Freshney, 1987). To the west, in Dorset, the Earnley Formation passes into the Branksome Sand (formerly the Bournemouth Beds) that has a clay assemblage (<5 μm) of illite and kaolin, with illite dominant (Gilkes, 1966, 1968; Perrin, 1971: four analyses from Gilkes, 1966, 1968).

**Marsh Farm Formation (Fisher Bed VIII).** The Marsh Farm Formation (18–25 m) consists of grey to brown estuarine, carbonaceous, laminated clayey silt, with thin fine- to coarse-grained sparsely glauconitic marine sand. The clay mineralogy is known from Gilkes (1966) and Edwards & Freshney (1987). New data are presented here for Whitecliff Bay (Fig. 16: 10.3 m, three analyses). Representative XRD traces are presented in Fig. 19e. At Whitecliff Bay, the clay mineral assemblage is dominated by illite and smectite with minor kaolin and chlorite. Glaucnites are rare and the clay pellets are incompletely glauconitized (Huggett & Gale, 1997). In the Ramnor Inclosure borehole, the lower part of the Marsh Farm Formation is dominated by illite and kaolin (<35%), with lesser amounts of smectite, whereas the upper part is dominated by illite and smectite (<30%) with minor kaolin (Edwards & Freshney, 1987).

**Selsey Formation (Fisher Beds IX–XVII).** The Selsey Formation (30–50 m thick) consists of marine, glauconitic silty, fine-grained sands, sandy silt and occasional clay-rich horizons (30–50 m thick). There are far fewer glauconite pellets in the Selsey Formation (≤15%) than either the Wittering or Earnley Formations (≤40%). The clay mineralogy is known from Gilkes (1966, 1968, 1978) and Edwards and Freshney (1987). New data are presented here for Whitecliff Bay (Fig. 16: 30 m, four analyses). Perrin (1971) includes three analyses from Gilkes (1966, 1968). Representative XRD traces are presented in Fig. 19f. At Whitecliff Bay, the clay fraction is dominated by illite and smectite with minor kaolin and chlorite. In the Ramnor Inclosure borehole, glauconite is abundant, and the <2 μm clay mineral assemblage consists of illite>smectite>kaolin. Kaolin content is greatest in the middle of the formation. Westwards, the Selsey Formation passes into the Boscombe Sand Formation with a clay assemblage (<5 μm) of illite and kaolin (Gilkes, 1966, 1968; Perrin, 1971: three analyses from Gilkes, 1966, 1968).
Barton Group

Barton Clay Formation (Fisher Beds XVII–XIX). The Barton Clay Formation (40–90 m) consists of marine, green clay and clayey silt with very fine-grained sand, either scattered in the clay or forming laminae. Westwards, the formation passes into the Hengistbury Beds at Hengistbury Head (Dorset).

The clay mineralogy is known from Gilkes (1966, 1968, 1978) and Edwards & Freshney (1987). Perrin (1971) includes 15 analyses from the Barton Clay Formation at Whitecliff Bay, Alum Bay and Barton on Sea from Gilkes (1966). New data are presented here for Whitecliff Bay (Fig. 16: 41 m, ten analyses). Representative XRD traces are presented in Fig. 19f. The clay assemblage consists of illite and smectite, minor kaolin and very small amounts of chlorite at Whitecliff Bay (Fig. 20a), Alum Bay and Barton on Sea (Gilkes, 1966, 1978). At Headon Hill smectite is rare and the assemblage is illite- and kaolin-dominated (Gilkes, 1966). The green colour of the <4 μm fraction and the large illite content are due to the presence of reworked and disaggregated glauconite derived from the sandstones of the Wittering, Earnley, Marsh Farm and Selsey Formations (Huggett & Gale, 1997). Because of its small grain size this glauconite contributes to the intensity of the 10 Å peak and is included along with illite in the total clay. In the Ramnor Inclosure borehole the assemblage is similar to that of Whitecliff Bay but without chlorite. The Hengistbury Beds have a clay assemblage of illite and kaolin, with smectite and chlorite either absent or present in trace amounts (Gilkes, 1966, 1968).

Becton Sand Formation (formerly Chama Sand Formation). The Becton Sand Formation consists of marine, slightly glauconitic, clayey, silty very fine-grained sand and extremely sandy clay. The clay mineralogy is known from Edwards & Freshney (1987) and Perrin (1971: six analyses from Gilkes, 1966; one analysis from Cosgrove & Salter, 1966). New data are presented here for Whitecliff Bay (Fig. 16, 63 m, ten samples). Representative XRD traces are presented in Fig. 20b. At Whitecliff Bay the clay mineral assemblage is dominated by illite and illite-smectite, with minor smectite and chlorite and no kaolin. Cosgrove and Salter (1966) reported a clay mineral assemblage from Barton on Sea that is rich in smectite or smectite-illite. In the Ramnor Inclosure borehole, the clay mineralogy is dominated by illite and smectite with lesser kaolin and minor vermiculite (Edwards & Freshney, 1987). The assemblage from Headon Hill is dominated by illite and/or kaolin, sometimes with minor smectite. However, one of Gilkes’s (1966) samples contains 100% kaolin (Perrin, 1971). In the Ramnor Inclosure borehole the clay mineral assemblage shows a gradual upwards decrease in smectite and increase in illite, apart from an abnormally large smectite content in the middle of the formation; kaolin is a minor component throughout (Edwards & Freshney, 1987).

Solent Group

Headon Hill Formation. The Headon Hill Formation (40–94 m) is a highly variable, mixed marine and freshwater succession of sandstones, siltstones and marls that occur in the Hampshire Basin. On the north coast of the Isle of Wight the Headon Hill Formation is exposed in numerous cliff sections. The sedimentary facies are more proximal than at Whitecliff Bay and widespread pedogenic modification is reflected in the composition of the clay fraction. Where pedogenic modification has been most intense, the proportion of illite and illite-smectite is greatest; the unmodified clay assemblages are dominated by illite and smectite. Minor chlorite and rare kaolin are present in much of the formation, but they are absent from some pedogenically modified intervals.

