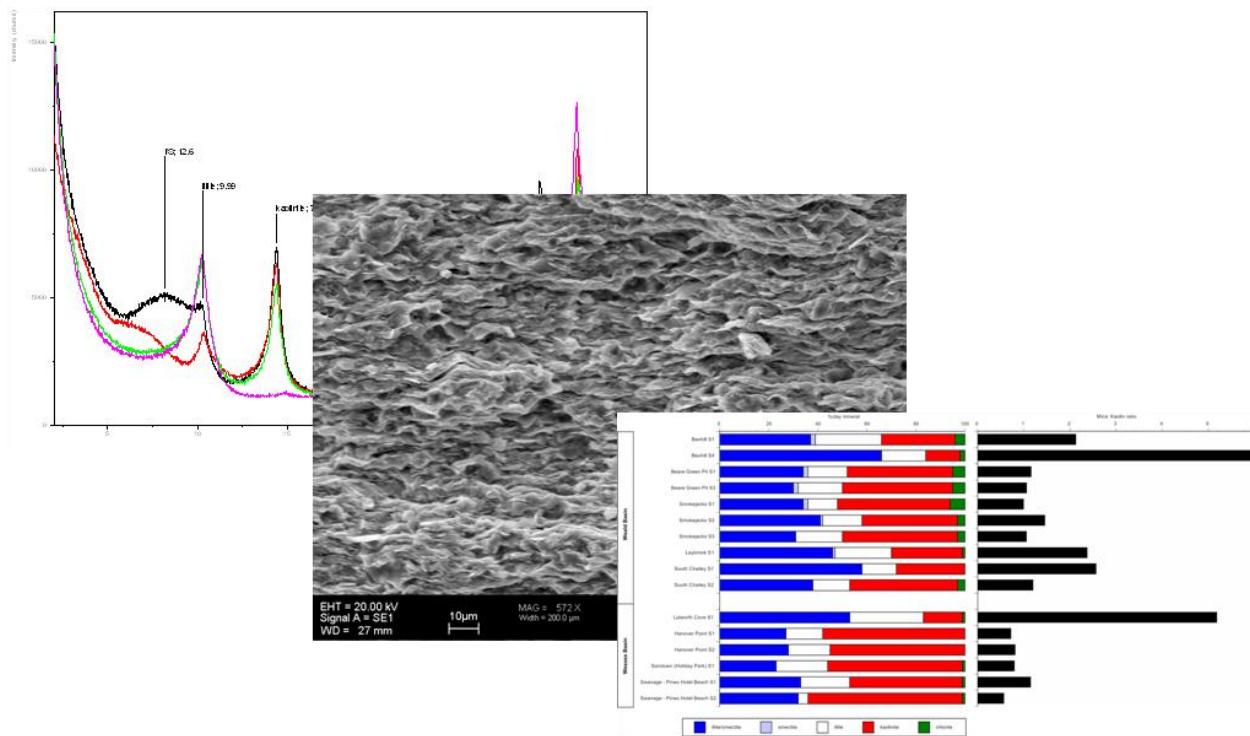




The mineralogy, surface area and geochemistry of samples from the Wealden Group of southern England

Land Use, Planning and Development Programme

Internal Report IR/10/079



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Keywords

mineralogy, Wealden Group, clay minerals, pyrite, illite/smectite, engineering properties.

Front cover

Montage of <2 µm X-ray diffraction traces, SEM photomicrograph (from Bouch, 2007) and clay mineralogy/mica: kaolin ratio bar chart

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Foreword

This report is the published product of a study by the British Geological Survey (BGS). It refers to work carried out as part of the Science Budget project investigating the shrink-swell properties of Wealden Group mudstones in southern England, initially under the Physical Hazards Programme and later the Land Use, Planning and Development Programme. The work provides geochemical, mineralogical and surface area analyses and interpretation for a suite of samples from the Wealden Group.

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Summary

This report describes the results of mineralogical and geochemical analysis of a suite of mudstones from the Wealden Group of southern England. The work was carried out as part of the ongoing ‘Ground Shrinkage Hazards’ project under the Land Use, Planning and Development Programme.

The first part of the report gives an introduction to the geology of the Wealden Group and a summary of previous mineralogical studies of these rocks. A summary of analytical methods employed (X-ray diffraction analysis, X-ray fluorescence spectrometry and surface area determinations) is then provided and the results discussed with reference to their likely effect on the engineering performance of the Wealden Group.

This study has generally confirmed the findings of previous workers with typical non-clay mineral assemblages are typically composed of quartz, ‘mica’, K-feldspar and a range of trace phases. Clay mineral assemblages are generally formed of I/S, illite, kaolinite, chlorite with occasional traces of discrete smectite. Interbedded ironstones are predominantly composed of siderite.

However, the geographic and stratigraphic distribution of the analysed samples from both the Weald and Wessex basins has provided important new information which will aid not only interpretation of the engineering behaviour of these rocks but also their diagenetic and geological histories.

The engineering properties of the Wealden Group are heavily influenced by its clay mineralogy and the proportion of clay minerals present. This study has shown variations in both the composition of the clay mineral assemblages and the proportion of phyllosilicate/clay mineral content of the mudstones across the Wealden Group outcrop.

The Wealden Group in the Wessex Basin contains the most expandable clay mineral (I/S, R_0 40%I) detected in this study but these mudstones are more massive, siltier, quartz-rich and clay mineral-poor resulting in relatively low surface areas. In comparison, the Wealden Group mudstones from the Weald Basin are generally laminated, more clay-rich, contain a less expandable I/S (typically R_0 80%I) and present higher surface areas. The detected clay mineral assemblages are mostly detrital in origin with a minimal diagenetic overprint.

The common presence of pyrite, together with gypsum in the Wealden Group means that concrete engineering sited in these rocks potentially risk acid attack and thaumasite formation.

1 Introduction

This report summarises the results of a mineralogical, geochemical and surface area study of a suite of mudstone samples from the Wealden Group of south and south-east England. This study forms part of the BGS geotechnical project, ‘Ground Shrinkage Hazards’ under the Land Use, Planning and Development Programme.

Since the early 1990’s, the ongoing ‘Engineering Geology of UK Rocks and Soils’ project has examined soils and rocks from different formations and attempted to database, characterise and explain their geotechnical behaviour. Previous studies have included the Gault Clay (Forster *et al.*, 1994), the Mercia Mudstone Group (Hobbs *et al.*, 2001), the Lambeth Group (Entwistle *et al.*, 2005), the Lias Group (Hobbs *et al.*, 2005) and the London Clay Formation (Jones *et al.*, in prep.).

The main aims of the ‘Ground Shrinkage Hazards’ project are to specifically determine the shrinkage and swelling properties of UK clays and mudrocks, and to investigate the relationship between them.

Due to their high surface area, residual charge and interaction with water, clay minerals (and smectite in particular) are most frequently cited as the reason for the shrink-swell behaviour noted in many fine-grained sedimentary rocks. For this reason, this study principally aimed to evaluate the nature of the clay minerals present to help explain the geotechnical behaviour of mudstones from the Wealden Group.

In addition, this study also focussed on detecting the presence of sulphate-bearing species (e.g. pyrite, gypsum etc). Oxidation of pyrite in the environment leads to the formation of sulphuric acid which considerably reduces the pH of groundwater. Where such acidic groundwaters make contact with concrete engineering at low temperatures (e.g. foundations, motorway bridges etc), the main cementitious binder C-S-H is converted to thaumasite (a non-binding calcium carbonate silicate sulphate hydrate) resulting in deterioration and failure (e.g. Hobbs & Taylor, 2000; Bensted, 1999; Burkart, *et al.* 1999). Greater awareness of the potential problems that thaumasite can cause has arisen with the increased use of limestone fillers in cements, the common employment of limestone aggregates in concrete and the introduction of Portland limestone cements, together with the realisation that structural foundations of buildings are, on average, below ambient temperature and are within the optimum temperature range for thaumasite to be formed (Bensted, 1999). A knowledge of the presence of sulphate-bearing species in the Wealden Group is therefore crucial to planning foundation construction in such strata.

2 Geology

The Wealden Group (Lower Cretaceous, Valanginian to Barremian) of southern England consists of a sequence of sands, silts, clays and occasional conglomerates that were deposited in river, lake and brackish coastal plain environments. Palaeosols are locally abundant and have led to distinctive red, purple and orange mottling. Wealden sedimentary rocks contain a distinctive flora and fauna including dinosaur (e.g. *Iguanodon*) footprints and are widespread across north-west Europe (Gale, 2000). The Wealden facies represents a humid, more seasonal climate compared to the preceding arid climate in which the Purbeck Limestone was deposited. This change was perhaps initiated by massif uplift and the development of a drainage pattern dominated by west-east flowing rivers. Sedimentation was terminated by sea-level rise in the Early Aptian.

In southern England, Wealden Group deposits are restricted to the Weald and Wessex basins (Figure 1).

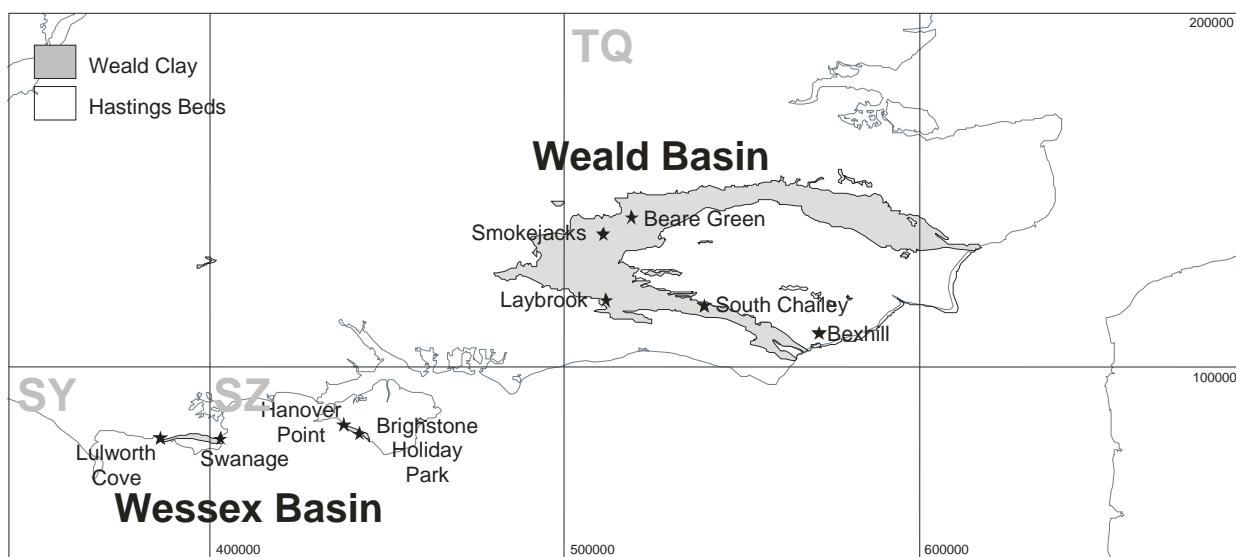


Figure 1. The distribution of the Wealden Group (Weald Clay and Hastings Beds) at surface and the location of the study sites.

