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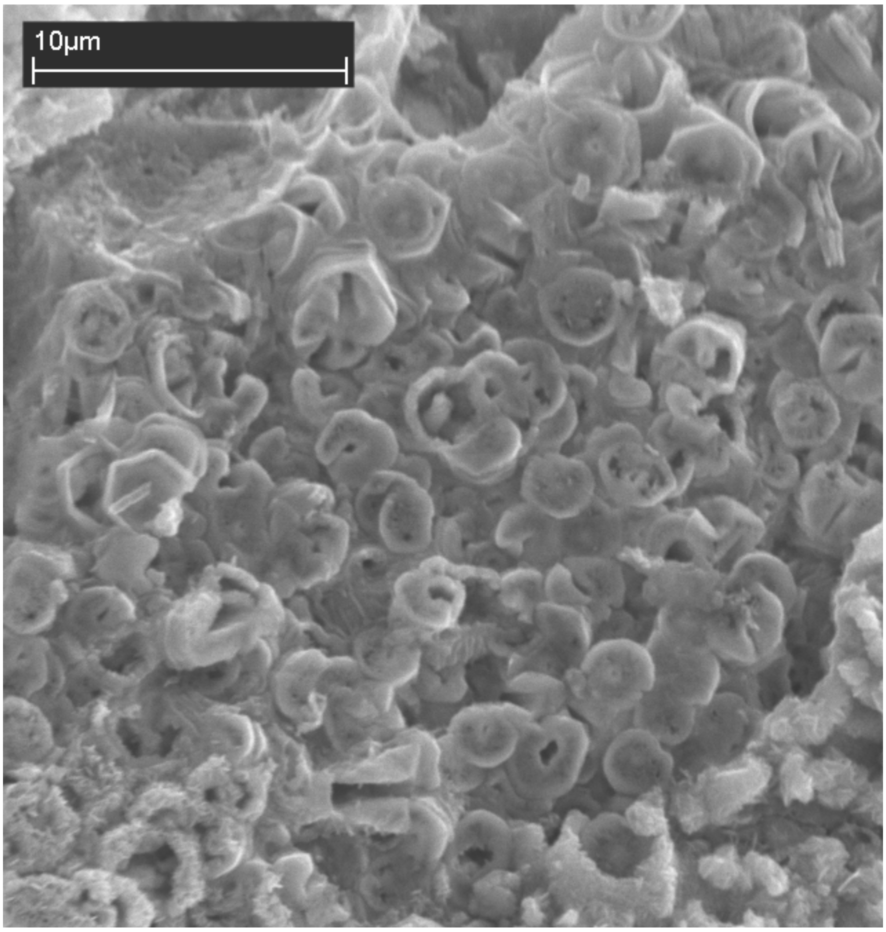
# SEM petrography of samples of the Lias Group of England and Wales

Urban Geoscience and Geological Hazards Programme

Internal Report IR/03/008



BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/03/008

# SEM petrography of samples of the Lias Group of England and Wales

J E Bouch



*Key words*

Lias Group, Mudrock, Petrography, Scanning Electron Microscopy, Clay..

*Front cover*

Scanning electron photomicrograph showing hexagonal chlorite grain coating. Marlstone Rock Formation, East Midlands Shelf.

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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 Lias Group mudstones in England and Wales, under the Urban Geoscience and Geological Hazards Programme. The work provides petrographical descriptions (based on scanning electron microscope observations) of material derived from several formations within the Lias Group from the main depositional basins across England and Wales that were active during Lower Lias times.

# Acknowledgements

This work has benefited from advice received from various members of the Shrink/Swell project team and the related Lias Weathering project. Gren Turner is thanked in particular for preparing the SEM stubs from occasionally difficult materials.

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**FIGURE**



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# Summary

This report summarises work undertaken in support of the Ground Movements: Shrink/Swell Project. It provides petrographical descriptions acquired using scanning electron microscopy (SEM) of a suite of samples (predominantly mudrocks) from the main Lias Group depositional basins across England and Wales. The main Formations sampled are the Scunthorpe Mudstone (n = 5), the Blue Lias (n = 8), the Charmouth Mudstone (n = 21 including 15 samples from weathering profiles), the Marlstone Rock (n = 4), and the Whitby Mudstone (n = 5). Small numbers of samples from the other Lias Formations are also described. The analyses largely confirm the observations made by earlier workers, and are broadly consistent with the results of XRD analyses.

The **Scunthorpe Mudstone Formation** samples are typically laminated with mineralogies probably dominated by illite and/or smectite (although XRD analysis would be required to confirm this). Very finely crystalline gypsum/anhydrite occurs throughout. A sample from the Barnstone Limestone Member is typical, dominated by fine grained calcite, with minor dolomite and clay. A sample from the Frodingham Ironstone Member is also typical being a goethitic oolitic ironstone.

The **Blue Lias Formation** samples are typically massive, hard, dense, highly calcareous mudrocks. Some less calcareous samples preserve lamination, and minor framboidal and euhedral pyrite is present. SEM analysis confirms that variations in surface area (Appendix Table 1.1) broadly correspond to variations in the relative proportions of carbonate and clay, with variations matching a regional trend in calcite content reported by Kemp and M$^{c}$Kervey (2001). Clay mineral assemblages in the two southernmost samples from this formation contain major illite, with minor kaolinite, chlorite and illite/smectite, whereas in the samples from further north, illite tends to be less dominant of the clay mineral assemblage and smectite and/or illite-smectite become more significant, suggesting either a difference in the primary makeup of the sediment, or that the smectite to illite transformation is more advanced in the most southernmost samples.

The **Charmouth Mudstone Formation** is characterised by well-laminated mudrocks with only minor amounts of silt and sand-grade material. EDXA analysis suggests a predominance of K-bearing (illitic) clays, although XRD indicates that the clay mineral assemblages comprise major kaolinite, with minor illite, chlorite and possible illite-smectite, with minor smectite also present in the samples from the Worcester basin. Samples of this formation from the Dorset Coast contain well-developed calcite veining, with cone-in-cone (beef) fabrics present. Gypsum/anhydrite is locally developed along lamination surfaces and early framboidal pyrite is present. The samples from weathering profiles at Dimmer and Blockley reveal development of locally abundant gypsum/anhydrite, nodularisation, rootleting and oxidation towards the surface as seen in hand specimen, but these features are poorly defined on the scale of SEM stubs. No appreciable, systematic differences clay mineralogy is noted through the weathering profiles.

The **Marlstone Rock Formation** is peloidal/ooidal with thick coatings of probable chloritic or glauconitic clay on well-rounded grains in a fine clay matrix. Cone-in-cone calcite cement is locally present.