The clay mineralogy is known from Gilkes (1966, 1978), quoted in Perrin (1971), and Edwards & Freshney (1987). Extensive new data (~200 analyses) are presented here for Whitecliff Bay (Fig. 16), Headon Hill, Colwell Bay and Sconce. Representative XRD traces are presented in Fig. 20c and 20d. Edwards & Freshney (1987) summarized the clay assemblage for the Ramnor Inclosure borehole as illite > smectite = kaolin, except from one level high in the Upper Headon Hill Formation that is illite > kaolin > smectite. Gilkes (1966, 1978) uses the old terminology of Lower, Middle and Upper Headon Hill Beds, equivalent to the Totland Bay Member, the Colwell Bay Member and the lower part of the Cliff End Member, respectively. Analyses from the Lower Headon Beds at Totland Bay, Hordle Cliff, Headon Hill and Whitecliff Bay range from very illite-rich (some >90% at Headon Hill and Whitecliff Bay) and illite-rich with minor smectite and kaolin, and with halloysite detected in one sample (Gilkes, 1966, 1978). Analyses from the
Middle Headon Beds range from illite-rich with minor kaolin and trace smectite at Colwell Bay and Headon Hill to more variable compositions at Whitecliff Bay (illite > kaolin and variable smectite) (Gilkes, 1966, 1978). The Upper Headon Beds contain an illite-dominated assemblage, with minor but variable kaolin and smectite (Gilkes, 1966, 1978).
The new data in Fig. 16 show how the clay mineralogy varies with lithology and also stratigraphically in the Headon Hill Formation. At the base of the Headon Hill Formation, the Totland Bay Member (~9.5 m thick) comprises green silty mudstones, lignitic silty claystones and muddy sandstones, with a brackish fauna in all but the uppermost beds. Sampled extensively at Headon Hill and Whitecliff Bay, the clay fraction is dominated by illite, with minor smectite, kaolin and rare chlorite. Illite is abundant in palaeosol intervals. Occasional fragments of glauconite, believed to be reworked from the underlying Bracklesham Group (Huggett & Gale, 1997; Gale et al., 1999), occur in the Totland Bay Member at Whitecliff Bay.

The ‘Colwell Bay Member’ (~32 m thick, equivalent to the old Middle Headon Beds) commences with the Brockenhurst Bed, a dark brown sandy mudstone with a marine fauna, passing up into green and yellow clayey sands. At Whitecliff Bay and Colwell Bay, the clay fraction of this bed is dominated by illite and kaolin, with minor chlorite, smectite and illite-smectite. The colour of the green sands is due to the presence of silt-size fragments of glauconite (<5% of the rock), in the yellow sandstones it is due to the presence of glauconite that has weathered to Fe-oxyhydroxides. The presence of slightly oxidized glauconite in the grey, pyritic, muddy sand overlying the yellow sands suggests that this glauconite is reworked, possibly from the yellow sandstones.

The ‘Cliff End Member’ (~14 m thick) is characterized by green, green-grey and brown silty claystones with a brackish fauna. The clay fraction of the green claystones is dominated by illite-rich illite-smectite, while the clay fraction of the grey-green and brown claystones is dominated by illite, illite-rich illite-smectite and smectite-rich illite-smectite, with minor kaolin and chlorite. Glauconite pellets are absent.

The ‘Lacey’s Farm Limestone Member’ (~7 m) is represented by green to white marls with pale concretionary limestones, 10–30 cm thick. The clay fraction is dominated by illite-rich illite-smectite. Glauconite pellets are absent.

The ‘Fishbourne Member’ (~6.5 m) comprises greenish grey, thinly laminated claystones, with a freshwater fauna. The clay mineral assemblage is illite, kaolin and smectite with rare chlorite.

The ‘Osbourne Marls Member’ (~10.5 m) is characterized by unfossiliferous red and green colour-mottled clay-rich soils with patchy calcrite. The clay fraction is dominated by illite and smectite with minor kaolin and rare chlorite. Kaolin decreases in abundance towards the top of the member.

The ‘Seagrove Bay Member’ (~8.5 m) comprises green mudstones with thin siltstones and calcite-cemented sandstones. The clay fraction of the dark green claystones is pure illite. Light green and red claystones are dominated by illite, with minor smectite, kaolin and chlorite.

**Bembridge Limestone Formation.** The Bembridge Limestone Formation (~7.5 m) crops out only on the Isle of Wight where it consists of lacustrine marls and partly concretionary limestones with thin green clay seams. The clay mineralogy is known from Gilkes (1966, 1968, 1978) and Huggett et al. (2001). New data for Whitecliff Bay are shown in Fig. 16, and representative XRD traces are presented in Fig. 20e. Data in Perrin (1971) are from Gilkes (1966, 1968). The clay mineral assemblage of the lower part of this horizon is dominated by illite and illite-rich illite-smectite with minor smectite, chlorite and kaolin. The clay mineral assemblage of the upper part of the formation contains a greater proportion of smectite with very broad XRD reflections. Traces of chlorite occur in the middle part of the formation (Figs 16, 20e). Halloysite is present in some horizons (Gilkes, 1968).

**Bouldnor Formation.** The Bouldnor Formation (<100 m) straddles the Eocene–Oligocene boundary; it comprises the Bembridge Marls, Hamstead and Cranbourne members. It is only found on the north coast of the Isle of Wight. The Bembridge Marls Member (~21.5 m) consists of blue-green marls and clays, the Hamstead Member of blue-green clays with occasional silts and sands, and the Cranbourne Member (~9.2 m) of brown to grey clays. The blue-green clays weather to brown within days of exposure to air, suggesting that their colour is due to the presence of akaganeite (‘green rust’) rather than to Fe-rich clay.

The clay mineralogy is known from Gilkes (1966, 1968, 1978) and Huggett et al. (2001). New data are presented here for Whitecliff Bay (Fig. 16: 21 m, 13 analyses) and Cranmore, on the north coast of the Isle of Wight. Representative XRD traces are presented in Fig. 20f. Data in Perrin (1971) are from Gilkes (1966, 1968). The clay mineral assemblage of the lower part of the Bembridge Marls Member at Whitecliff Bay is dominated by smectite with lesser amounts of illite, minor kaolin and trace chlorite. The amount of illite
increases upwards at the expense of smectite, so that at the top of the member illite is the dominant clay mineral. The clay assemblage of the Hamstead Member at Cranmore is predominantly illite with minor illite-smectite and kaolin, rare chlorite and trace smectite. The clay assemblage of the Cranbourne Member at Cranmore is illite and smectite, plus minor kaolin and trace chlorite.