2.1 WEALD BASIN

The Wealden of the Weald is sub divided into the lower Hastings Group (c.400 m thickness) and the upper Weald Clay Group (Figure 2). The Hastings Group comprises three sand-clay couplets; the Ashdown Formation, overlain by the Wadhurst Formation and the Tunbridge Wells Formation. The sandier units are mostly outwash fans and sandy braided stream deposits while the clay units represent mud-plains, lakes and lagoons. Towards the north-west there was a connection with the Boreal Sea and towards it, the marine influence increased, illustrated by an increase in brackish species of water mollusc.

The arenaceous formations record the successive advances of alluvial braid plains southwards from the London-Brabant Massive into the Weald. The Ashdown and Lower Tunbridge Wells Sands both display progressive coarsening upwards, reflecting initial meander-plain development followed by a later phase of coarser braid-plain development.

The cycles have been attributed to eustatic sea level changes. Rising base levels during transgression and high stand may have caused the formation of extensive lakes and lagoons. It has not yet been possible to prove that this control was truly eustatic. It is therefore likely that arenaceous units correspond to periods of maximum uplift of source areas and the argillaceous units to times when those areas were most degraded. The highest part of the Wealden; the Weald Clay Group, up to 400 m thick, probably formed at a time when the London-Brabant Massif was at its lowest. It contains a number of marine horizons, which record short lived breaching of the Weald mud-plains by the Boreal Sea (Gale, 2000).

Detailed heavy mineral provenance studies have shown that most of the detritus was derived from the Jurassic and to a lesser extent Palaeozoic rocks of the London Platform to the north. However in the upper part of the Hastings Group, detritus originating from Cornubia spilled over from the Wessex Basin. The general abundance of detritus derived from the west, which includes material from the Iberian Peninsula, points to doming on the continental margin west of the UK during Early Cretaceous times.

The overlying Weald Clay has also been proved cyclic in nature, predominantly comprising grey shale's and mudstones with intervening clastic rich layers representing periods of higher energy.

The Weald Clay mudstones are characteristically bioturbated-laminated clays. There is common cyclicity throughout the clays. The fresh colour of the clays is characteristically a dark-medium green grey, and when weathered this changes to an orange ochre-brown type colour. There are bands of red mudstones associated with sandstone horizons and rootlet beds; diagnostic of periods of uplift to the surface.

The cyclicity and lithology changes outlined above may be attributed to environmental changes. The arenaceous formations, including sand and pebbly units is believed to have been deposited during periods of progradation of alluvial fans. At the time of this deposition the material was travelling from the London-Brabant Massive into the Weald Basin.

2.2 WESSEX BASIN

It is important to note that the Wealden of the Wessex Basin (Isle of Wight, Dorset) has a different sedimentary history to that of the Weald (Figure 2).

The Wessex Formation comprises pedogenically altered, strongly mottled silts and clays which represent muddy floodplain deposits. Subsidiary sandstones, 5-10 m thick, were deposited as point bars within a major east-west river, flowing just south of the fault-bounded north basin margin. The regular vertical distribution of these sands suggests that the river development was controlled by long-term climatic factors. Units of mud, sand, coarse detritus and plant debris represent mudflows following heavy seasonal rainfall. Westwards into Dorset the Wessex Formation thins rapidly and coarse quartz gravels are locally developed, formed as proximal braided fan deposits.

The Vectis Formation, which overlies the Wessex Formation comprises dark silty clays and was deposited in a large standing body of water of varying but generally low salinity. In the eastern Isle of Wight, the Vectis Formation contains Jurassic fossils and clasts derived from the adjacent fault-bounded basin margin. The source of detritus is thought to be Cornubia to the west with a lesser input from Armorica to the south.

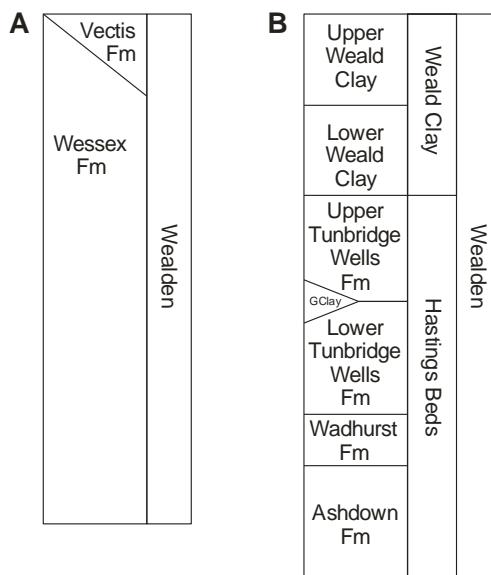


Figure 2. Wealden Group stratigraphy in (A) the Wessex Basin and (B) the Weald Basin.

3 Previous mineralogical studies of the Wealden Group

Tank (1962, 1964) produced the first study of the clay mineral assemblages of the Wealden Group. He found mica- and kaolinite-rich assemblages and suggested that these were probably recycled from older rocks while minor vermiculite was indicative of penecontemporaneous weathering.

More extensive research was carried out by Sladen (1980, 1983 and 1987) who found similar clay mineral assemblages in the English Wealden Group and coeval strata on the continent. He suggested that the variation in assemblages resulted from the changing nature of soils in the Anglo-Brabant source areas and were not affected by burial diagenesis (low burial depth of 1.1 – 1.5 km and low temperatures of 53 – 65 °C) or differential settling. The kaolin- and Al-vermiculite-rich assemblages typical of the sandier units (upper Ashdown Fm., Lower Tunbridge Wells Sand Fm.) were sourced from soils associated with high relief and tectonic uplift that had undergone podsolization in a humid climate. The finer-grained units (Wadhurst Clay Fm., Grinstead Clay member of the Tunbridge Wells Sand Fm.), characterised by a mixed layer smectite-mica assemblage with only minor kaolin, were sourced from less common podsolized soils that had developed on low relief areas during less humid, tectonically quiet periods.

Sladen's climate-controlled model was taken-up and extended by Allen (1998) and Wright *et al.* (2000) added further support for the absence of neoformed clay minerals and modification of detrital clay minerals in the Weald and Wessex basins.

Although considerable variations have been described within the Wealden Group clay mineral assemblages, most authors observe that these are mica-, kaolin- (of varying crystallinity) and collapsible (mixed-layer vermiculite, mica and smectite) mineral-rich. Well-defined smectite is rare and chlorite may be present as trace amounts. Ruffell & Batten (1990) also reported the presence of sepiolite, palygorskite and chlorite/smectite mixed layer minerals from the Wessex Formation (Isle of Wight) but these were not found by subsequent authors.

Most recently and based on an extensive study of 450 new analyses of borehole and cliff exposure samples, Jeans (2006) produced a stratigraphical and regional analysis of the clay mineralogy of the Wealden Group. He noted particularly high levels of kaolinite in the Ashdown Fm. and Tunbridge Wells Sand Fm. in several boreholes but lower levels in the Ashdown Fm.-Grinstead Clay in the Warlingham borehole and more generally in the Wadhurst Clay and its suggested correlatives in the Wessex Fm. at Worbarrow Bay. Berthierine, a kandite-group mineral whose X-ray diffraction (XRD) peaks display a considerable loss of intensity following heating at 400°C, was also identified in kaolin-rich assemblages, particularly in the sandier formations. Mica/kaolin values also appear stratigraphically-controlled. The sandy formations have values between 0.2 and 2.4 while the Wessex Formation of the Isle of Wight, the Weald Clay Fm. and the Vectis Fm. show values of between 1.2 and 3.1.

Jeans (2006) suggests that recent evidence indicates that Sladen's climate-controlled hypothesis is either untenable or requires modification. Cited examples include authigenic kaolinite replacing feldspar in sandstones of the Ashdown Fm and berthierine/kaolin-rich assemblages considered to represent secondary volcanogenic deposits. Grain-size mineralogical variations within the $<2\text{ }\mu\text{m}$ fractions of the Wealden Group may indicate that differential settling during transport could be responsible for some variation. Interpretation of the mica/kaolin ratios suggests three detrital clay sources: (1) the predominant source with ratios of ~1.8-2.2 and high proportions of collapsible minerals, (2) a westerly source with ratios of 0.1-1.2 and (3) a source active during deposition of the Wadhurst Clay with ratios >2.2 and enriched in collapsible minerals. Jeans (2006) concludes that the Wealden Group clay mineral assemblages result from a combination of authigenesis, differential settling and various detrital sources and are not simply the result of climate switching.

4 Samples

During 2006, field visits were made by BGS staff to sample the Wealden Group at nine locations across southern England (Figure 1). The aims of these visits were to collect undisturbed samples for geotechnical tests and disturbed samples for a suite of geotechnical, mineralogical, geochemical and petrographical analyses. The results of petrographical analyses were reported by Bouch (2007).