The **Whitby Mudstone Formation** is confirmed as a typically well-laminated mudrock with minor silty material. EDXA suggests a predominance of illite and/or illite-smectite (K and K-Ca-bearing) compositions, consistent with earlier, quantitative, XRD data on samples from the Cleveland Basin by Kemp and M$^{c}$Kervey (2001) which indicates that the smectite to illite transformation is well advanced. Qualitative XRD on these samples indicates major kaolinite with minor illite, illite-smectite and chlorite.

# 1 Introduction

This report provides petrographical descriptions of a suite of samples (predominantly mudrocks) from the Lias Group, across England and Wales, undertaken as part of the Science Budget funded, Ground Movements: Shrink/Swell Project under the Urban Geoscience and Geological Hazards Programme. The Shrink/Swell project aims to determine the shrinkage and swelling properties of UK clays and mudrocks, with earlier work covering the Gault Clay Formation, the Mercia Mudstone Formation and the Lambeth Group. A number of samples from profiles through weathered Lias Group deposits collected as part of the Weathering Project (also under the Urban Geoscience and Geological Hazards Programme) are also reported here.

## 1.1 LIAS GROUP - GEOLOGICAL BACKGROUND

The Lias Group of the UK comprises predominantly argillaceous sediments of latest Triassic, and early Jurassic age (180 – 205 Ma), which dip gently to the east or south-east, and principally occur in outcrop from the coast of Dorset, through the Midlands, and up to Yorkshire and Cleveland (Figure 1; Cox et. al. 1999). The deposits were laid down when the region that is now the UK probably lay at latitudes of equivalent to the modern day Mediterranean, and represent shallow marine, intercalated mudstones, shales and muddy limestones, deposited in an extensive epicontinental sea during the major world-wide transgression that marked the end of the Triassic (Anderton *et al.* 1979). The deposits form thick sequences (up to approximately 1300 m; Cox *et al.* 1999) deposited in four main basins; the Cleveland Basin, the East Midlands Shelf, the Worcester Basin and the Wessex Basin (Figure 1), separated by structural highs at Market Weighton, Moreton-in-the-Marsh and the Mendips. The East Midlands Shelf is subdivided into north (Leicester to Market Weighton) and south (Moreton in Marsh to Leicester) areas. The stratigraphic subdivisions within each of the basins, as standardised by Cox *et al.* (1999) are given in Table 1.

The older Formations within the Lias Group are predominantly mudstones/limestones (Redcar Mudstone, Scunthorpe Mudstone, Blue Lias and Charmouth Mudstone Formations), which are overlain by sandy shales, limestones and ironstones (Cleveland Ironstone, Dyrham, Marlstone Rock, and Beacon Limestone Formations), followed by the mud-dominated Whitby Mudstone Formation in the northern basins, and the sand/silt-dominated Bridport Sand Formation to the south. Descriptions of the lithologies of each of the Lias Group's component formations are given by Cox *et al.* (1999).

## 1.2 LIAS GROUP - MINERALOGY AND PETROGRAPHY

Whilst there are several studies of the stratigraphy, sedimentology and facies within Lias Group mudrocks in the literature, relatively little information about the mineralogical and petrographical character of these deposits is available. The following sections attempt to summarise previous work on the clay/mudstone-dominated formations, where appropriate in decreasing age order, from north to south.

Using XRD analysis of Lias Group mudrocks from across the UK (including material from some sites that were also sampled as part of this study), Kemp and M^c^Kervey (2001) demonstrated that the Lias Group is notably more calcareous in Southern England (West Midlands, Worcester and Wessex Basins) than in Northern England (Cleveland Basin and East Midlands Shelf). Furthermore, whilst the Lias Group invariably has a relatively complex clay-mineral assemblage of illite, smectite, kaolinite and chlorite, in Southern England discrete smectite occurs, whereas in Northern England the burial-controlled transformation of smectite to illite is more advanced, with the development of interlayered illite-smectite (80-90% illite). This difference suggests that the basins in Northern England have been subjected to greater burial depths/temperatures (burial to approximately 3-4 km) than those in Southern England (burial to approximately 1.5-2 km). As a consequence of this variation in clay mineralogy, the shrink/swell capacities of Lias Group mudrocks are likely to be higher in Southern England than in Northern England (Kemp and McKervey 2001).

In a survey of the geotechnical properties of Lower Lias mudrocks in the Scunthorpe area, Bell (1995) indicated that the deposits have low compressibilities, suggesting overconsolidation, and that plasticity, moisture content and porosity all decrease, and consequently that shear strength increases with depth. Calcium carbonate content was identified as a further control on shear strength.