**Plio-Pleistocene deposits**

No published analyses have been located for any Plio-Pleistocene deposits other than the data in Perrin (1971) for a single analysis of Norwich Crag from near Aldeburgh in Suffolk. The Norwich Crag has a small clay content, dominated by illite and with trace kaolin.

**Western and Northern Britain**

A series of Tertiary basins containing non-marine sediments occur along the western margin of the British Isles, both onshore and offshore.

**Southwest Britain**

**Bovey Formation.** The Bovey Formation is Lower Eocene to Oligocene in age, and possibly extends into the Miocene. It consists of non-marine gravels, sands, lignites and clays including commercially extracted ball clays that occur in the Bovey Tracey and Petrockstow basins, Devon (Bristow, 1968; Vincent, 1983; Sellwood et al., 1984). These clays are composed predominantly of kaolin, clay-grade quartz and illite (Bristow et al., 1991; Perrin, 1971; Mitchell & Stentiford, 1973). Other minerals are present in trace amounts, including illite-smectite and smectite (Vincent, 1983). Ball clays of varied colour occur mainly in the Middle Bovey Formation. The compositional range for commercial ball clays is kaolin 20–95%, clay-grade quartz 1–70%, and illite 5–45% (Mitchell & Stentiford, 1973).

The kaolin in ball clays is usually disordered and very fine-grained, typically ~0.1–1 μm (Sellwood et al., 1984). In the upper Bovey Formation (mainly Blatchford Sand Member), well-crystallized kaolin is the dominant clay mineral, with minor illite (Sellwood et al., 1984).

**St Erth Beds.** Perrin (1971) presents five analyses of the Plio-Pleistocene St Erth Beds from the pit at St Erth, Cornwall. Assemblages are dominated by illite and smectite with minor to moderate amounts of kaolin.

**Tremadoc Bay Basin.** The Llanbedr (Mochras Farm) borehole penetrated 525 m of Tertiary sediments in the Tremadoc Bay Basin. These comprise conglomerates, sands, silts, clays and lignites, of Middle Oligocene to Early Miocene age (Herbert-Smith, 1971; Woodland, 1971). No published clay mineral data are, however, available for this succession.

**Northern Ireland**

The Oligocene Lough Neagh Clays of Northern Ireland are plastic clays with ~50% kaolin, with smaller amounts of chloritized low-charge vermiculite (in some analyses it is ordered 1:1 chlorite-vermiculite), minor quartz and rare illite and feldspar (Bain et al., 1976).

**Western Scotland**

Paleocene clay-bearing sediments occur on the Island of Mull, interlayered with basalt lavas, but no published data on the clay mineral assemblage are available. Late Oligocene clays occur in small offshore basins southwest of Skye and in the Little Minch slightly further north (Evans et al., 1991). The Little Minch clays comprise a mixed assemblage of smectite, kaolin, chlorite, illite and gibbsite, formed in a swampy floodplain environment (Evans et al., 1991). The smectite/kaolin ratio increases upwards through the clay-rich sediments, possibly reflecting a change to less weathered source material.

**Eastern Scotland**

Pre-glacial, Tertiary weathering can be identified most readily in northeast Scotland, where deeply weathered rocks have been least reworked by glaciation (Fitzpatrick, 1963; Wilson et al., 1984). Remnants of Tertiary weathering may be identified elsewhere in Scotland through the presence of kaolin-rich weathering deposits (Fitzpatrick, 1963; Wilson et al., 1984).

**Origin of the Clay Assemblages**

Several factors need to be taken into account in interpreting the origin of clay mineral assemblages...
in the Tertiary of northwest Europe, including major changes in both climate and tectonic setting, periods of substantial pyroclastic activity and possible reworking of pre-existing clay-rich sediments.

The climatic, tectonic and volcanic influences on sedimentation are summarized in Fig. 2. Studies of Tertiary climatic evolution have demonstrated: (1) progressive climatic warming from warm temperate to sub-tropical in the early Paleogene, culminating in the early Eocene (e.g. Robert & Chamley, 1991); (2) rapid climatic cooling in the latest Eocene, associated with the establishment of southern polar ice-caps (Prothero et al., 2003); (3) rapid climatic cooling in the early Miocene, associated with a major expansion of the southern polar icecaps (Kennett and von der Borch, 1986, p. 1503).

Because of its location on the margin of the developing North Atlantic Ocean, northwest Europe also experienced successive changes in the patterns of source-area uplift and basin subsidence, allowing the recognition of a succession of tectono-sedimentary cycles (Knox, 2002; Fig. 2). Of particular note are the two phases of mantle plume activity and related uplift in the late Paleocene (base Cycle 2) and earliest Eocene (base Cycle 3), the change in tectonic configuration at the end of the Eocene (base Cycle 5), and the further change in tectonic configuration associated with enhanced uplift of Scandinavia in late Miocene times (base Cycle 8). Intense pyroclastic volcanism took place in late Paleocene times and earliest Eocene times, reaching a maximum immediately prior to the onset of sea-floor spreading between Greenland and Europe. Pyroclastic activity, associated with the Iceland hot-spot, no doubt continued throughout the Tertiary, but discrete pyroclastic deposits have not been recognized.

The coincidence of the latest Eocene and Mid-Miocene cooling events with major changes in tectonic regime make it difficult to separate climatic from tectonic (and hence provenance) control.