A total of 16 disturbed, outcrop samples (Figure 1, Table 2) were submitted for mineralogical analysis using X-ray diffraction (XRD), surface area analysis and major and trace element geochemical analysis by X-ray fluorescence spectrometry (XRFS).

Table 1 List of sampling locations and samples studied.

Basin	Formation	Site name	Grid Reference	Sample MPL Code	Original Sample ID	Stratigraphic Position (informal) Comments
Weald	Wadhurst Formation	Bexhill	TQ 71990 09707	MPLM227	S1	<i>Top Blue Clay</i>
			TQ 72029 09678	MPLM230	S4	<i>Lower Blue Clay</i>
	Weald Clay Formation	Beare Green	TQ 19102 42247	MPLM231	S1	-
			TQ 19098 42170	MPLM233	S3	-
		Smokejacks	TQ 11026 37589	MPLM234	S1	<i>Lower Blue Clay</i>
			TQ 11011 37587	MPLM235	S2	<i>Upper Brown Clay</i>
			TQ 11011 37587	MPLM236	S3	<i>Upper Brown Clay</i> Ironstone
		Laybrook	TQ 12245 19104	MPLM238	S1	<i>Lower Mottled Red-Green Clay</i>
		South Chailey	TQ 39300 17592	MPLM240	S1	<i>Lower Mottled Red-Green Clay</i>
			TQ 39290 17571	MPLM241	S2	<i>Lower Grey Clay</i> Near water seep
Wessex	Wessex Formation	Lulworth Cove	SY 86617 80214	MPLM245	S1	-
		Hanover Point	SZ 37822 83783	MPLM246	S1	-
			SZ 37822 83783	MPLM247	S2	-
		Brightstone Holiday Park	SZ 41500 81940	MPLM248	S1	-
		Swanage	SZ 03304 80144	MPLM249	S1	-
			SZ 03304 80144	MPLM250	S2	-

5 Laboratory methods

5.1 GENERAL SAMPLE PREPARATION

Representative portions of each sample were separated, dried at 55°C and jawcrushed. Approximately ¼ of the jawcrushed material was then tem-a-milled for surface area and whole-rock XRD analyses.

5.2 SURFACE AREA DETERMINATION

Surface area determinations were performed on all samples using the 2-ethoxyethanol (ethylene glycol monoethyl ether, EGME) technique (Carter *et al.*, 1965). The method is based on the formation of a monolayer of EGME molecules on the clay surface under vacuum. Aluminium dishes containing approximately 1.1 g tem-a-milled sample/clay standard (Patterson Court Blue bentonite) were placed in a desiccator containing anhydrous phosphorus pentoxide. The desiccator was evacuated and allowed to stand overnight before the dishes were reweighed. The

samples were then saturated with 2-ethoxyethanol and placed in a second desiccator containing dry calcium chloride. After 1½ hours, the desiccator was evacuated and left overnight. The sample was then rapidly re-weighed and the weight of 2-ethoxyethanol absorbed determined and the surface area calculated. Finally, a correction based on the Patterson Court Blue standard was applied.

Smectite has a surface area of c.800 m²/g while other clay minerals and quartz have surface areas typically less than 100 m²/g and 1 m²/g respectively. Such a difference in value means that the surface area of a sample can provide a useful estimate of its smectite content.

5.3 X-RAY DIFFRACTION ANALYSIS

5.3.1 Preparation

In order to achieve a finer and uniform particle-size for whole-rock XRD analysis, approximately 3 g portions of the tem-a-milled material was micronised under acetone for 5 minutes and dried at 55°C. The dried material was then disaggregated in a pestle and mortar and back-loaded into a standard aluminium sample holder for analysis.

Approximately 10 g subsamples of the jawcrushed material was dispersed in distilled water using a reciprocal shaker combined with treatment with ultrasound. The suspension was then sieved on 63 µm and the <63 µm material placed in a measuring cylinder and allowed to stand. In order to prevent flocculation of the clay crystals, 2 ml of 0.1M 'Calgon' (sodium hexametaphosphate) was added to each suspension. After a period dictated by Stokes' Law, a nominal <2 µm fraction was removed and dried at 55°C. 100 mg of the <2 µm material was then re-suspended in a minimum of distilled water and pipetted onto a ceramic tile in a vacuum apparatus to produce an oriented mount. The mounts were Ca-saturated using 2 ml 0.1M CaCl₂.6H₂O solution and washed twice to remove excess reagent.

5.3.2 Analysis

XRD analysis was carried out using a PANalytical X'Pert Pro series diffractometer equipped with a cobalt-target tube, X'Celerator detector and operated at 45kV and 40mA. The whole-rock samples were scanned from 4.5-85°2θ at 2.76°2θ/minute. The diffraction data were then initially analysed using PANalytical X'Pert Pro software coupled to the latest version (2009) of the International Centre for Diffraction Data (ICDD) database.

The <2 µm oriented mounts were scanned from 2-35°2θ at 0.55°2θ/minute after air-drying, ethylene glycol solvation, heating at 400°C for 2 hours and 550°C for 2 hours. Clay mineral species were then identified from their characteristic peak positions and their reaction to the diagnostic testing program.

5.3.3 Whole-rock quantification

Following identification of the mineral species present in the samples, mineral quantification was achieved using the Rietveld refinement technique (e.g. Snyder & Bish, 1989) using PANalytical HighScore Plus software. This method avoids the need to produce synthetic mixtures and involves the least squares fitting of measured to calculated XRD profiles using a crystal structure databank. Errors for the quoted mineral concentrations are typically ±2.5% for concentrations >60 wt%, ±5% for concentrations between 60 and 30 wt%, ±10% for concentrations between 30 and 10 wt%, ±20% for concentrations between 10 and 3 wt% and ±40% for concentrations <3 wt% (Hillier *et al.*, 2001).

5.3.4 XRD-profile modelling

In order to gain further information about the nature of the clay minerals present in the samples, modelling of the XRD profiles was carried out using Newmod-for-Windows™ (Reynolds & Reynolds, 1996) software.

Modelling was also used to assess the relative proportions of clay minerals present in the <2 µm fractions by comparison of sample XRD traces with Newmod-for-Windows™ modelled profiles. The modelling process requires the input of diffractometer, scan parameters and a quartz intensity factor (instrumental conditions), and the selection of different sheet compositions and chemistries. In addition, an estimate of the crystallite size distribution of the species may be determined by comparing peak profiles of calculated diffraction profiles with experimental data. By modelling the individual clay mineral species in this way, *mineral reference intensities* were established and used for quantitative standardization following the method outlined in Moore & Reynolds (1997).

5.4 X-RAY FLUORESCENCE SPECTROMETRY

X-ray fluorescence spectrometry (XRFS) analysis was carried out using both Wavelength Dispersive X-ray fluorescence spectrometers (WD-XRFS) and Energy Dispersive polarised X-ray fluorescence spectrometers (ED-[P]XRFS).

PANalytical Axios Advanced and Philips MagiX-PRO WD-XRF spectrometers fitted with automatic sample changers were used for this study. The spectrometers were fitted with a 60 kV generator and 4 kW rhodium (Super Sharp) end–window X-ray tube. A PANalytical Epsilon5 ED-[P]XRFS spectrometer, with polarised optics, fitted with a 100 kV 600 W Gadolinium side windowed tube and liquid nitrogen cooled germanium detector was also used.

Fused beads for major element analysis were prepared by fusing 0.9 g sample plus 9.0 g flux (66/34 Li₂B₄O₇ and LiBO₂) at 1200°C. Loss on ignition (LOI) was determined on c.1 g sample heated at 1050°C for one hour.

6 Results

The results of whole-rock XRD and surface area analyses are shown in Table 2. <2 µm clay mineral XRD analyses are summarised in Table 3. Major and trace element geochemical analyses are summarised in Tables 4 and 5. Example labelled whole-rock and <2 µm clay mineral XRD traces are shown in the Appendix.

6.1 WHOLE-ROCK MINERALOGY AND SURFACE AREA

Whole-rock XRD analysis indicates that the samples from the Wealden Group are composed of variable amounts of quartz (25-69%) and phyllosilicates/clay minerals (25-74%) together with a variable range of minor-trace phases including K-feldspar, calcite, dolomite, siderite, anatase, rutile, hematite, pyrite, halite and gypsum.

The ironstone sample (Smokejacks S3) is predominantly composed of siderite with minor amounts of phyllosilicates/clay minerals and quartz and traces of gypsum and hematite. A noticeable shift in the position of the siderite XRD peaks when compared with those of standard siderites suggests a non-standard chemistry, perhaps a manganoan- and/or calcian-species.

As shown in Figure 3, it is noticeable that samples from the Weald Basin (excluding the ironstone) contain higher proportions of phyllosilicates/clay minerals (mean c.54%) compared to those from the Wessex Basin (mean c.33%). Additionally, the samples from the Wessex Basin appear more quartz-rich (mean c.63%) than those from the Weald Basin (mean c.43%). Within the Weald Basin, there appears to be no great stratigraphic difference between the mineralogies of the Wadhurst Fm. samples and those from the Weald Clay Fm.

Surface area analyses for the sample suite (Figure 3) indicate a range of values from 73-161 m²/g, which assuming a surface area of 800 m²/g for pure smectite is equivalent to smectite contents of 5–20%. Mean surface area values for the Weald Basin samples (119 m²/g) are slightly higher than those recorded for the Wessex Basin (104 m²/g). The Weald Basin samples Bexhill S4 (161 m²/g), Laybrook S1 (156 m²/g), Beare Green S1 (148 m²/g) and South Chailey S1 (142 m²/g) have the highest values equivalent to c.20% smectite.

6.2 CLAY MINERALOGY

Oriented mount XRD analysis of separated <2 µm fractions indicates that the clay mineral assemblages of the Wealden Group samples are composed of varying proportions of illite/smectite (I/S), smectite, illite, kaolinite and chlorite (Table 3, Figure 4). Typically the clay assemblages are dominated by I/S (mean 38%) and kaolinite (mean 41%) with minor proportions of illite (mean 18%) and traces of chlorite (mean 2%). Traces of discrete smectite were identified in a small number of the samples.