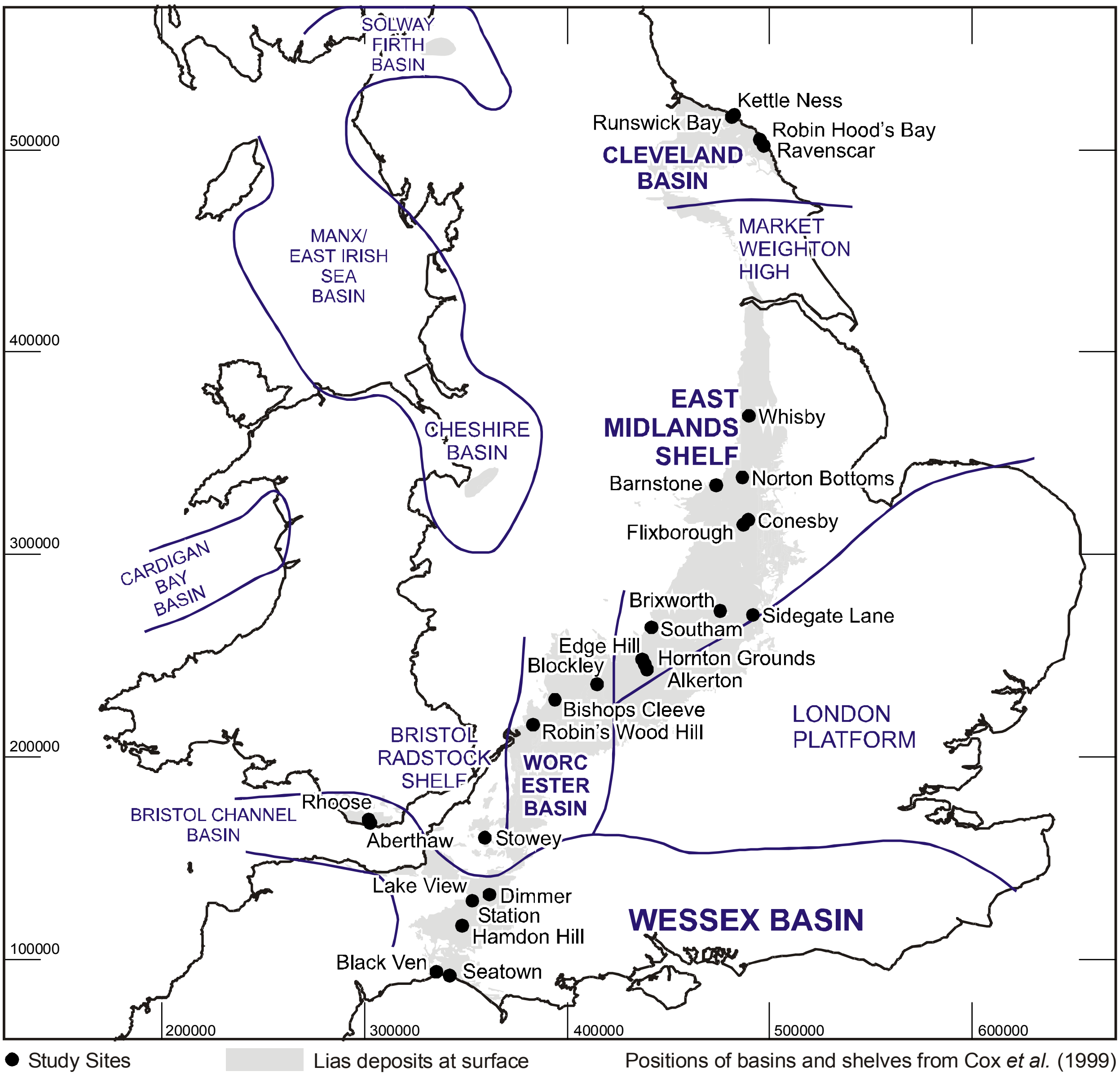


Figure 1 Map showing the positions of the study sites, the distribution of Lias Group outcrops in the UK, and the main structural elements that controlled deposition.

**D) WESSEX BASIN** (including Central Somerset Basin) **AND SOUTH WALES**

| FORMATION | MEMBER (Dorset Coast) | MEMBER (South Wales) |
|---|---|---|
| **Bridport Sand** | Down Cliff Clay | |
| **Beacon Limestone** | Eype Mouth Limestone | |
| | Marlstone Rock | |
| **Dyrham** | Thorncombe Sand | |
| | Down Cliff Sand | |
| | Eype Clay | |
| **Charmouth Mudstone** | Green Ammonite | |
| | Belemnite Marl | |
| | Black Ven Marl | |
| | Shales-with-Beef | |
| **Blue Lias** | | Porthkerry |
| | | Lavernock Shale |
| | | St Mary's Well Bay |

**C) WORCESTER BASIN**

| FORMATION | MEMBER |
|---|---|
| **Bridport Sand** | pending |
| **Whitby Mudstone** | pending |
| **Marlstone Rock** | none |
| **Dyrham** | pending |
| **Charmouth Mudstone** | pending |
| **Blue Lias** | Rugby |
| | Satford Shale |
| | Wilmcote |

**B) EAST MIDLANDS SHELF**

| SOUTH FORMATION | SOUTH MEMBER | NORTH FORMATION | NORTH MEMBER |
|---|---|---|---|
| **Whitby Mudstone** | pending | **Whitby Mudstone** | pending |
| **Marlstone Rock** | none | **Marlstone Rock** | none |
| **Dyrham** | pending | | |
| **Charmouth Mudstone** | | **Charmouth Mudstone** | Pecten Ironstone |
| **Blue Lias** | Rugby | **Scunthorpe Mudstone** | Frodingham Ironstone |
| | | | Foston |
| | Saltford Shale | | Beckingham |
| | | | Granby |
| | | | Barnby |
| | | | Barnstone |

**A) CLEVELAND BASIN**

| FORMATION | MEMBER |
|---|---|
| **Blea Wyke Sandstone** | Yellow Sandstone |
| | Grey Sandstone |
| **Whitby Mudstone** | Fox Cliff Siltstone |
| | Peak Mudstone |
| | Alum Shale |
| | Mulgrave Shale |
| | Grey Shale |
| **Cleveland Ironstone** | Kettleness |
| | Penny Nab |
| **Staithes Sandstone** | |
| **Redcar Mudstone** | Ironstone Shale * |
| | Pyritous Shale * |
| | Siliceous Shale * |
| | Calcareous Shale* |

| KEY | |
|---|---|
| Predominantly Mudstone | |
| Predominantly Mudstone/Limestone | |
| Predominantly Ironstone/Limestone | |
| Predominantly Sandstone/Siltstone | |

**SE** **NW**

**Table 1 Lithostratigraphical subdivisions of the Lias Group in (A) the Cleveland Basin (* to be formalised), (B) the East Midlands Shelf (south: Moreton in Marsh to Leicester area, north: Leicester area to Market Weighton), (C) the Worcester Basin, and (D) the Wessex Basin (keyed by dominant lithology for each formation; Cox *et al.* 1999).**

**Redcar Mudstone (Cleveland Basin):** van Buchem and M$^{c}$Cave (1989) and van Buchem *et al.* (1992) described the general characteristics of the various members of the Redcar Mudstone Formation. The lowermost *Calcareous Shales* are characterised by the presence of laterally continuous shelly horizons, with well-sorted beds deposited by storms, with poorly sorted, sparitic beds testifying to in-situ winnowing just above storm wavebase. These are overlain by the *Siliceous Shales* which comprise, bioturbated, fine quartz sand and silt and are interpreted as storm-dominated deposits. The overlying *Pyritous Shales* are black, very fine-grained, with a sparse fauna and siderite concretions, interpreted as hemipelagic, restricted, below storm wave base deposits. *The Banded Shales* comprise alternating layers of light-grey quartz-calcite-rich layers interpreted to have been deposited above storm wavebase, and darker silt-clay-rich layers deposited below storm wavebase. SEM analysis of the organic fractions of the light-grey shales indicates wide variations in the shape and size of woody material, plant-tissue fragments and palynomorphs, whereas the dark-grey shales organic matter is of uniform size and shape and dominated by woody material with minor palynomorphs and rare plant tissue fragments (van Buchem and M$^{c}$Cave (1989). In all the members, van Buchem *et al.* (1992) reported kaolinite/illite ratios of <1, indicating a predominance of illite, and interpreted variations in this ratio as being related to changes in the composition of the terrestrial influx, grain size separation during transportation and diagenetic overprinting.

The **Scunthorpe Mudstone (East Midlands Shelf, north):** forms fining-upwards cycles of variably calcareous silty mudstone. The bases of these cycles comprise calcareous, shelly siltstones that grade into blocky, typically kaolinitic (with subordinate chlorite and traces of smectite), slightly silty, calcareous, and micaceous mudstones that form the major component of the cycle. Cycles are capped by finer-grained laminated mudstones with calcite and siderite concretions (Gaunt *et al.* 1992). Limestones and calcareous siltstones are abundant at the base and in the upper half of the formation, and may be traced laterally for many kilometres. Some limestones are of primary bioclastic origin and others are well-cemented, argillaceous mudstones of secondary origin (Berridge *et al.* 1999). The *Barnstone, Granby* and *Foston Members* consist of mudstone with numerous widespread, closely-spaced, thin limestone beds. These members are separated by the *Barnby* and *Beckingham Members* which consist of mudstone with rare limestones (Berridge *et al.* 1999).