**Offshore detrital clay mineral assemblages**

All records of the clay mineral succession in the North Sea Basin show a predominance of smectite in the Paleocene and Eocene sections, followed by a progressive increase in illite and, subsequently, chlorite at the expense of the smectite. The association of abundant smectite in the Paleocene and early Eocene, together with evidence of intense pyroclastic activity in the North Atlantic Igneous province, has led to the conclusion that the smectite was derived through alteration (either halmyrolytic or diagenetic) of volcanic glass (Karlsson et al., 1978; Malm et al., 1984; Pearson & Small, 1988; Pearson, 1990; Huggett, 1992). While alteration of glass to smectite undoubtedly took place, as indicated by the presence of bentonitic tephra layers, it is not clear whether the huge volume of smectite clay within the Late Paleocene to Early Eocene interval can be attributed entirely to this process. Any interpretation must take account of the presence of highly smectitic clays in the higher parts of the Upper Cretaceous (Pearson, 1990, Figs 3a, 4a and 5b) and Danian (Pearson, 1990, p. 535), and also the persistence of abundant smectite in rocks as young as early Miocene (Fig. 3).

Regarding the abundance of smectite in the Upper Cretaceous, Pearson (1990) concluded that while an air-borne ash contribution could not be ruled out, it is more likely that the smectite was derived from weathering of basement rocks in Greenland (Hancock, 1986) or Scandinavia, or from weathering of volcanic rocks in the Rockall Trough. Pearson (1990, p. 535) also considered that similar processes, operating under an increasingly humid climate, may account in part at least for the higher smectite content in the Lower Paleocene (Danian). While alteration of volcanic ash undoubtedly accounts for much of the smectite in the Tertiary, a continued detrital contribution from other sources cannot be ruled out.

Berstad & Dypvik (1982) addressed this question by determining the distribution of Th, U and K2O within the lower part of the Tertiary succession. They interpreted the very low U and Th values in their Unit 1 (reinterpreted here as equivalent to the Paleocene and Eocene Lista, Sele and Horda formations) as indicating a high volcaniclastic component (~60–80% of the total sediment). They interpreted the sharp increase in U and Th values at the base of their Unit 2 (reinterpreted here as equating with the base of the Oligocene Lark Formation) as indicating a marked increase in the detrital component (>80%) over the volcaniclastic component (~20%). This is consistent with the change in tectonic regime that led to shallowing of the basin and relative uplift of Scandinavia (base
Cycle 5). The upwards change from smectite-rich clays to smectite-poor clays with unaltered volcanic glass particles noted by Huggett (1992) is believed to occur at the same level (see discussion above), with the change in preservation of ash particles representing more rapid erosion and burial of the sediment.

Although non-volcanogenic smectite appears to constitute only a small proportion of the total smectite in the pre-Oligocene sediments, a significant detrital contribution could still have been involved through the recycling of argillized ash deposited on adjacent land areas. Although the East Shetland Platform was the principal source of siliciclastic sediment at this time, low-relief, stable land areas existed elsewhere in northern Britain and southern Norway at this time, and could have developed a substantial ash-derived, smectite-rich soil cover. Erosion of this cover could account for the persistence of high amounts of volcanogenic smectite after the period of intense pyroclastic activity ceased in early Eocene times. A direct pyroclastic contribution at this time is also indicated by the presence of disseminated tephra particles (Huggett, 1992). Other sources of detrital smectite in the Late Palaeocene to Eocene succession could have included weathered basement rocks and reworked smectite-rich Early Palaeocene (Danian) and Cretaceous clays (see discussion in Huggett, 1992, p. 502).

Other variations in the clay mineralogy include Fe-rich chlorite in some sections and intervals of relatively high kaolin abundance in both the late Palaeocene and early Eocene. Chlorite is regarded as a product of diagenesis (see below). Abundant kaolin in the Palaeocene succession is associated with sand-dominated submarine fans. Most of the kaolin described by Huggett (1996) from mudrocks of the Forties Sandstone Member (Sele Formation) of the Central North Sea is coarsely crystalline and clearly authigenic. Discrete clay-grade kaolin is rare and the detrital kaolin difficult to quantify. It is therefore not possible to determine how much of the kaolin recorded from mudstones in wells 22/10a-4 and 22/17-A12 (Fig. 5) is detrital and how much is authigenic. The mudstone-dominated section at the base of the 22/10a-4 core is significant in this respect, however, as the appearance of kaolin is associated with a major influx of freshwater palynomorphs, representing a major sea-level fall and displacement of sediment of terrestrial or marginal marine facies into the basin centre (Knox, 1996). Some of this sediment is thought to have been derived from Jurassic and Lower Cretaceous sediments of the Moray Firth area. Since these sediments are relatively rich in kaolin (Pearson, 1990), it is possible that a significant amount of the kaolin in the Paleocene mudstones was derived from this source. Kaolin could also have formed in soil profiles on the Paleocene coastal plain. Beyond the limits of the submarine fans, the clay mineral assemblages are dominated by smectite, with only low proportions of kaolin (Fig. 4).

By contrast, kaolin enrichment in the lower part of the Early Eocene Horda Formation (Figs 3, 4) is not associated with the introduction of deep-water sands but rather with a condensed succession of hemipelagic claystone. The kaolin peak is poorly defined in the condensed succession of 30/1-1 (Fig. 3), but is more clearly defined in 38/25-1 and especially in 53/5-1 and 81/46A (Figs 3, 4). The same feature is found in the Danish succession, where it is associated with the Rønæs Clay and Lillebælt formations (Heilmann-Clausen et al., 1985; Deyu, 1987), marking the maximum extent of Eocene marine transgression. Since this coincides with the peak of Tertiary climatic warming as identified from oxygen isotope studies (Buchardt, 1978; Robert & Chamley, 1991; Fig. 2), the kaolin may have entered the basin through marine reworking of tropical soil profiles developed on land areas to the south (Heilmann-Clausen et al., 1985; Deyu, 1987). The origin of the associated chlorite is uncertain (Deyu, 1987).

As described above, the sharp reduction in smectite abundance at the base of the Lark Formation is believed to reflect a pronounced change in the tectonic and depositional regime. Shallowing, accompanied by an increase in sedimentation rate, caused the focus of sedimentation to switch from the shelf and slope to the basin centre (see Knox & Holloway 1992, fig. 1). Thin and incomplete successions developed along the basin margins, with the potential for significant reworking of older Tertiary deposits. While such reworking could have contributed to smectite supply, the relatively high U and Th values (Berstad & Dypvik, 1982) favour a non-volcanogenic source. This implies that despite the establishment of cooler climates in the early Oligocene, smectitic soils continued to develop through weathering of basic rocks, particularly in Scandinavia, which became a major source of sediment at this
time. Following a second phase of uplift at the base of Cycle 6 (base Upper Oligocene), progressive transgression led to a general decrease in grain size and increase in smectite content.