XRD peak positions and Newmod-for-Windows™ modelling indicates that the I/S is *R*0-ordered in all cases but the proportion of illite and smectite interlayers show some variation from 40% illite/60% smectite through to 85% illite/15% smectite (Table 3). It is noticeable that the Wealden Basin samples are characterised by more illitic I/S (75 or 85% illite) compared to the more smectitic I/S of the majority of samples from the Wessex Basin (typically 40 or 50% illite). However, the I/S of the Weald Basin samples shows no apparent stratigraphic difference between the Wadhurst Fm. and the Weald Clay Fm.

Berthierine was tentatively identified in three of the samples (Smokejacks S3, South Chailey S2 and Hanover Point S2) on the basis of its considerable loss of XRD peak intensity following heating at 400°C for 2 hours. Kaolinite remains stable at 400°C. This is most apparent when

examining the 3.52 \AA d_{002} spacing which is resolved to the low angle side of the kaolinite 3.58 \AA d_{002} spacing (See Appendix).

The kaolinite in most of the samples appears to be poorly-ordered with Newmod-modelling suggesting a mean defect-free distance of ~9 layers and a size range of 1 to 45 (7 \AA) layers. However, the kaolinite in the Swanage S2 sample presents particularly broad peaks, suggesting an even greater degree of disorder. Newmod-modelling suggests a mean defect-free distance of only 5 layers and a size range of 1 to 25 (7 \AA) layers for this sample.

Mica: kaolinite ratios derived from their proportions of the clay assemblages (Table 3), where mica concentrations include contributions from both illite and I/S, are shown in Figure 3. These show values of 1.0 - 6.0 (mean 2.0) for the Wealden Basin and values of 0.6 - 5.2 (mean 1.5) for the Wessex Basin.

Traces of discrete smectite were only identified in some of the Weald Basin samples and not in the Wessex Basin samples.

6.3 GEOCHEMISTRY

In general terms the major element geochemistry concurs with the identified mineralogical assemblages.

SiO_2 and Al_2O_3 contents are predominantly controlled by variations in the major mineral components of quartz and phyllosilicate/clay minerals. CaO contents are low except where carbonate minerals are present (Bexhill S4 and Smokejacks S3). MgO contents are also low. The positive correlation of K_2O and Al_2O_3 content provides evidence that most of the K_2O and Al_2O_3 is hosted by 'mica' and to a lesser extent, K-feldspar species. The much smaller Na_2O concentrations are indicative of the presence of traces of halite and probably below XRD-detection amounts of plagioclase (albite) feldspar. TiO_2 is hosted by trace amounts of rutile and anatase.

Fe_2O_{3t} contents for the Wealden Group samples are relatively high for mudstone lithologies (c.2 – c.45%). XRD identified major amounts of siderite in one of the samples (Smokejacks S3) to account for the Fe_2O_{3t} content of this sample. However, minor amounts of siderite together with traces of chlorite, pyrite and hematite identified in the remaining samples would contribute to but not fully account for the measured Fe_2O_{3t} contents. The positive correlation between Fe_2O_{3t} content and 'mica' suggest that much of the iron may be contributed by micas and illitic clay minerals. Alternatively, such a discrepancy is most likely to be explained by the presence of small amounts of X-ray amorphous iron oxyhydroxides in the Wealden Group samples. The detection of small quantities of goethite in four of the separated <2 μm fractions (Table 3, Smokejacks S2, S3, Laybrook S1, South Chailey S1) would appear to provide further evidence for such a possibility.

No significant trace-element geochemical anomalies are apparent from the limited number of samples analysed in this study. In general terms the concentration of all trace elements increase with decreasing SiO_2 content due to a decreasing quartz-dilution effect.

Table 2. Summary of whole-rock X-ray diffraction and surface area analyses of the Wealden Group samples

Basin	Formation	Site name	Grid Reference	Sample MPL Code	quartz	K-feldspar	anatase	rutile	hematite	pyrite	'mica'	smectite	kaolinite	chlorite	Others	Surface area (m ² /g)
Weald	Wadhurst Formation	Bexhill	TQ 71990 09707	MPLM227	61.3	2.6	<0.5	nd	nd	<0.5	25.3	<0.5	7.5	2.7	calcite (6.7), siderite (0.5)	74
			TQ 72029 09678	MPLM230	29.5	7.4	<0.5	nd	nd	<0.5	44.4	nd	9.7	1.6		161
	Weald Clay Formation	Beare Green	TQ 19102 42247	MPLM231	25.1	nd	0.7	0.6	nd	nd	42.0	1.1	27.6	2.9		148
			TQ 19098 42170	MPLM233	35.7	nd	0.6	0.6	nd	<0.5	36.6	<0.5	22.6	3.3		125
		Smokejacks	TQ 11026 37589	MPLM234	53.6	nd	0.7	0.6	nd	<0.5	26.1	<0.5	16.4	2.3	siderite (74.0), gypsum (2.5)	80
			TQ 11011 37587	MPLM235	39.1	nd	1.0	0.6	0.6	nd	33.2	<0.5	21.8	3.4		114
	Laybrook		TQ 12245 19104	MPLM238	38.1	4.0	0.6	nd	<0.5	nd	34.3	<0.5	22.6	nd		156
	South Chailey		TQ 39300 17592	MPLM240	46.6	5.4	0.8	nd	1.2	nd	29.9	nd	16.1	nd		142
			TQ 39290 17571	MPLM241	56.4	nd	0.8	0.9	1.1	nd	27.0	nd	11.5	2.3		73
Wessex	Wessex Formation	Lulworth Cove	SY 86617 80214	MPLM245	55.4	5.4	nd	nd	nd	nd	25.0	nd	8.2	1.3	dolomite (4.2), halite (<0.5)	94
		Hanover Point	SZ 37822 83783	MPLM246	58.5	3.7	0.6	nd	nd	<0.5	26.2	nd	9.8	1.0		137
			SZ 37822 83783	MPLM247	67.8	1.7	0.7	nd	nd	<0.5	20.5	nd	7.7	1.3		107
		Brightstone Holiday Park	SZ 41500 81940	MPLM248	61.4	3.2	<0.5	1.0	nd	<0.5	24.3	nd	8.5	0.9		74
		Swanage	SZ 03304 80144	MPLM249	69.4	3.4	<0.5	nd	nd	<0.5	19.1	nd	6.6	nd	gypsum (1.1)	107
			SZ 03304 80144	MPLM250	59.6	2.1	0.6	nd	nd	nd	20.4	nd	11.0	nd	siderite (6.4)	105

KEY: nd – not detected, 'mica' – undifferentiated mica species including muscovite, illite, illite/smectite

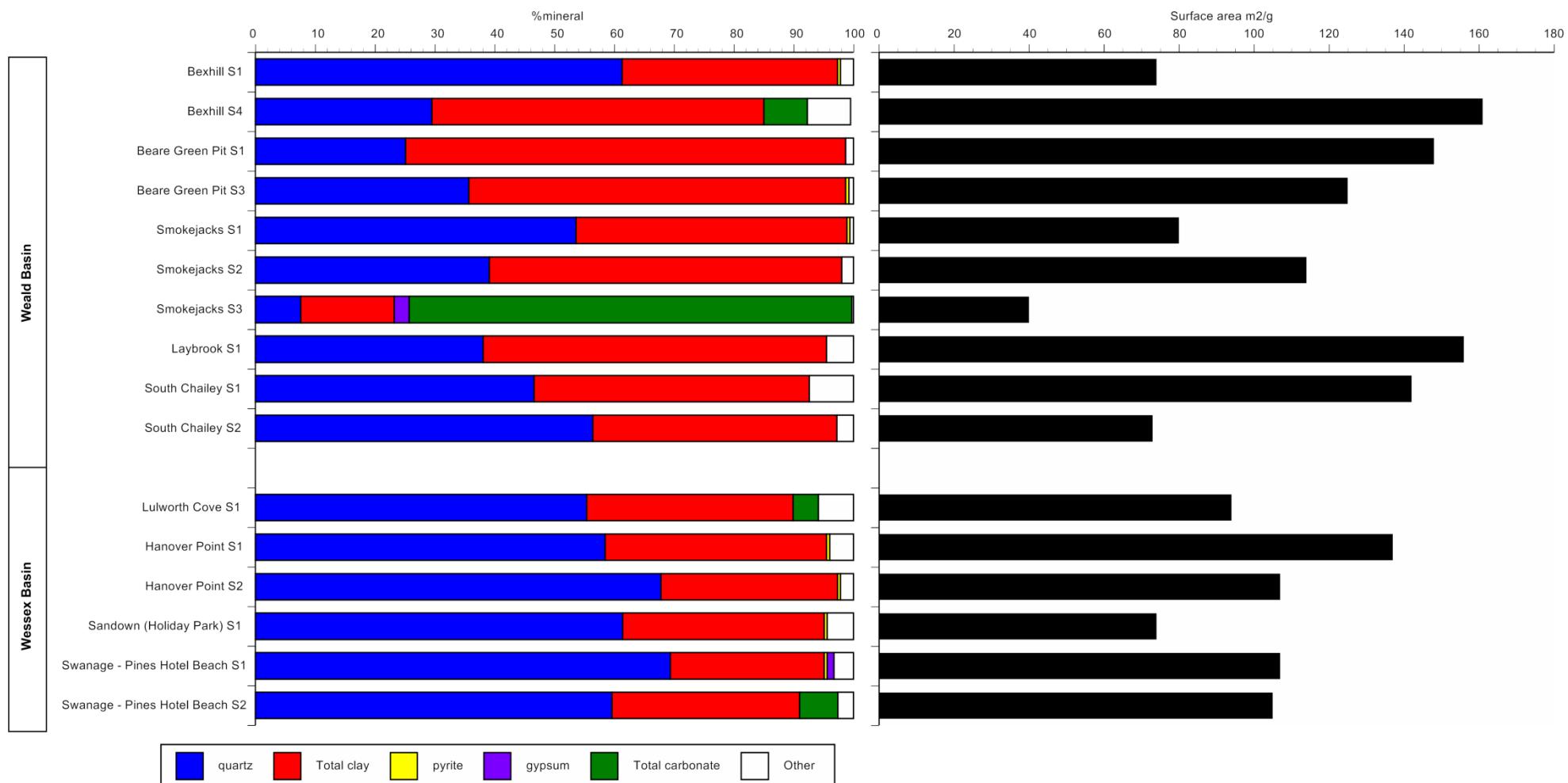


Figure 3. The whole-rock mineralogy and surface area of the Wealden Group samples