The *Frodingham Ironstone Member* is the uppermost member of the formation and is restricted to the area just south of the Market Weighton High at the northernmost extent of the East Midlands Shelf. The member is a bioclastic, ooidal ironstone containing goethite ooids, with minor berthierine and well developed calcite and siderite cements (Aggett 1990; Gaunt *et al.* 1992; Taylor and Curtis 1995; Taylor 1998). The Member is interpreted to have been deposited in a shallow marine, high-energy, oxygenated environment with near-surface diagenesis responsible for precipitation of berthierine and siderite under suboxic conditions. Oxidation of berthierine to geothite occurred when sediment was reworked or exhumed and exposed to oxidising marine waters (Taylor and Curtis 1995).

**Blue Lias Formation (South Wales; Wessex Basin):** Wobber (1965) described mudstones, calcareous shales and carbonaceous shales associated with limestones. The calcareous shales are poorly fissile, become more massive and tough with increasing carbonate content, and contain shredded carbonaceous matter on bedding planes. Gypsum crystals occur parallel to bedding planes and may be displacive. Bands of "Beef" (calcite), and probable faecal pellets were also noted. Framboidal pyrite is commonly seen in thin-section, and rounded bodies of glauconite are evident. The carbonaceous shales are dark grey or black and contain 36-45 % carbonaceous matter, which may be associated with finely divided pyrite, and less common quartz than the calcareous shales. The mudstones represent indurated calcareous clays that lack fissility. Wobber (1965) took the glauconite to indicate deposition under relatively quiet conditions, and interpreted the pyrite as early diagenetic.

**Charmouth Mudstone Formation (East Midlands Shelf, north):** Cox et al. (1999) revised the nomenclature of the Brant Mudstone Formation (Grantham District; Brandon et al. 1990; Berridge et al. 1999), and the Coleby Mudstone Formation (Kingston upon Hull-Brigg District; Gaunt et al. 1992) to include them within the Charmouth Mudstone Formation. In both districts the formation is described as grey mudstone, containing relatively few limestones (argillaceous-calcite mudstones), numerous clay-ironstone concretions, containing abundant argillaceous calcite mudstone, and fine-grained sandy or silty beds in the lower part.

The only formally defined member within the formation is the *Pecten Ironstone Member*, which is an ooidal ironstone of similar extent to the Frodingham Ironstone. In contrast to the Frodingham Ironstone, this member is dominated by berthierine ooids and glauconite peloids rather than goethite. The member contains well-developed calcite and siderite cement (Taylor and Curtis 1995; Taylor 1998).

**Charmouth Mudstone Formation (Worcester Basin):** Kemp and Hards (2000) provided XRD analysis of a suite of mudstone samples from boreholes in Gloucestershire, and reported an increase in calcite content with depth, and relatively uniform clay mineral assemblages of illite (approximately 40 %), kaolinite (35 %), smectite (20 %) and chlorite (5 %), although surface area determinations suggest that smectite contents are locally higher (up to approximately 30 %).

**Charmouth Mudstone Formation (Wessex Basin):** the diagenesis of the *Shales-with-Beef Member* has been studied by Rukin (1990) who described essentially closed system diagenesis with early pyrites formed by sulphate reduction. A complex history of carbonate cementation is also recorded with four distinct generations of fibrous calcite that grew during burial. The earlier generations developed coeval to feldspar degradation and organic matter oxidation, and later calcites formed as Fe-reduction and aragonite dissolution became significant.

**Cleveland Ironstone Formation (Cleveland Basin):** MacQuaker and Taylor (1996) described the Cleveland Ironstone Formation as comprising clay-rich mudstones, silt-rich mudstones, sand-rich mudstones, berthierine-dominated ooidal ironstones with siderite and berthierine cement, and concretionary apatite-rich horizons. Upwards-fining, and upwards-coarsening grain-size variations within the mudstones were interpreted to represent beds (0.001–0.05 m scale), parasequences (0.1–1.0 m) and systems tracts (1–3 m) formed in response to variations in relative sea level. Clay-rich mudstones and apatite-dominated units were deposited during times of increased accommodation and reduced sedimentation rates, with coarser material deposited in times of reduced accommodation, shorter sediment transport paths, and higher sedimentation rates. Ooidal material was deposited due to extensive sediment reworking during very low stand conditions. Taylor and MacQuaker (2000) reported that differences in diagenetic pyrite morphology can be used to infer differences in depositional environment, with framboidal pyrite formed in finer-grained, clay-rich mudstones from iron-dominated, high-sulphide (due to high levels of bacterial sulphate reduction) pore waters which were supersaturated with respect to FeS. In the more rapidly deposited silt- and sand-rich mudstones, lower organic-matter contents and reactivity meant that FeS supersaturation was not attained and that euhedral pyrite precipitated directly.

**Whitby Mudstone Formation (Cleveland Basin):** Pye and Krinsley (1986) described the microfabrics and early diagenetic history of samples from the Whitby Mudstone Formation. The deposits were described as being poorly laminated in the “normal” and “restricted” facies, and well-laminated in the “bituminous” facies (facies designations based on Morris, 1979). These variations were interpreted as reflecting variations in bottom water anoxia, with lamination preserved in more anoxic sediments due to a lack of bioturbation. Pye and Krinsley (1986) also suggested that the main authigenic assemblage comprised pyrite-carbonate-kaolinite, interpreted to reflect sulphide-dominated, but variably carbon-rich pore-fluids. Textural and isotope data indicated that the diagenetic phases were formed during early diagenesis in the sulphate reduction zone or the upper fermentation zone.

# 2 Samples and Methods

The studied samples were collected in the period between July 2001 and March 2003 from 27 sites across the UK. The locations, stratigraphy and the general characteristics of the 49 samples are given in Table 2. A detailed account of the geology and conditions at each sampling location was provided by Rowlands and Jones (2002). Throughout this report the samples are referred to using the site name, and the Mineralogy and Petrology Laboratories "MPL" sample code of the sub-sample used for petrographical analysis[1]. Qualitative X-ray Diffraction (XRD) analyses, surface area analysis data and XRF data for the majority of samples were reported by M$^{c}$Kervey (2002).

At the Blockley and Dimmer sites, additional sample material was also taken to assess variations in texture and mineralogy associated with weathering profiles in the Lias Group. These samples were taken as part of the Urban Geoscience and Geological Hazards Programme's Weathering Project. Thin-sections of a subset of these samples are currently in preparation and will be reported separately. XRD and surface area analysis data for these samples are reported here for the first time.