The next major change in clay mineral composition occurs at the base of the Nordland Group (base Cycle 7, see Fig. 2) in the upper Middle Miocene, which was associated with the establishment of a new tectonic regime, under which uplift of Scandinavia led to increased sediment influx from the east (Doré et al., 1999). A marked decrease in smectite content at this level is accompanied by an increase in plagioclase (Berstad and Dypvik, 1982, Fig. 3; Huggett, 1992, Fig. 4). These trends are regarded as reflecting the deposition of increasingly immature sediments with time, as a result of increasing rates of uplift in the source areas combined with climatic cooling (Karlsson et al., 1979; Berstad & Dypvik, 1982; Huggett, 1992). A further decrease in smectite content in the Pliocene is accompanied by an increase in chlorite and amphibole (Berstad & Dypvik, 1982, p. 85) and may be attributed to a marked increase in subsidence and sedimentation rates from the Pliocene onwards (Wensaa et al., 1994, p. 43).

Onshore detrital clay mineral assemblages

The distinction between detrital and authigenic clay components in the Tertiary strata of the London and Hampshire Basins has been the subject of much discussion. Early interpretations (Gilkes, 1966; Weir & Catt, 1969) attempted to link clay mineral composition to the mineralogy of the coarse silicate detritus, with varying degrees of success. Weir & Catt (1969) identified three heavy mineral suites in the Tertiary sediments of the London Basin: one derived from the Chalk, one with an Armorican granite source and one metamorphic suite of unknown provenance. Although there may be some justification for attempting to link heavy mineral assemblages to clay mineral assemblages, their very different hydrodynamic behaviors make this an unreliable approach to determining clay provenance.

The Chalk was favoured by Gilkes (1966) and, to a more limited extent, by Weir & Catt (1969) as a source of smectite and illite in the Paleocene and the lowermost part of the London Clay Formation, because a similar clay assemblage with similar particle morphologies occurs in the Chalk. However, Weir & Catt (1969) realized that the lack of flint reworking into the Tertiary strata suggests that the Chalk was not the main source of clay detritus. Weathered Armorican granite in southwest England was suggested as a source of kaolin for both the London Basin (Weir & Catt, 1969) and the Hampshire Basin, where the kaolin is associated with varying amounts of illite and Upper Greensand chert detritus picked up during its transport from the southwest (Gilkes, 1966, 1968).

A turning point in understanding the origin of Tertiary clay mineral assemblages was the identification of volcanic ash in the Eocene Beds of southeast England (Elliott, 1971). Subsequently, Jacqué & Thouvenin (1975) reported thick sequences of volcanic tuffs in the Eocene strata of the North Sea. By the early 1980s, volcanic ash or its argillization products had been described from several Tertiary formations in the London Basin, including the Ormesby Clay Formation (Knox et al., 1990), the Thanet Sand Formation (Knox, 1979; Knox & Morton, 1983; Merriman in Ellison & Lake, 1986), the Woolwich Formation (Knox & Morton, 1983) and the Harwich Formation (Knox, 1983). It is highly probable that ash also contributed to sediments in the Hampshire Basin, although dilution by non-volcanogenic detrital clays will have been much greater, especially in the west of the basin. Pure smectite clay assemblages at the base of the Reading Formation in Whitecliff Bay (Fig. 16) may have formed through the argillization of ash. Some of the volcanic ash and its alteration products that accumulated on land would also have been transported by rivers into the London and Hampshire basins.

Knox and Morton (1983, 1988) identified two main periods of pyroclastic sedimentation in their review of the North Sea Basin, both related to volcanic activity in the North Atlantic Igneous Province. The first was between 58 Ma and 57 Ma, corresponding to the period of deposition of the Ormesby Clay and Thanet Sand formations. The second was between 55 Ma and 52 Ma, corresponding to the period of deposition of the Lambeth Group and the lower part of the Thames Group. The volcanic ash generated in these two episodes is believed to have been dominantly basaltic in composition (Knox & Morton, 1983, 1988).

Palaeobotanical evidence in the Tertiary sediments of southern England indicates that the climate was both hot and seasonal during the Eocene (Daley, 1972), but changed to cooler, more
seasonal climates in the Oligocene. The vegetation cover was dense and tropical during the Eocene, shifting to more open grassland vegetation in the Oligocene. During the periods of sub-tropical to tropical weathering, rapid chemical weathering occurred, with resultant high rates of clay mineral neof ormation. Remains of the soils developed over the British Isles during the Paleocene–Oligocene are preserved only in upland areas. Glacial and periglacial processes have removed all evidence from the areas of low relief. In southwest England, truncated patches of deep kaolin-rich soils are present (Bristow, 1968; Isaac, 1983). Regional variations in clay mineral composition in the Tertiary sediments of the London and Hampshire indicate that of the river systems proposed by Gibbard & Lewin (2003), only the proto-Solent could have played a significant role. The high proportion of kaolin, derived from southwest England, is reflected in the greater abundance of kaolin in the Tertiary sediments of the western part of the Hampshire Basin (Gilkes, 1968). This is probably accentuated by the fact that coarser detritus (kaolin) settles out of suspension faster than finer detritus (smectite).

Gilkes (1966) considered that the primary source of detrital illite in the Hampshire Basin was the Upper Greensand Formation of Devon. However, reworked palynomorphs in Hampshire Basin are dominated by Middle and Upper Jurassic species, indicating that Middle and Upper Jurassic rocks were an important sediment source (G. Eaton, pers. comm., 2004). The clay mineral assemblages of the Mesozoic are illite-dominated with subordinate smectite, kaolin and minor chlorite. Most of the Tertiary sediments of southern England have clay assemblages dominated by illite and smectite. Although some illite can be demonstrated to be authigenic, especially in the Solent Group (see below) most of the illite in the Tertiary sediments can reasonably be assumed to be detrital. K/Ar age dating of illite from the Solent Group (Huggett et al., 2001) and glauconite from the Bracklesham Group (Clauser et al., 2005) give ages greater than their depositional age, indicating that neoformed illite is mixed with much detrital illite.