Table 3. Summary of <2 µm clay mineral XRD analyses of the Wealden Group samples

Basin	Formation	Site name	Grid Reference	Sample MPL Code	Clay minerals (%)					I/S ordering/ composition	Non-clay minerals
					illite/smectite	smectite	illite	kaolinite	chlorite		
Weald	Wadhurst Formation	Bexhill	TQ 71990 09707	MPLM227	37	2	27	30	5	R0 75%I	quartz, K-feldspar
			TQ 72029 09678	MPLM230	66	0	18	14	2	R0 85%I	quartz, K-feldspar, calcite
	Weald Clay Formation	Beare Green	TQ 19102 42247	MPLM231	34	2	16	43	5	R0 75%I	quartz, K-feldspar
			TQ 19098 42170	MPLM233	30	2	18	45	5	R0 75%I	quartz, K-feldspar
		Smokejacks	TQ 11026 37589	MPLM234	34	2	12	46	6	R0 75%I	quartz, K-feldspar
	South Chailey	Laybrook	TQ 11011 37587	MPLM235	41	1	16	39	3	R0 85%I	quartz, K-feldspar, goethite
			TQ 11011 37587	MPLM236	31	0	19	47*	3	R0 85%I	quartz, K-feldspar, goethite
		South Chailey	TQ 12245 19104	MPLM238	46	1	23	29	1	R0 75%I	quartz, K-feldspar, goethite
			TQ 39300 17592	MPLM240	58	0	14	28	1	R0 75%I	quartz, K-feldspar, goethite
			TQ 39290 17571	MPLM241	38	0	15	44*	3	R0 75%I	quartz, K-feldspar
Wessex	Wessex Formation	Lulworth Cove	SY 86617 80214	MPLM245	53	0	30	16	1	R0 85%I	quartz, K-feldspar
		Hanover Point	SZ 37822 83783	MPLM246	27	0	15	58	0	R0 40%I	quartz, K-feldspar
			SZ 37822 83783	MPLM247	28	0	17	55*	0	R0 40%I	quartz, K-feldspar
		Brightstone Holiday Park	SZ 41500 81940	MPLM248	23	0	21	55	1	R0 40%I	quartz, K-feldspar
		Swanage	SZ 03304 80144	MPLM249	33	0	20	46	1	R0 50%I	quartz, K-feldspar
			SZ 03304 80144	MPLM250	32	0	4	63	1	R0 50%I	quartz, K-feldspar

KEY: *includes berthierine

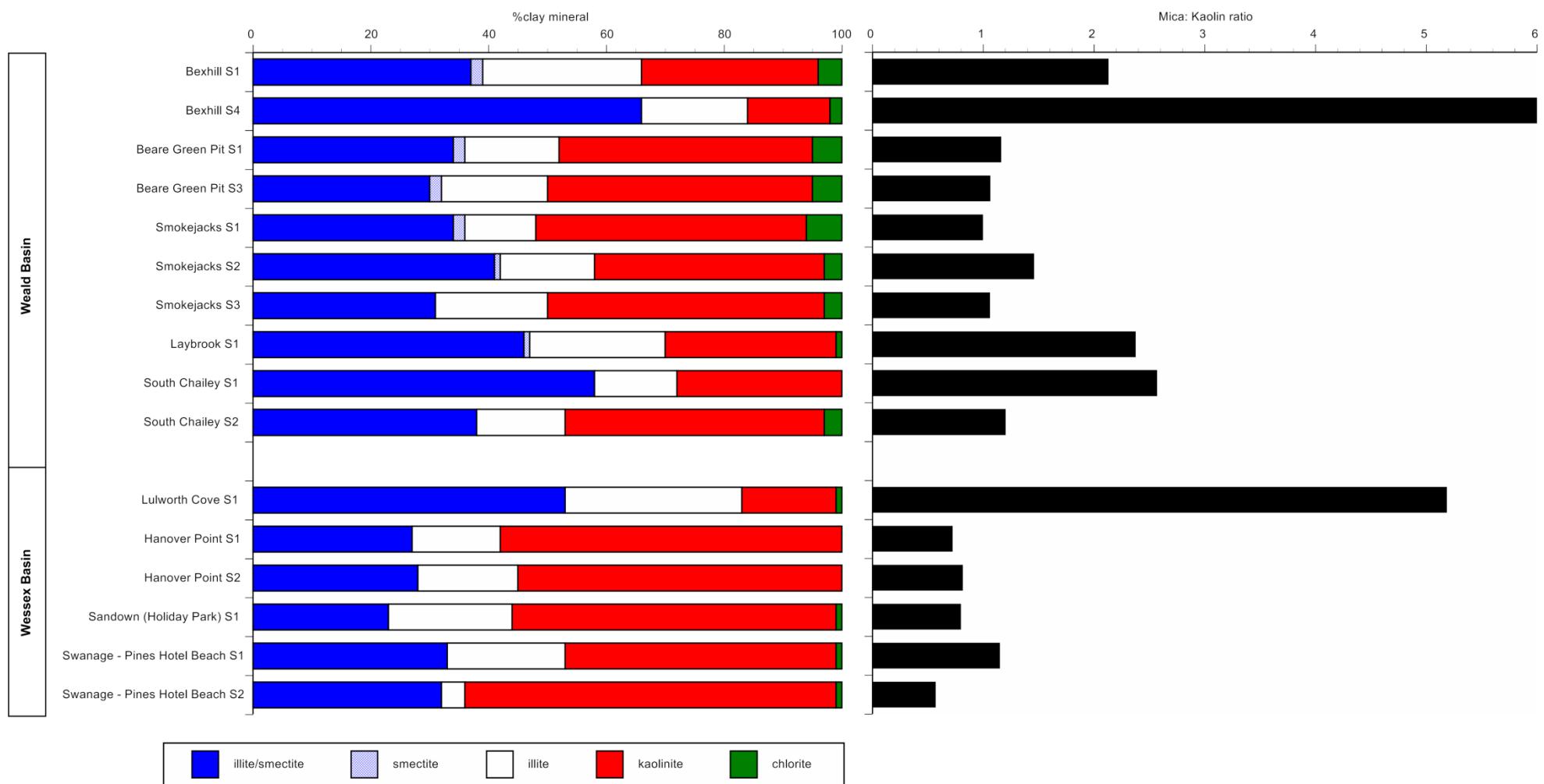


Figure 4. The clay mineralogy of the Wealden Group samples and their mica: kaolinite ratios

Table 4. Summary of the major element (%) geochemistry and loss-on-ignition (LOI) of the Wealden Group samples.

BGS Code	Location	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ t	Mn ₃ O ₄	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃	Cr ₂ O ₃	SrO	ZrO ₂	BaO	NiO	CuO	ZnO	PbO	LOI
MPLM 227	Bexhill	71.70	1.28	13.56	3.76	0.16	0.90	0.53	0.24	2.27	0.19	<0.1	0.02	0.01	0.03	0.05	0.01	<0.01	0.02	<0.01	5.42
MPLM 230		55.22	0.90	18.77	6.69	0.11	1.59	3.92	0.39	3.74	0.22	<0.1	0.02	0.02	0.02	0.05	0.01	<0.01	0.02	<0.01	8.51
MPLM 231	Beare Green	52.30	1.04	25.94	7.65	0.04	1.17	0.40	0.21	2.80	0.08	0.3	0.02	0.01	0.02	0.06	<0.01	<0.01	0.01	<0.01	8.37
MPLM 233		54.91	1.24	22.08	9.11	0.06	1.09	0.34	0.38	2.62	0.10	0.2	0.02	0.02	0.03	0.06	0.01	<0.01	0.02	<0.01	8.54
MPLM 234	Smokejacks	65.96	1.56	17.77	5.49	0.07	0.79	0.27	0.29	2.13	0.12	0.3	0.02	0.01	0.04	0.05	0.01	<0.01	0.01	<0.01	6.01
MPLM 235		57.48	1.16	20.56	8.32	0.38	1.08	0.48	0.23	2.50	0.09	0.2	0.02	0.01	0.03	0.05	<0.01	<0.01	0.01	<0.01	7.25
MPLM 236		11.36	0.24	4.92	44.99	4.61	0.87	5.45	0.06	0.62	1.20	0.2	<0.01	0.01	<0.02	0.03	<0.01	<0.01	<0.01	<0.01	26.24
MPLM 238	Laybrook	59.00	1.05	21.05	7.71	0.02	0.92	0.43	0.30	2.91	0.15	<0.1	0.02	0.02	0.03	0.06	0.01	<0.01	0.03	<0.01	6.33
MPLM 240	South Chailey	62.96	0.91	17.18	7.75	0.02	0.94	1.31	0.41	2.53	0.77	<0.1	0.02	0.02	0.02	0.05	<0.01	<0.01	0.01	<0.01	5.18
MPLM 241		70.12	1.52	15.06	5.23	0.05	0.80	0.19	0.22	2.18	0.06	0.3	0.02	0.01	0.04	0.05	0.01	<0.01	0.01	<0.01	5.08
MPLM 245	Lulworth Cove	68.58	0.99	13.33	3.60	0.09	1.77	1.71	0.21	2.98	0.13	<0.1	0.01	0.01	0.04	0.04	<0.01	<0.01	<0.01	<0.01	5.89
MPLM 246	Hanover Point	70.76	1.35	14.70	3.89	0.02	0.75	0.46	0.18	1.81	0.09	0.2	0.01	<0.01	0.04	0.05	<0.01	<0.01	<0.01	<0.01	5.43
MPLM 247		73.37	1.29	12.36	4.24	0.03	0.70	0.40	0.17	1.64	0.09	0.4	0.01	<0.01	0.05	0.04	<0.01	<0.01	<0.01	<0.01	4.78
MPLM 248	Brightstone Holiday Park	73.56	1.39	13.45	3.73	0.06	0.68	0.30	0.25	1.89	0.08	0.3	0.01	<0.01	0.05	0.04	0.01	<0.01	<0.01	<0.01	4.92
MPLM 249	Swanage	78.52	0.81	11.16	1.81	<0.01	0.52	0.29	0.12	1.48	0.04	0.2	0.01	0.01	0.05	0.04	0.02	<0.01	0.02	<0.01	4.90
MPLM 250		72.07	1.12	12.65	5.65	0.23	0.45	0.81	0.11	0.80	0.21	<0.1	0.02	0.02	0.06	0.03	<0.01	<0.01	<0.01	<0.01	6.24

Table 5. Summary of the trace element (ppm) geochemistry of the Wealden Group samples.