For scanning electron microscope (SEM) analysis, centimetre-sized blocks of material were excavated from the central (i.e. least likely to be disturbed) portions of the hand-specimen samples, and were freeze- or air-dried. Once dried, a fresh fracture surface was prepared for each stub, with at least one fracture surface perpendicular to lamination prepared for each sample where possible. In addition to these fresh fracture surfaces, a number of samples, also had surfaces prepared by cutting with a scalpel. Whilst this preparation disturbs the details of the structural relationships between the fine particles, it has the advantage of creating a relatively flat surface upon which compositional variations, as inferred from variations in back-scattered electron intensity (BSEM), are more apparent. The stubs were carbon-coated and analysed using a LEO 435VP digital SEM fitted with a KE Developments four-element solid-state backscattered electron detector, and an Oxford Instruments ISIS 300 EDXA system (for mineral identification by qualitative and semi-quantitative energy-dispersive X-ray analysis; EDXA).

[1] To derive a full, National Geoscience Data Centre-approved, unique sample identifier for each petrographic sample the prefix "MPL" should be added to each sample code. This prefix is omitted in this report for the purposes of brevity.

| Site | Site Type | County | Site Elevation (m aOD) | National Grid Ref | Formation (Member) | Sample ID | Petrographic Sample MPL Code | XRD/ XRF sample MPL Code | Sample Description |
|---|---|---|---|---|---|---|---|---|---|
| **CLEVELAND BASIN** | | | | | | | | | |
| **Runswick Bay** | Cliff | North Yorkshire | 0 | NZ$^{4}$817$^{5}$154 | Whitby Mudstone | Runswick | H595 | H606 | Poorly fissile, dark grey-black mudstone |
| **Ravenscar** | Quarry | | 150 | NZ$^{4}$971$^{5}$015 | Whitby Mudstone (Alum Shale) | Ravenscar (03-03-02) | H592 | H608 | Fissile, dark grey-black mudstone |
| | | | | | | Ravenscar (15-04-02) | J088 | - | Highly weathered, oxidised and rubbled material cut by numerous fractures with green and red Fe-oxides |
| **Kettleness** | Inactive brick pit / cliff | | 50 | NZ$^{4}$833$^{5}$160 | Cleveland Ironstone | Kettleness | H591 | H605 | Fissile, dark grey-black, mudstone. The SEM sample is of a red-purple hard mudrock ?concretion?. |
| **Robin Hood's Bay** | Cliff | | 0 | NZ$^{4}$954$^{5}$042 | Redcar Mudstone | Robin Hood's Bay | H590 | H607 | Poorly cemented, massive, dark grey mudstone |
| **E. MIDLANDS SHELF (north)** | | | | | | | | | |
| **Conesby** Quarry | Quarry | Leicester-shire | 30 | SK$^{4}$895$^{3}$147 | Charmouth Mudstone | Conesby-S2 | J452 | J452 | Similar to J450. Weakly to moderately laminated mudstone. |
| | | | 20 | SK$^{4}$895$^{3}$145 | | Conesby-S1 | J450 | J450 | Dense, weakly laminated, dark-grey mudstone with shelly debris. |
| | | | 30 | SK$^{4}$895$^{3}$146 | Scunthorpe Mudstone (Frodingham Ironstone) | Conesby-I | J451 | J451 | Oolitic, ferruginous sediment with calcite-cemented horizon containing green-grey mudstone clasts/nodules. |
| **Flixborough** Quarry | Quarry | | 48 | SK$^{4}$877$^{3}$142 | Scunthorpe Mudstone | Flixborough | J453 | J453 | Black, laminated, weakly fossiliferous mudstone with some Fe-staining. |
| **Norton Bottoms** | - | Lincolnshire | 20 | SK$^{4}$867$^{3}$360 | | Norton Bottoms | J454 | J454 | Black, laminated mudstone with rare bioclasts. |
| **Whisby** Quarry | Quarry | | 20 | SK$^{4}$896$^{3}$668 | | Whisby | J455 | J455 | Fractured, black, laminated mudstone with cm-scale nodules. |
| **Barnstone** Quarry | Quarry | Nottingham-shire | 25 | SK$^{4}$735$^{3}$335 | Scunthorpe Mudstone (Barnstone Limestone) | Barnstone | J449 | J449 | Dense, hard, laminated mudstone with laminae of more friable (?silty) material. |
| **E. MIDLANDS SHELF (south)** | | | | | | | | | |
| Site Landfill, **Brixworth** | Landfill - new cell under construction | Northamp-tonshire | 140 | SP$^{4}$757$^{2}$720 | Whitby Mudstone | BW1 | H416 | H280 | Poorly fissile, medium-grey mudstone, rare fossil fragments |
| **Sidegate Lane,** Finedon | Landfill - face at base of quarry and hand-dug pit | | 80 | SP$^{4}$916$^{2}$703 | | SL2 | H412 | H282 | Poorly fissile, medium-dark grey mudstone |
| | | | | | | SL1 | H411 | H281 | Poorly fissile, medium-dark grey mudstone |
| **Edge Hill,** Banbury | Quarry - base of the south face of quarry | Warwick-shire | 210 | SP$^{4}$375$^{2}$474 | Marlstone Rock | EH1 | H417 | H286 | Orange-brown ?mudstone/carbonate |
| **Hornton Grounds,** Wroxton | Quarry - base of the south face | Oxfordshire | 170 | SP$^{4}$382$^{2}$449 | | HT1 | H409 | H288 | Massive, orange-brown ?mudstone/carbonate |
| **Alkerton,** Edge Hill | Quarry | | 100 | SP$^{4}$395$^{2}$429 | | AL1 | H413 | H287 | Massive, light brown ?mudstone/carbonate |
| **Southam** Cement, Southam | Quarry - base of east face of quarry | Warwick-shire | 100 | SP$^{4}$419$^{2}$630 | Blue Lias | SH1 | H410 | H283 | Fissile, medium-dark grey mudstone |
| **WORCESTER BASIN** | | | | | | | | | |
| Tufley, **Robin's Wood Hill** | Inactive brick pit | Gloucester-shire | 140 | SO$^{3}$836$^{2}$149 | Dyrham | RW3 | H419 | H290 | Poorly fissile, light green-grey mudstone |
| | | | | | Marlstone Rock | RW2 | H418 | H289 | Poorly fissile, light green-grey mudstone |
| Wellacre, **Blockley** | Brick pit | | 100 | SP$^{4}$181$^{2}$371 | Charmouth Mudstone | 1a-1 (B1) | H265 | H265 | Site 1a - top of Profile. Orange-Yellow material near top of profile, containing gravel-rich (head?) material |
| | | | | | | 1b-2 (B2) | H266 | H266 | Site 1b - terrace beneath site 1a. Mottled orange-grey w/ ferruginous nodules |
| | | | | | | 2-3 (B3) | H267 | H267 | Site 2 - top of track down to levels beneath site 1. Green-grey with orange mottling, rare ferruginous nodules |
| | | | | | | 3-4 (B4) | H268 | H268 | Site 3 - further down track leading to levels beneath site 1. Grey, increased ped size compared with site 2. Some greenish infiltrated clay noted on small fractures |
| | | | | | | 4-5 (B5) | H269 | H269 | Site 4 - further down track from site 3 (?directly beneath site 1). Grey, more competent clay, with some brownish nodules/concretions |