The clays of the London Clay Formation are for the most part much more smectite-rich than the main Middle to Upper Jurassic clay-bearing sediments of southern England (the Oxford Clay Formation and the Kimmeridge Clay Formation). As stated previously, the clay fraction of the Chalk, although smectite-rich, could not have provided sufficient smectite to account for the London Clay Formation. In recent soils formed on the Upper Greensand, glauconite has been replaced by smectite-rich clay (Loveland, 1981; Loveland & Findlay, 1982). If the same weathering process occurred during the Tertiary then the soils covering the large areas of exposed Upper Greensand in western England may have been smectite-rich. However, the overall contribution of these clays to the riverine detritus relative to that of the kaolin-rich regolith from further west, remains unknown. A proportion of smectite in the Paleocene and Thames Group sediments may be derived either directly from ash fall, or from reworking of soils containing air-borne ash. The homogenous composition of the London Clay Formation in the London Basin (Figs 12, 17) suggests that the latter was the principal volcanogenic source, rather than intermittent ash falls.

Throughout the Paleocene and Eocene, kaolin was an important component of laterites formed in the hinterland of the Hampshire and London Basins (Isaac, 1983). There are three detrital kaolin sources in UK Tertiary sediments: laterite, ‘china clay’ formed through hydrothermal alteration of Cornubian granites and reworking of pre-Tertiary and Tertiary kaolin-bearing mudstones. In the Petrockstow and Bovey basins the Bovey Formation ball clays were derived through Tertiary weathering of Upper Palaeozoic shales and slates (Bristow, 1968; Vincent, 1983). The coarsely crystalline kaolin in the Upper Bovey Formation is reworked ‘china clay’ kaolin of hydrothermal origin. Kaolin in the early Eocene Buller’s Hill and Tower Wood Gravels in south Devon are a mixture of well-crystallized ‘china clay’ kaolin of hydrothermal origin and poorly crystallized kaolin derived through weathering of Upper Palaeozoic shale (Hamblin, 1973). The variable illite content of ‘ball clays’ may represent variation in the degree of dilution of Dartmoor detritus by highly illitic, post-Kimmeridgian clays (Gilkes, 1966).

Gilkes (1966, 1968) and Burnett & Fookes (1974) reported an overall increase in kaolin and a decrease in smectite from east to west in the Tertiary sediments of the Hampshire Basin. In the new data presented here, the higher kaolin percentages are largely restricted to the Bracklesham Group (Fig. 21). High kaolin percentages in the London Clay Formation are restricted
to the central part of Division D in Whitecliff Bay (the Whitecliff Sands). As proposed by Gilkes (1966, 1968), this distribution is believed to indicate that detrital kaolin in the Lower and Middle Eocene sediments of the Hampshire Basin originated through the fluvial reworking of laterite and china clay deposits in southwest England. The smectite that dominates assemblages in the east was believed by Gilkes (1966, 1969) to have been derived from the dissolution of chalk, but here it is considered to be largely of authigenic origin (see below).

Chlorite is a minor component of the U.K. onshore Tertiary sediments. Gilkes (1966) observed that chlorite is present in the marine Tertiary sediments but is absent from the terrestrial deposits and suggested that the marine chlorite may have formed during early diagenesis. However, this would require that chlorite was absent from the sediment source. This is considered to be unlikely since chlorite is present in the majority of the Mesozoic clay-rich sedimentary rocks that probably supplied the bulk of the detritus. The discovery by Huggett et al. (2001) that chlorite (as well as smectite) is absent from pedogenically modified sediments in the Solent Group suggests that the distribution of chlorite may be due to dissolution (or lack of it) rather than precipitation.
Onshore authigenic clay minerals

While much of the clay present in Tertiary strata appears to have a detrital origin, there is also widespread evidence that a variable but significant proportion of clay assemblages have an authigenic and neof ormational origin. The evidence is twofold: firstly, crystal morphology and petrographic relationships between certain clay minerals and its host sediment indicates post-depositional formation; secondly, the restricted occurrence of particular clay mineral assemblages, dominated usually by a single clay mineral, suggests that it formed in situ. Five groups are recognized and are described below.

Glaucnite. Sand and silt-grade grains of glauconite occur throughout most of the British Tertiary marine formations. The glauconite is mostly mixed-layer glauconite-smectite, and the pellets have the appearance of immature to mature pellets in the classification of Odin (1988). K/Ar radiometric ages for glauconite from Whitecliff Bay are mostly older than the depositional age, indicating a substantial detrital component (Clauer et al., 2005). In the London Basin glauconite is particularly abundant in the Ormesby Clay Formation, the Thanet Sand Formation, the Upnor Formation and the Harwich Formation. Many of these glauconite grains may have been formed through alteration of volcanic ash particles close to the sediment-water interface (e.g., Knox, 1979). In the Hampshire Basin, sand and silt grade glauconite grains are particularly common in the Wittering, Earnley and Selsey formations. Many of these grains were faecal pellets that were subsequently glauconitized close to the sediment water interface. Glaucnite has also replaced quartz and feldspar grains, and may have replaced volcanic rock ash, though no direct evidence of this has been observed. Neoformed glauconite grains were also readily reworked into younger sediments. For example, Huggett & Gale (1997) have demonstrated that much of the glauconite in the Barton Clay Formation has been reworked from older Tertiary strata. During recycling glauconite grains were also liable to alteration and replacement. Huggett & Gale (1998) reported the widespread occurrence of coarsely crystalline kaolin (>4 μm) and Fe- oxyhydroxides in the sandstones of the London Clay Formation, and have attributed these minerals to pneocontemporaneous oxidation of glauconite, during sub-aerial emergence and prior to deposition of the overlying mudstone.