BGS Code	Location	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	La	Ce	Nd	Pb	Th	U
MPLM 227	Bexhill	110	93	20	51	44	136	12	119	86	47	269	25	57	113	50	33	16	5
MPLM 230		140	109	11	49	32	146	8	194	197	37	196	22	52	94	44	32	13	2
MPLM 231	Beare Green	179	141	9	47	38	97	9	181	119	32	170	19	46	79	35	32	16	4
MPLM 233		167	131	18	72	38	128	24	167	112	39	199	22	49	96	42	36	18	5
MPLM 234	Smokejacks	150	112	19	60	37	85	17	129	97	46	293	28	55	97	41	41	19	6
MPLM 235		154	110	17	48	30	115	15	141	126	40	233	22	57	108	45	36	17	5
MPLM 236		69	31	<1	18	7	74	8	39	92	72	42	4	40	129	83	15	<1	4
MPLM 238	Laybrook	149	107	27	57	25	186	17	168	201	37	210	20	51	95	40	35	15	4
MPLM 240	South Chailey	125	93	14	36	15	93	8	153	188	44	267	16	43	87	44	29	12	5
MPLM 241		119	88	22	56	30	110	17	121	88	46	292	28	50	110	44	33	16	6
MPLM 245	Lulworth Cove	108	85	14	37	19	74	2	129	130	40	326	23	44	87	40	21	12	3
MPLM 246	Hanover Point	119	82	15	39	26	71	14	132	92	41	322	26	48	96	41	27	14	5
MPLM 247		106	75	15	38	22	75	17	116	83	42	392	24	50	101	44	25	13	5
MPLM 248	Brightstone Holiday Park	113	89	25	51	29	68	14	108	86	42	368	26	50	97	41	27	15	5
MPLM 249	Swanage	91	73	98	104	21	180	17	92	130	51	347	16	54	119	53	22	10	3
MPLM 250		93	92	3	14	14	38	6	63	157	35	440	23	39	73	34	21	9	5

7 Discussion

Mineralogical analysis of a small suite of Wealden Group mudstone samples from a range of sampling sites across southern England indicates that they have generally similar mineralogies to those described in previous studies (e.g. Tank, 1962, 1964; Perrin, 1971; Sladen, 1980, 1983, 1987; Jeans, 2006; Bouch, 2007). Non-clay mineral assemblages are typically composed of quartz, ‘mica’, K-feldspar and a range of trace phases. Clay mineral assemblages are generally formed of I/S, illite, kaolinite, chlorite with occasional traces of discrete smectite. Interbedded ironstones are predominantly composed of siderite (cf. Bouch, 2007).

Some of the earlier authors identified the presence of minor amounts of vermiculite (e.g. Tank 1962, 1964; Sladen 1980, 1983 and 1987) on the basis of a 14 Å XRD peak that was invariant following glycerolation. However in this study, without the benefit of glycerolation, the 14 Å XRD is interpreted as resulting from the presence of minor amounts of chlorite and not vermiculite.

Similarly as corroborated by other authors, no evidence was found in this study for the more exotic sepiolite, palygorskite and chlorite/smectite clay mineral assemblages described by Ruffell & Batten (1990) from the Wessex Formation (Isle of Wight).

Previous studies of the clay mineralogy of the Weald Group have been based on the interpretation of XRD traces following a diagnostic testing program – typically running samples following air-drying, glycol- or glycerol-solvation and heating. While this approach is essential to establishing an idea of which clay mineral species are present, it is incapable of distinguishing the precise nature of mixed-layer clays where these are present in complex mixtures. This is one of the principal reasons that Jeans (2006) groups smectite, vermiculite, mixed-layer minerals and poorly-defined minerals together as ‘collapsible minerals’. However in this study, the more sophisticated Newmod-modelling-approach employed has shown subtle differences in the complex 15 – 10 Å region and particularly in the nature of the I/S present (see below).

Mineralogical analyses in this study also suggest that pyrite is commonly developed throughout the Wealden Group, but typically forms <0.5% rock. Pyrite has also been described in the Wealden Group by several previous workers (e.g. Radley, 1994; Martill & Unwin, 1997; Robinson & Hesselbo, 2004). Gypsum is also sporadically developed but can form up to 3% rock. Its presence may indicate development as an insitu weathering product of pyrite or may have formed post sampling. Bouch (2007) shows that pyrite occurs as strings of framboids, possibly replacing organic matter in the Wealden Group. Concrete engineering sited in the Wealden Group mudstones therefore potentially run a risk of acid attack and thaumasite formation.

7.1 BASIN-COMPARISON

Mineralogical and geochemical analysis indicates that samples from the Weald Basin have higher proportions of phyllosilicates/clay minerals (mean c.54%) compared to those from the Wessex Basin (mean c.33%) reflecting their different sedimentary histories. Additionally, the samples from the Wessex Basin appear more quartz-rich (mean c.63%) than those from the Weald Basin (mean c.43%). Differences in the nature of the mudstones between the Weald and Wessex basins were also suggested by Bouch (2007). He noted that the Wessex Formation samples were notably siltier, typically coarser-grained and possessed more massive fabrics than the mudstones from the Weald Basin.

The I/S species identified in the Wealden Group samples are generally similar within each sampling site and vary in character from the illitic (e.g. Smokejacks ~85%I) to more smectitic species (e.g. Hannover Point 40%I). Importantly the I/S in the Wessex Basin samples (mean 50%I) appears to be more smectitic than the Wealden Basin samples (mean 80%I). In terms of

engineering behaviour potential, the greater the smectite content of the I/S, the greater the potential for shrink swell. However, this simplistic suggestion is complicated by the fact that the samples from the Weald Basin contain greater quantities of I/S in their <2 µm clay assemblages (mean 42% I/S) compared to samples from the Wessex Basin (mean 33% I/S). This is also the case in terms of their relative phyllosilicate/clay whole-rock contents.

Newmod-for-Windows modelling suggests that all the clay minerals present in the Wealden Group have small mean defect-free distances, typically <10 units thick. Such small crystallite sizes indicate that all clay species will provide an input to the surface area of the rock, not just the I/S component. This, together with the relative phyllosilicate/clay whole-rock contents, explains why the surface area values for the Wealden Basin (mean 119 m²/g) are larger than those from the Wessex Basin (mean 104 m²/g) despite the more smectitic nature of the I/S in the Wessex Basin. It will therefore be interesting to determine whether the quantity of clay minerals present or the nature of the swelling clay mineral has a greater effect on the engineering properties of the Wealden Group.

Bouch (2007) also draws attention to the fact that the Wealden Group mudstones show some basin-dependant variability in their fabrics which vary from highly-laminated to massive. For the most part, mudstones from the Weald Basin exhibit mm-scale grain size lamination (e.g. see cover photomicrograph), with variable relative proportions and thicknesses of clay-rich/silt-poor and clay-poor/silt-rich layers. More massive fabric were only observed in the “Lower Mottled Red-Green Clay” at Laybrook and South Chailey. The Wessex Basin mudstones tend to be characterised by similarly massive fabrics.

Spot chemical analysis (SEM-EDXA) of the clay matrix of both Weald and Wessex basin samples produced an ambiguous K-Fe-Al-Si composition, suggestive of illite but with Al: Si ratios suggestive of kaolinite (Bouch, 2007). Such a chemical composition would concur with the mixed clay assemblage (I/S, illite, kaolinite, chlorite) identified by XRD in this study.

Kaolinite forms a greater proportion of the clay mineral assemblage in the Wessex Basin (mean 49%) compared to the Weald Basin (mean 37% clay assemblage) although kaolinite crystallinity appears to be similarly poorly-ordered in both basins with an exception of the very poorly-ordered material present in the sample Swanage S2. Mica: kaolin ratios (1.0 - 6.0, mean 2.0, Wealden Basin and 0.6 - 5.2, mean 1.5, Wessex Basin) fall within previously published ranges (Jeans, 2006).

The identification of berthierine in samples from both the Weald (Smokejacks S3 and South Chailey S2) and Wessex (Hanover Point S2) basins is interesting. Berthierine was identified where kaolin-group minerals appear to form a greater proportion of the clay assemblage and where non-clay minerals form a greater part of the whole-rock mineralogy. This may reflect the localised, authigenic development of berthierine in these sedimentary rocks, perhaps representing secondary volcanogenic deposits as suggested by Jeans (2006). Alternatively, this may simply relate to the easier detection of berthierine in such conditions.

7.2 ORIGIN OF THE CLAY MINERAL ASSEMBLAGES

In order to more fully understand the nature and distribution of the clay mineral assemblages of the Wealden Group, and their engineering behaviour, it is necessary to consider their origins.

Differences in the nature of the identified I/S species may represent differences in the burial histories of the Wealden Group across southern England. During burial of sedimentary sequences, the clay minerals contained in mudstones and shales undergo diagenetic reactions in response to increasing depth and temperature. Quantitatively, the most important change is the progressive reaction of smectite to form illite via a series of intermediate I/S mixed-layer minerals. In general, progressive changes are irreversible so that where basinal sequences have been inverted clay mineral evidence of the maximum burial depth is retained and can be used to estimate the amount of uplift. According to the Basin Maturity Chart of Merriman & Kemp

(1996), the presence of I/S (mean 80%I) in the rocks from the Weald Basin suggests burial depths of perhaps 4 km, assuming a 'normal' geothermal gradient of 25-30°C/km. The I/S (mean 50% illite) in the samples from the Wessex Basin suggests shallower burial to perhaps <2 km. However, petrographic studies suggest that the Wealden Group has experienced only relatively light diagenetic overprints (e.g. Bouch, 2007) and that the clay mineral assemblages are largely detrital in nature. Such findings are in agreement with Sladen (1983) who suggested low burial depths (<1.5 km) and low temperatures of (<65 °C).