**Table 2 Details of sampling sites and samples analysed as part of this study.**

## WORCESTER BASIN (continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Wellacre, **Blockley** | Brick pit | Gloucester-shire | 100 | SP$^{4}$181$^{2}$371 | Charmouth Mudstone | 5-6 (B6) | H270 | H270 | Site 5 - levels beneath Sites 2-4. Grey, obvious bedding, fossiliferous. Some nodule-rich horizons. Samples taken just below nodular horizon. |
| Wingmoor, **Bishops Cleeve** | Landfill - new cell under construction | | 30 | SO$^{3}$946$^{2}$272 | Blue Lias | BC1 | H414 | H284 | Poorly fissile, medium grey mudstone |
| | | | | | | BC2 | H415 | H285 | Massive, medium grey mudstone |
| **Stowey,** Bishops Sutton | Quarry | Avon | 150 | ST$^{3}$598$^{1}$587 | | Stowey | H593 | H609 | Massive, medium grey mudstone |

## WESSEX BASIN

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Hamdon Hill,** Yeovil | Quarry | Somerset | 30 | ST$^{3}$482$^{1}$162 | Bridport Sand | Hamdon | H597 | H603 | Massive, light brown ?mudstone/carbonate. (Shelly-limestone) |
| **Seatown** Cliffs | Cliff | Dorset | ?? | ST$^{3}$425$^{0}$915 | Dyrham (Eype Clay) | Seatown N | J083 | - | Dark green-grey, hard mudstone. Highly laminated |
| | | | | ST$^{3}$412$^{0}$918 | Charmouth Mudstone (Green Ammonite) | Seatown | J084 | - | Black, plastic mudstone with abundant bioclasts and faint lamination |
| **Black Ven** Landslide | Cliff | | 0 | SY$^{3}$355$^{0}$932 | Charmouth Mudst (Belemnite Marl) | Belemnite Marl | J086 | - | Black, massive, hard mudstone that breaks along conchoidal fractures. Contains minor cement bands (<< 1mm thick) |
| | | | | | (Black Ven Marls) | Upper Cement Bed | J085 | - | Black, plastic, laminated mudstone with 0.5 mm thick cement band |
| | | | | | (Shales-with-Beef) | Shales-with-Beef | J087 | - | Black, highly laminated, hard mudstone with minor bioclasts. Some gypsum/anhydrite on lamination surfaces |
| **Dimmer** | Landfill - new cell under construction - West Side of pit | Somerset | 40 | ST$^{3}$615$^{1}$313 | Charmouth Mudstone | 2a-10 (D10) | H274 | H274 | Site 2a - grey/orange mottled with rootlets, just above shear plane. 0.7 m bGL. Green-orange, faintly laminated with pores to a couple of mm-diameter. Some oxidised patches, typically associated with pores |
| | | | | | | 2a-11 (D11) | H275 | H275 | Site 2a – large block (20x20x20 m) cut out containing shear plane. 1.0 m bGL. |
| | | | | | | 1-15 (D15 / DM1) | H279 | H279 | Site 1 – orange mottled on one surface. Breaks into cm-scale peds, with sandy orange material between some peds. Very plastic clay. 1.75 m bGL. |
| | | | | | | 2b-9 (D9) | H273 | H273 | Site 2b – lighter grey than sample 08, more extensive mottling, very abundant gypsum (gypsum band passes through samples). Mottled green-grey and orange. Oxidation typically associated with pores. Patchy mm-scale crystals. Extensive rootlets. 1.7 m bGL. |
| | | | | | | 2b-8 (D8) | H272 | H272 | Site 2b – dark grey, lightly mottled clay, with some gypsum crystals to a few mm. Green-grey, relatively massive (relative to H271), but lamination still evident. Some mm-scale clear crystals of ?gypsum. Near vertical shear/fracture observed. Some orange mottling, commonly related to microfractures and pores. 2.9 m bGL |
| | | | | | | 2b-7 (D7) | H271 | H271 | Site 2b – laminated clay with minor gypsum/mottling noted. c. 60cm below nodular band. 4.2 m bGL. Dense, grey laminated mudrock. No mottling evident. Some bioclasts, microfractures parallel to lamination |
| | East side of pit | | | | | 3-14 (D14) | H278 | H278 | Site 3. 1.0 m bGL. Approximately equivalent stratigraphic level to sample D11 (H275). |
| | | | | | | 3-13 (D13) | H277 | H277 | Site 3 - pale grey/green with orange-green mottling. Crumbly texture. Lots of pores throughout and dispersed crystals. Some ferruginous nodules. 2.1 m bGL, Stratigraphically between samples D8 and D7 (H272 and H271). |
| | | | | | | 3-12 (D12) | H276 | H276 | Site 3 - dark grey, bedded clay. Sample D in two small bags. 3.5 m BGL Stratigraphically between samples D8 and D7 (H272 and H271). Dark-grey, well laminated with no obvious mottling. Minor small < mm-scale pores |
| Lliswerry, **Rhoose** | Quarry | South Glamorgan | 10 | ST$^{3}$032$^{1}$679 | Blue Lias (Porthkerry) | Rhoose | H594 | H601 | Poorly fissile, green-grey mudstone |
| **Aberthaw,** Barry | Quarry | | 40 | ST$^{3}$038$^{1}$672 | | Aberthaw | H596 | H604 | Loosely cemented, dark grey-black mudstone |
| **Station,** Somerton | Quarry | Somerset | 40 | ST$^{3}$536$^{1}$292 | Blue Lias | Station | H599 | H602 | Fissile, dark grey – black mudstone |
| **Lake View**, Street | Quarry | | 50 | ST$^{3}$548$^{1}$304 | | Lake View | H598 | H600 | Loosely cemented, massive, medium grey mudstone |

**Table 2 continued.**

# 3 Results

Descriptions of individual samples, including representative photomicrographs are given in Appendix 1. The following sections summarise the petrographical characteristics of each of the formations in each basin.

## 3.1 CLEVELAND BASIN

Five samples from the Cleveland Basin were included in the study (Table 1). Of these, one sample is from each of the Redcar Mudstone and Cleveland Ironstone Formations and three are from the Whitby Mudstone Formation.

**Redcar Mudstone Formation:** this sample (Robin Hood's Bay; H590) contains abundant well-rounded quartz grains (locally with authigenic overgrowths), in a matrix of predominantly probably illitic (K-bearing), and kaolinitic (Al-silicate) clays. Minor smectite or illite/smectite is suggested by Fe, Ca and Mg-bearing clays. The clays are commonly aligned parallel to the surfaces of the detrital grains, and may have platy authigenic crystals emanating from them.