Illite-rich palaeosols. Illite-rich clay mineral assemblages are frequently associated with palaeosols in the Reading Formation (Figs 10c, 16), Headon Hill Formation (Figs 16, 20c), and the Bembridge Marls Member of the Boulder Formation (Fig. 16). Examples from the Headon Hill Formation and the Bembridge Marls Member have been investigated in some detail by Huggett et al. (2001). These authors suggest that the illite has formed through the illitization of smectite-rich clays during repeated seasonal wetting and drying of soils in a sub-aerial environment. Illitization may have been driven by iron reduction in the octahedral layer of the smectite, thereby increasing the layer charge and allowing the irreversible fixation of K⁺ in the interlayer sites (Huggett & Cuadros, 2005). In the Solent Group at Whitecliff Bay, illite and smectite abundances vary cyclically. This cyclicity correlates with the curve produced by the interaction of the 400k year and 100k year Milankovitch cycles, implying that the illitization is climatically controlled (Gale et al., 2006). In the Lambeth Group such cyclicity is not apparent, either because seasonal wetting and drying was less frequent or because the succession is much less complete. The illite-rich assemblages in the Bembridge Limestone Formation are not associated with palaeosols; they may have been derived by reworking of illite-rich soils or they may have formed in hypersaline lakes (Huggett et al., 2001; Huggett & Cuadros, 2005).

Kaolin-rich palaeosols. Thin kaolin-rich beds are known from a number of horizons in the Tertiary of southern England, where they are located below lignite beds. One such bed occurs below the lignite bed at the top of the Upnor Formation (e.g. at Swancombe, Kent) and another occurs below a reworked lignite horizon in the Upper Mottled Beds of the Reading Formation (e.g. at Alum Bay, Isle of Wight). Perhaps the best known is the Whitecliff Bay Bed, which is associated with a rooted lignite horizon in the Wittering Formation in the Hampshire Basin. At Whitecliff Bay this bed contains both smectite-rich and kaolin-rich horizons. The kaolin-rich horizons are probably scat earths developed by the leaching of smectitic and illitic clays with organic acids generated within the lignite beds.

Kaolin/mica stacks and kaolin pseudomorphs after mica. These are relatively abundant in the London Clay Formation of the London Basin (Huggett, 1994) but are rarely observed elsewhere. They appear to have formed through the partial...
replacement of mica grains by kaolin during early diagenesis, prior to appreciable compaction.

_Halloysite_. Halloysite has been reported from three localities in the Hampshire Basin. In the Heaton Hill Formation it was detected in one sample where it may have replaced glauconite, a mode of origin associated with weathering in humid or wet environments (Baioumy & Hassan, 2004). Halloysite in the Reading Formation of the Bunker Hill borehole is thought to have formed by in situ subaerial weathering of the underlying volcanogenic clay (Edwards & Freshney, 1987). In the Bembridge Limestone the halloysite reported by Gilkes (1966) may also have formed by sub-aerial weathering, though whether it formed in situ is not known.

_Zeolite-opal-CT-smectite assemblage._ Two examples of this mineral assemblage are known from the U.K. onshore Tertiary sediments. In the lower part of the Ormesby Clay Formation in the Thanet Sand Formation, clinoptilolite-heulandite, opal-CT and a smectite-rich clay mineral assemblage are widespread. The euhedral crystal morphology of these minerals indicates an authigenic origin (Fig. 11a; Weir & Catt, 1969), while their association with ash-bearing sediment implies that they formed by replacement of ash. In the Wittering Formation of Whitecliff Bay, the estuarine sediments immediately underlying the Whitecliff Bay Bed were originally rich in siliceous sponge spicules and now contain authigenic clinoptilolite-heulandite, opal-CT and a smectite rich clay assemblage, with smectite showing an open boxwork texture (Huggett et al., in press). Formation of the zeolite requires silica and alumina plus alkali and alkaline earth metal cations. Bowers & Burns (1990) indicate that the formation of clinoptilolite is favoured by a temperature of ~25°C and SiO₂ activities higher than allowed for by the presence of quartz. The presence of an organic-rich, rooted palaeosol (histosol) immediately overlying the unit is believed to have contributed significantly to the early diagenetic history of the estuarine sediments, in particular the formation of zeolite. Although the pH and dissolved silica of unmodified seawater are too low for zeolite formation, high dissolved silica concentrations are believed to have resulted through dissolution of the abundant siliceous sponge spicules (opal-A) and formation of silica-organic acid complexes. Organic acid dissolution of feldspars (absent from the zeolite-bearing interval), is the most probable source of alumina and cations for zeolite formation. REE data provide no evidence for the former presence of volcanic ash, which is therefore unlikely to have been the source of the zeolite.

_Smectite-rich clay assemblages._ Clay mineral assemblages characterized by smectite and illite with little or no kaolin are widespread in the marine strata of the London and Hampshire Basins, and in the offshore strata. In the predominantly sandy Thanet Sand, Harwich, Virginia Water and Bagshot formations, detailed investigations of the < 2 μm fractions (Gilkes, 1966; Weir & Catt, 1969), shows that smectite occurs as euhedral, thin elongate single crystals, or in aggregates. By contrast, the illite occurs as composite crystals that appear to consist of euhedral lath-shaped overgrowths on a detrital core. These morphologies suggest neoformation of these clay crystals, either by the recrystallization of detrital clays or by direct precipitation from solution. The presence, or supposed former presence, of volcanic ash within the sediment is a potential source of cations for neoformation of clay minerals. However, the situation is complicated by the presence of similar clay mineral assemblages in the Chalk (Weir & Catt, 1965), which is known to have contributed detrital material to the Tertiary sediments of southern England. In the offshore, reworking of smectite from the Lower Paleocene (Danian) Chalk cannot be ruled out (Huggett, 1992). Weir and Catt (1969) considered this to be a relatively minor contribution, whereas Gilkes (1966) suggested that the Chalk might be the major source of smectite in Hampshire Basin. Calculations suggest that an enormous and unrealistic volume of Chalk would need to be dissolved to provide all the smectite in the Tertiary strata of southern England. For example, the volume of Chalk needed for the London Clay Formation alone would be far in excess of the total amount now present in England as a whole.