Further evidence for a general detrital origin for the clay mineral assemblages of the Wealden Group is suggested by mica: kaolin ratios (1.0 - 6.0, mean 2.0, Wealden Basin and 0.6 - 5.2, mean 1.5, Wessex Basin). These values fall within previously published ranges which Jeans (2006) ascribes to three different sources: (1) the predominant source with ratios of ~1.8-2.2 and high proportions of collapsible minerals, (2) a westerly source with ratios of 0.1-1.2 and (3) a source active during deposition of the Wadhurst Clay with ratios >2.2 and enriched in collapsible minerals.

In this study, evidence for limited diagenesis is only provided by the presence of berthierine, which is very prone to oxidation if reworked.

This study therefore reinforces the arguments proposed by Jeans (2006) that the Wealden Group clay mineral assemblages result from a combination of authigenesis, differential settling and various detrital sources and are not simply the result of climate switching.

8 Conclusions

This mineralogical, geochemical and surface area study of a suite of samples from the Wealden Group of southern England has generally confirmed the findings of previous workers. Non-clay mineral assemblages are typically composed of quartz, 'mica', K-feldspar and a range of trace phases. Clay mineral assemblages are generally formed of I/S, illite, kaolinite, chlorite with occasional traces of discrete smectite. Interbedded ironstones are predominantly composed of siderite.

Although limited to a relatively small sample suite, the geographic and stratigraphic distribution of the analysed samples from both the Weald and Wessex basins has provided important new information which will aid not only interpretation of the engineering behaviour of these rocks but also their diagenetic and geological histories.

The engineering properties of the Wealden Group will be heavily influenced by its clay mineralogy and the proportion of clay minerals present. This study has shown variations in both the composition of the clay mineral assemblages and the proportion of phyllosilicate/clay mineral content of the mudstones across the Wealden Group outcrop. The use of advanced modelling techniques has also provided more detailed speciation of potential swelling clay minerals than have previously been published.

The Wealden Group in the Wessex Basin contains the most expandable clay mineral (I/S, R_0 40%I) detected in this study but these mudstones are more massive, siltier, quartz-rich and clay mineral-poor resulting in relatively low surface areas. In comparison, the Wealden Group mudstones from the Weald Basin are generally laminated, more clay-rich, contain a less expandable I/S (typically R_0 80%I) and present higher surface areas. It will therefore be interesting to relate these mineralogical characteristics with measured engineering parameters when these are completed.

It would appear most likely that the detected clay mineral assemblages are mostly detrital in origin with a minimal diagenetic overprint.

The common presence of pyrite, together with gypsum in the Wealden Group means that concrete engineering sited in these rocks potentially risk acid attack and thaumasite formation.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: <http://geolib.bgs.ac.uk>.

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Appendix 1 Example X-ray diffraction traces:

KEY

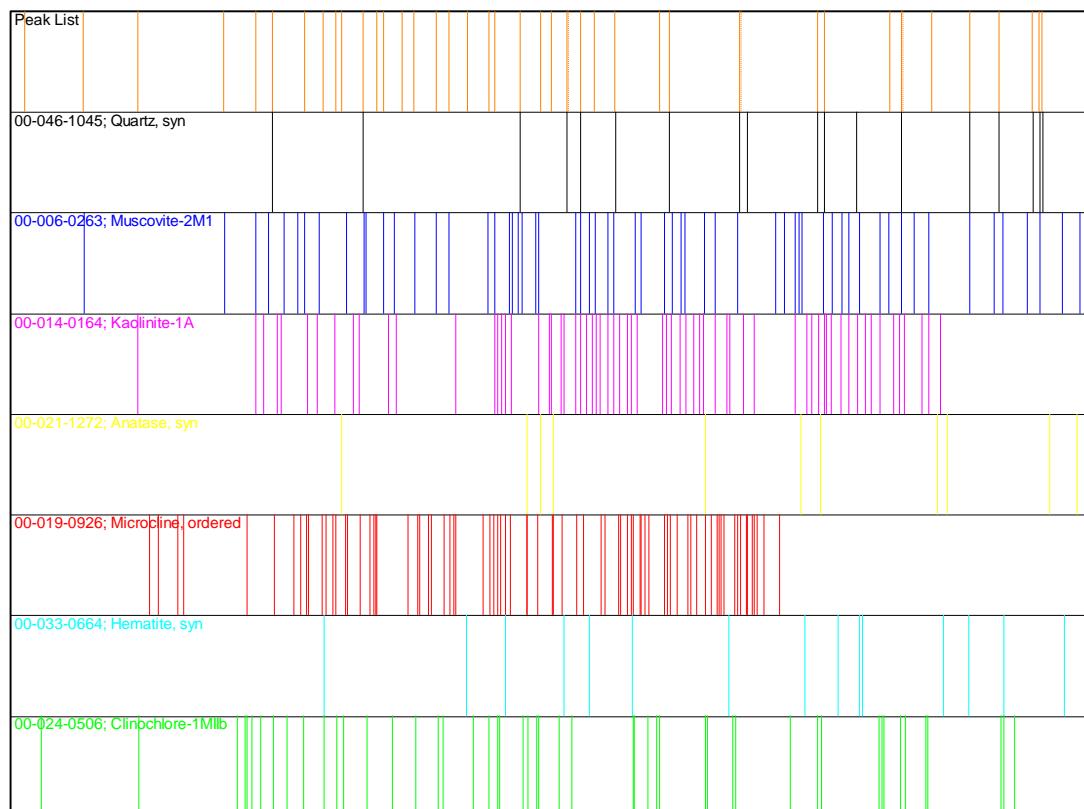
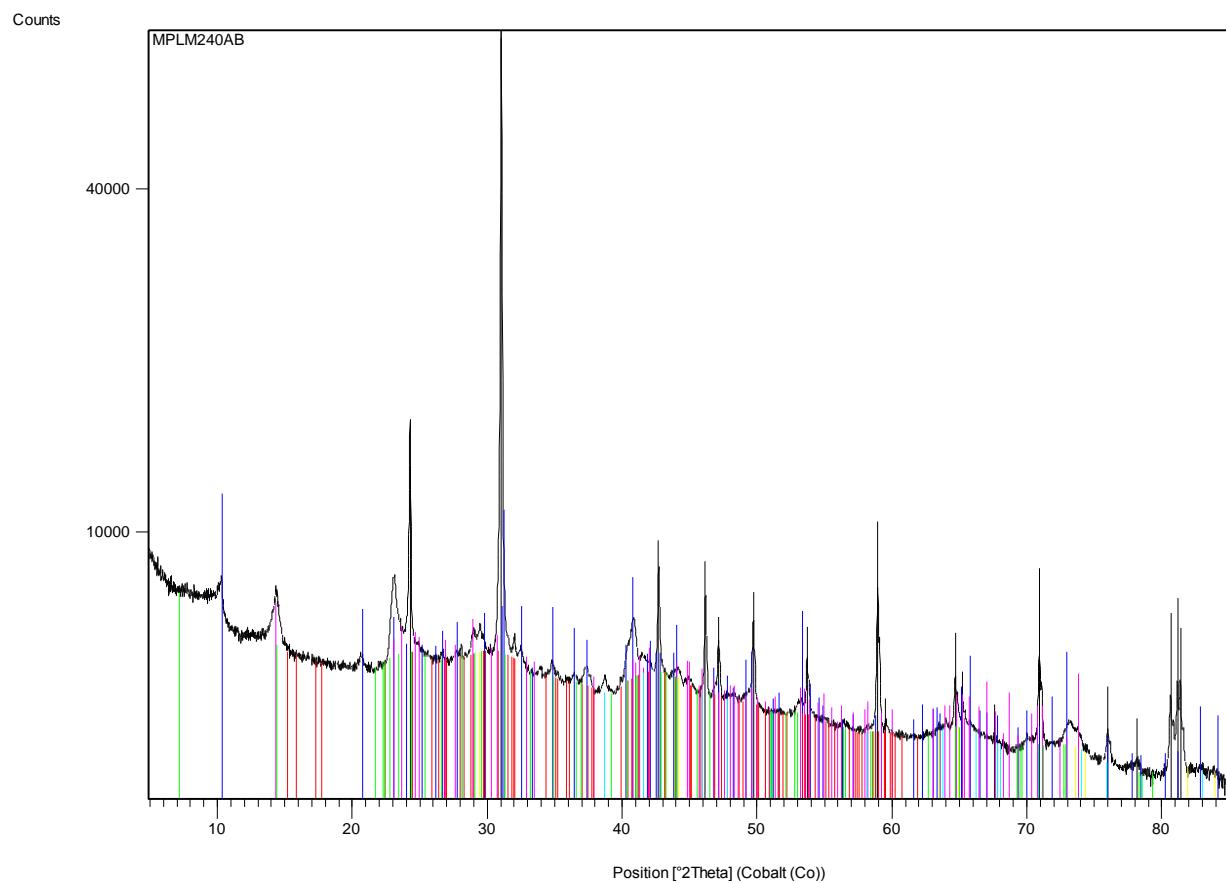
Vertical axis – Intensity (counts per second)