**Cleveland Ironstone Formation:** this sample (Kettleness; H591) represents a hard, red-purple, possible concretion. SEM analysis indicates a poorly porous, indurated, apparently structureless fabric. The darker-coloured portions of the sample represent almost botryoidal clusters of material of ambiguous mineralogy. The red portions of the sample contain abundant Fe-oxides, and very closely packed, irregular platelets of variable chemistry (Fe-K-Ca-Mg-Na-bearing alumino-silicates). Minor pyrite euhedra are also noted.

**Whitby Mudstone Formation:** these samples are dark-grey, variably well-laminated and fissile, densely-packed and clay-dominated with minor amounts of silt grade material. Clay particles are predominantly flat-lying, commonly crenulated and may have incipient authigenic outgrowths. EDXA indicates predominantly K-bearing clays (?illite), with minor amounts of webby smectite noted. Pyrite framboids occur throughout within elongate pores, and these mudrocks are typically poorly porous. XRD data (M$^{c}$Kervey 2002; Appendix Table 1.1) indicates major quartz, with a clay mineral assemblage of major kaolinite and minor illite, chlorite, and illite-smectite. One sample (Runswick; H595) contains a 1 mm wide veinlet containing blocky crystals of calcite and sphalerite, which engulf vermiform, kaolinite.

## 3.2 EAST MIDLANDS SHELF (NORTH)

Seven samples from the central to northern portion of the East Midlands Shelf were included. Of these, five are from the Scunthorpe Mudstone Formation and two are from the Charmouth Mudstone Formation.

**Scunthorpe Mudstone Formation**: samples include one sample from each of the Frodingham Ironstone and Barnstone Limestone Members, and three samples from unspecified Member(s) in-between.

*Barnstone Limestone Member:* this sample (Barnstone; J449) is dense, hard and well-laminated in hand specimen, although this lamination is less well defined under SEM observation. The sample is poorly porous and dominated by fine-grained calcite, with minor rhombic dolomite (crystals <10 microns diameter), and clay of possible illite/smectite composition.

The three samples taken between the Barnstone Limestone and Frodingham Ironstone Members are all well-laminated, clay-dominated, poorly porous mudstones. Abundant gypsum/anhydrite is very finely crystalline and occurs throughout the matrixes of the mudstones. In all cases, EDXA suggests that the clay is predominantly of illite-smectite composition. Minor bioclasts occur throughout and these are predominantly $CaCO_3$, but rare phosphatic material is also present. The sample from Whisby is extensively altered (?weathered), being cut by very abundant horizontal and vertical fractures that significantly reduce the strength of the mudstone. The fractures commonly contain relatively coarse gypsum/anhydrite euhedra. In addition a number of phosphatic concretions (cm-scale) are developed.

*Frodingham Ironstone Member:* this sample (Conesby-I; J451) is of similar character to material described by Aggett (1990) and Taylor and Curtis (1995) being dominated by oblate, well-rounded goethite ooids and peloids that are cemented by near-pervasive coarsely crystalline calcite. An early-diagenetic origin for the calcite is inferred from the loosely-packed fabric. In addition the sample contains a 4 cm wide calcite-cemented horizon, within which ooids are rare, but rounded, green-grey nodules/clasts (1 cm diameter) of finely-crystalline Fe-bearing clay (?chlorite/berthierine) which are partially replaced by fine rhombs of siderite are common.

**Charmouth Mudstone Formation**: these samples (both from Conesby) are of similar character, being dark grey, hard, weakly to moderately well-laminated mudstones containing minor bioclastic material. Sample Conesby S1 (J451) contains minor silt-grade grains, is relatively poorly laminated, and contains cm-scale relatively porous domains (pores typically <10 μm diameter). EDXA suggesting a predominance of kaolinitic and illitic clays. In addition, a number of ambiguous aggregate grains are present (?possible pellets/clasts). These are made up of very fine particles of silica, gypsum/anhydrite and clay. In contrast, sample Conesby S2 (J452) is finer-grained, more strongly laminated and contains a predominance of K-Ca-bearing clay (possibly illite-smectite?). This sample is also cut by a number of fine fractures which are typically uncemented and closed, although two fractures (0.2 mm aperture) contain framboidal pyrite cement. Very minor gypsum/anhydrite occurs as fine crystallites on some clay platelets.

## 3.3 EAST MIDLANDS SHELF (SOUTH)

Seven samples from the southern portion of the East Midlands Shelf were included in the study. Of these, one is from the Blue Lias Formation, three are from the Marlstone Rock Formation and three are from the Whitby Mudstone Formation.

**Blue Lias Formation:** this sample (Southam Cement; H410) has a relatively massive fabric and contains finely crystalline (micritic) calcite, and on the basis of EDXA analysis sub-equal proportions of probable kaolinite and smectite or illite-smectite.

**Marlstone Rock Formation**: the three samples from this formation all contain well-rounded peloids or ooids, and other coated grains in a matrix of fine clay. The peloids/ooids, grain coatings and interstitial clays all have distinctive Fe-bearing Al-silicate compositions, suggestive of chlorite/berthierine or glauconite. In one sample (Edge Hill; H417) the grain coating clay is seen to be recrystallised to skeletal, and irregular platelets. The sample from Alkerton (H413) contains well-developed, cone-in-cone style calcite cement which completely fills the intergranular volume. Mn-oxides and botryoidal Fe-oxy-hydrides occur throughout.

**Whitby Mudstone Formation:** these two samples are of similar character to the samples described above from this formation in the Cleveland Basin. They represent typically well-laminated mudstones with abundant mica flakes and some silt-grade quartz grains. EDXA suggests a predominance of illite (K-bearing) within the clay fraction and minor smectite (Ca-Mg-bearing). Clay particles are flat-lying, and crenulated with minor possible authigenic outgrowths. Lamination is seen to curve around framboidal pyrite cement, suggesting formation of pyrite prior to compaction (i.e. during early diagenesis). Minor gypsum/anhydrite occurs in clusters, and a sphalerite-calcite-kaolinite cemented fracture is present in one sample (Runswick Bay; H595). The mudrocks are predominantly poorly porous, but surfaces cut with a scalpel and examined using SEM, reveal the presence of tightly packed, and less tightly packed domains. The less packed domains typically occur parallel to lamination, and also along possible shear surfaces.

## 3.4 WORCESTER BASIN

Eleven samples were available from this Basin, including three from the Blue Lias Formation, six from a weathered profile through the Charmouth Mudstone Formation, and one from each of the Dyrham and Marlstone Rock Formations.