The nature of the smectite-illite clay assemblage in the London Clay Formation has been investigated by Weir & Catt (1969) and Gilkes (1966). At the base of the London Clay Formation, the smectite displays the lath morphology characteristic of the underlying Harwich Formation and other sandy formations. The lath-like morphology is progressively replaced by aggregates of very small platy particles of smectite with decreasing age of the London Clay Formation. The origin of both
these morphologies warrants further investigation. Clay assemblages consisting almost entirely of smectite occur in the offshore (Pearson, 1990), in the Ormesby Clay Formation (at ~124 m, Ormesby borehole; Fig. 7), in the Reading Formation (Staines borehole, Fig. 9, and Whitecliff Bay, Fig. 16) and in the Harwich Formation (Halesworth borehole, Fig. 9). Whilst smectite-dominated and pure smectite clay assemblages can often be shown to have formed through replacement of ash (e.g. Jeans et al., 1977), it is only in the Harwich Formation (Knox, 1983) and its offshore equivalents (Berstad & Dypvik, 1982; Huggett, 1992) that a clear association between such clay assemblages and volcanic ash has been demonstrated. Petrographic evidence clearly demonstrates that volcanic glass has undergone alteration to smectite (Knox, 1983; Huggett, 1992). The alteration of the volcanic particles appears to have been a diagenetic rather than a halmyrolytic process since particles preserved within early diagenetic calcite concretions (and concretionary layers such as the Harwich Stone Band) show only incipient argillation, while those outside the concretions have undergone total argillation. Further evidence for a volcanogenic origin for smectite in the bulk sediment (i.e. outside identifiable tephra layers) has been acquired in the offshore succession though analysis of U and Th contents (Berstad & Dypvik, 1982, see below). In the London Clay Formation, the occasional presence of aggregates of smectite with a high proportion of face-to-edge contacts (Fig. 11d) is suggestive of in situ alteration of volcanic ash.

Offshore authigenic clay minerals

Detailed accounts of clay mineral authigenesis within offshore Tertiary mudrocks are provided by Malm et al. (1984) for Eocene tuffaceous mudrocks and Huggett (1992) for Paleocene to Pliocene mudrocks of the East Shetland Basin. The textural evidence for the alteration of ash to smectite presented by Huggett (1992), at least partly accounts for the high smectite content of much of the offshore Tertiary. Malm et al. (1984) demonstrated that although smectite is the principal alteration product, chlorite may also have replaced volcanic ash. Berstad & Dypvik (1982) considered it probable that the Fe-rich chlorite in their Unit 1 (dated as Paleocene to Eocene herein) also resulted from the alteration of volcanic ash. They argued that detrital chlorite is unlikely to have survived the tropical weathering conditions that prevailed in early Eocene times. The restriction of the Fe-rich chlorite to the deeper parts of the basin, and alternation of clays rich in chlorite with clays rich in smectite (Fig. 5) are perhaps also suggestive of an authigenic rather than a detrital origin for the chlorite. Electron micrographs (SEM and TEM) of authigenic chlorite from the Paleocene in well 20/10a-4 support this origin (Fig. 22). Huggett (1996) found authigenic chlorite replacing biotite in mudrocks, and authigenic kaolin replacing muscovite, with very rare authigenic illite laths at the base of the investigated Paleocene section (~2300 m). Although the proportion of authigenic illite in this well is small, it is in contrast to the well investigated in the East Shetland basin by

![Fig. 22. Authigenic chlorite in the Late Paleocene Lista Formation of well 22/10a-4, North Sea: (a) field emission SEM image showing euhedral platelets of chlorite with an open boxwork texture (arrow). Scale bar = 1 μm. (b) High-resolution TEM image of a chlorite crystallite showing defect-free 14 Å lattice spacings.](image-url)
Huggett (1992). Here, no trace of illitization of smectite was found in the Tertiary, or in the underlying Cretaceous which was buried to a similar depth (2000–2500 m). This lack of diagenesis is attributed to overpressuring in the East Shetland Basin well.

Despite the importance of Paleocene and Eocene sandstones as hydrocarbon reservoirs in the North Sea and Faroe-Shetland basins, few details of authigenic clays within the sandstones have been published. The principal clay cements are kaolin and chlorite, with only minor illite reported. Authigenic kaolin has been reported from the Upper Paleocene to Lower Eocene Maureen, Andrew and Forties sandstones of the central North Sea, where it occurs as pore-filling aggregates (Wills, 1991, p. 304; Stewart et al., 1994; Huggett, 1996, p. 525; Chandler & Dickinson, 2003a, p. 596, 2003b, p. 607; Gambaro & Currie, 2003, p. 406; Kunka et al., 2003, p. 638–639). In all three formations, authigenic kaolin abundances are too small to have a significant detrimental effect on reservoir quality. Stewart et al. (1994) considered that the kaolin cements in the Andrew sandstones developed as a result of meteoric flushing during a period of low sea level in late Paleocene times. Huggett (1996, p. 534), however, considered that the kaolin in the Forties sandstones developed during early diagenesis through feldspar hydrolysis that resulted from internally derived acidity.

Authigenic chlorite has been reported from the Upper Paleocene Maureen and Lower Eocene Forties sandstones of the central North Sea (Tonkin & Fraser, 1991, p. 241; Wills, 1991, p. 304; Huggett, 1996, p. 525; Chandler & Dickinson, 2003a, p. 596; Kunka et al., 2003, p. 638–639), and also from the Upper Paleocene Vaila Formation of the Faeroe–Shetland Basin (Sullivan et al., 1999, p. 630; Carruth, 2003, p. 128). Authigenic chlorite abundances are too low to have a significant detrimental effect on reservoir quality, and in some instances pore-lining chlorite cements are reported to have preserved porosity by inhibiting quartz cementation (Tonkin & Fraser, 1991, p. 241; Sullivan et al. 1999, p. 630). The pore-lining chlorite cements were considered by Sullivan et al. (1999, p. 630–631) to be of very early diagenetic origin and perhaps to have resulted from the decomposition of tuffaceous material within the sandstones.

Authigenic illite has been reported from the Forties Sandstone, where it appears to occur as overgrowths on detrital clay (Huggett, 1996, p. 526). It is relatively scarce and has minimal effect on reservoir quality.

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