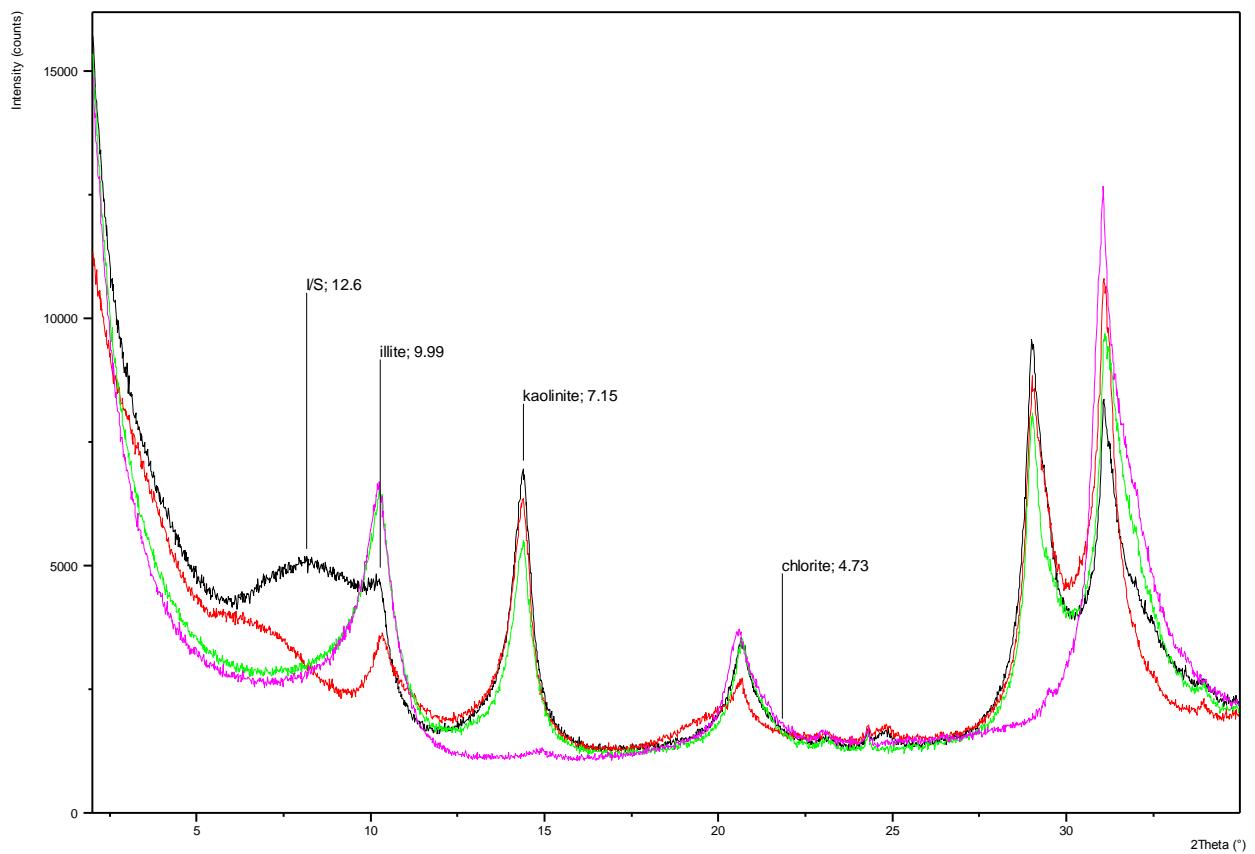
Horizontal axis - $^{\circ}2\theta$ Co-K α

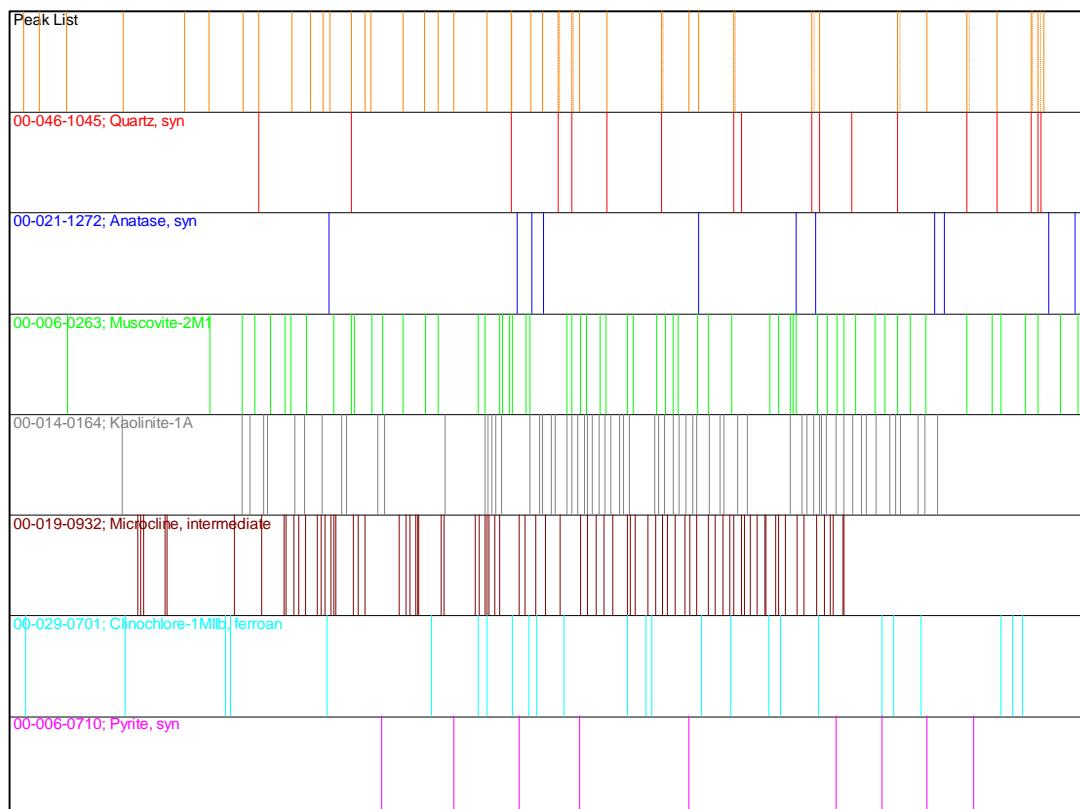
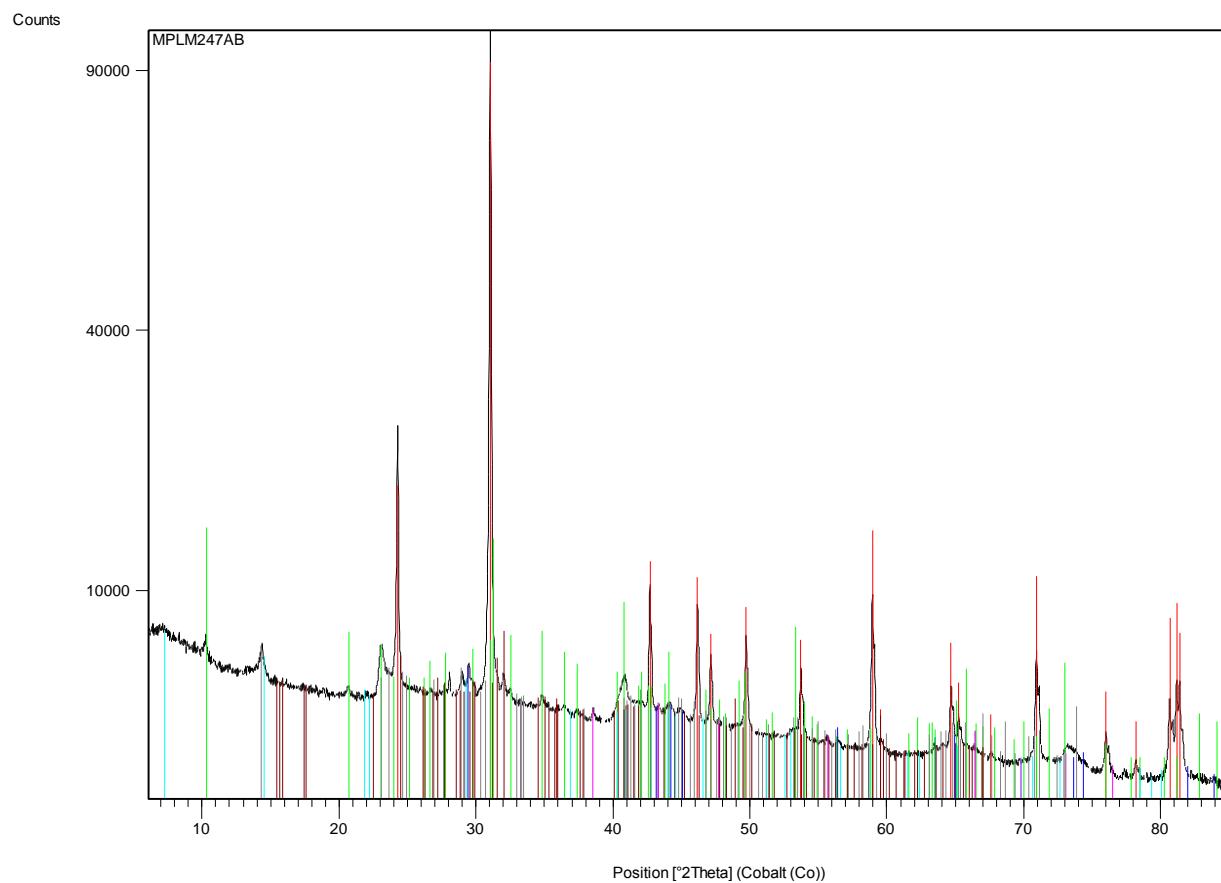
For the whole-rock samples, the upper figure shows the sample diffraction trace. The lower figure shows stick pattern data for the extracted sample peaks (orange) and the identified mineral standard data.

For the $<2 \mu\text{m}$ samples. Black trace (air-dry), red trace (glycol-solvated), green trace (heated $400^{\circ}\text{C}/2$ hours) and magenta trace (heated $550^{\circ}\text{C}/2$ hours). Only the most diagnostic peak of each identified clay mineral is labelled.

South Chailey S1, Wealden Clay Fm., Weald Basin



South Chailey S1, Wealden Clay Fm., Weald Basin

Hanover Point S2, Wessex Fm., Wessex Basin

Hanover Point S2, Wessex Fm., Wessex Basin