**Blue Lias Formation:** SEM analysis of these samples confirms the XRD observation of high calcite contents (M[c]Kervey 2002), with clay platelets wrapped around the small (10 micron diameter) spherules of micritic calcite. The clays are variably "lumpy" and platy and minor possible authigenic outgrowths are observed. Framboidal pyrite and pyrite euhedra occur in close proximity within the sample from Bishops Sutton (Stowey; H593).

**Charmouth Mudstone Formation:** the six samples from this formation were taken specifically to investigate possible mineralogical and geochemical variations through a profile of weathered Lias Mudstone (Blockley; H265-H270). The shallowest samples represent possible Head material just below present day ground level, with samples taken down to the lower most quarry levels several 10's of meters below ground level.

The Head material (sample B1; H265) contains lenses of abundant very coarse sand-grade (mm-scale) grains of well rounded quartz in a clayey matrix. Within these sandy lenses, clay fabrics are variable, with grain coatings, meniscus-style bridges between grains, and interstitial clay. Within the Charmouth Mudstone Formation proper, lamination is evident within the shallower material although this is less pronounced than in the deeper, less weathered, portions of the section. In addition, oxidation features such as orange staining, and ferruginous nodules are more common in the shallower material. EDXA generally indicates illitic or illite-smectite compositions for the clays, although minor authigenic kaolinite is present.

**Dyrham Formation and Marlstone Rock Formation:** the two samples from these formations, both derived from the Tufley, Robin's Wood Hill site (H419 and H418 respectively), are of very similar character and both represent well laminated silty mudrocks, with abundant sub-rounded quartz grains, around which finer particles are deformed. EDXA suggests predominantly illitic or illite-smectite for the clay, with minor amounts of bookleted (?authigenic) kaolinite. Examination of surfaces cut using a scalpel indicates that these mudrocks are relatively porous. The sample ascribed to the Marlstone Rock Formation (Robin's Wood Hill, H418) bears little resemblance to material described from Marlstone Rock Formation on the East Midlands Shelf (see above), suggesting it may have been ascribed to the wrong formation.

## 3.5 WESSEX BASIN

Nineteen samples from the Wessex Basin (including South Wales), including four from the Blue Lias Formation, thirteen from the Charmouth Mudstone Formation, and one sample from each of the Dyrham and Bridport Sand Formations were included in this study.

**Blue Lias Formation:** the four samples from this formation are all massive, dense, highly calcareous mudrocks with only minor porosity. The mineralogy of these samples is dominated by micro-rhombic and micritic calcite, with minor rhombic dolomite also present. This is supported by surface area measurements which are particularly low (40-50 $m^2 g^{-1}$ for three of the samples; Appendix Table 1.1) indicating a low clay content. The sample from Aberthaw, Barry (H596) has a surface area more typical of a mudrock (124 $m^2 g^{-1}$), and is seen in SEM to be more clay-rich. In all the samples, the clay assemblage is dominated by K- and Ca-bearing phases, most probably illite, smectite and/or illite-smectite (this mineralogy is supported by the XRD data; Appendix Table 1.1). Minor pyrite framboids are locally present.

**Charmouth Mudstone Formation:** all four members of the Charmouth Mudstone Formation have been sampled in the Wessex Basin on the Dorset Coast (Seatown and Black Ven Sites). The four samples all represent similarly well-laminated mudrocks, with clay mineralogies dominated by K-bearing clays (probably illite). Individual clay particles are typically flat lying to crenulated, with minor wispy, possible authigenic emanations. Minor authigenic dolomite is incipiently developed in the sample from the Black Ven Marl Member (J085), and framboidal pyrite occurs in the sample from the Shales-with-Beef Member (J087). Clay particles wrap-around these pyrite framboids suggesting an early, pre-compactional, origin for the pyrite. Calcite-cemented veins occur in the samples from the Belemnite Marl (J086) and Black Ven Marl (J085) Members. These veins are typically of the order of 100 microns wide, and tend to have one sharp boundary and one more diffuse margin, with the calcite crystals aligned perpendicular to the fracture margins. Gypsum/anhydrite occurs along lamination surfaces in the sample from the Shales-with-Beef Member.

In addition, a weathering profile through the formation has been sampled at Dimmer (H271-H279). The mudrocks are typically well-laminated throughout the profile. However, the samples from higher up the weathered profile commonly contain numerous microfractures and probable rootlet structures (samples H274 and H273). The orange-green mottling seen in hand-specimen that extends down to approximately 3 m from present day ground level is reflected in detail by variations in structure and mineralogy within the clays. The cut surface of sample H277, reveals that circular features up to 0.25 mm in diameter that appear “bright” under BSEM, within a “darker” matrix. In detail the “bright” mottles are seen to be more porous with possibly recrystallised clay platelets which have notably lower Ca-contents than the clays in the darker matrix. Minor pyrite euhedra are noted within the deeper samples (H276), and gypsum/anhydrite occurs in clusters of relatively coarse crystals (up to 0.5 mm) within distinct patches/laminae through the profile.

**Dyrham Formation:** this sample (Seatown Cliffs; J083) represents a well-laminated, fossiliferous mudstone with flat-lying mica platelets. EDXA indicates that the clays are predominantly kaolinitic with lesser proportions of illite and /or illite/smectite. Minor gypsum, anhydrite and pyrite are present.

**Bridport Sand Formation:** this sample (Hamdon Hill, Yeovil; H597) is a fine-grained sandstone/wackestone with well rounded quartz, and more blocky/tabular feldspar grains, with abundant interstitial spongy clay. In addition to the spongy clay, small volumes of skeletal hexagonal clay similar to that seen in the Marlstone Rock Formation in the of the East Midlands Shelf. EDXA of the spongy and the skeletal clay indicates a Fe-Mg-bearing composition for the clay suggestive of chlorite/berthierine.

# 4 Discussion and Conclusions

SEM analyses of mudstones from the Lias Group across England and south Wales largely confirm the observations made by earlier workers (see references), and are broadly consistent with the results of XRD analyses. Each of the Lias Group Formations studied is discussed below in stratigraphic (oldest-youngest) and regional (North-South) order. For each formation, the basin(s) within which the formation occurs are given, along with the numbers of samples from each basin (in brackets).

### 4.1.1 Redcar Mudstone Formation

*Basin: Cleveland (1).* The single sample (Robin Hood's Bay; H590) is relatively sandy with well-rounded quartz grains. XRD and SEM analysis indicate a predominance of illitic and kaolinitic clays. This sample is consistent the characterisation by van Buchem and M$^c$Cave (1989) of this formation in the Cleveland Basin.

### 4.1.2 Scunthorpe Mudstone Formation

*Basin: E. Midlands Shelf (north only; 5).* These samples are broadly consistent with descriptions in the literature. The samples from the unspecified member(s) are typically well-laminated and clay-dominated. Although the formation is typically described as kaolinite-dominated, EDXA analysis suggests clay mineralogies possibly dominated by illite-smectite (although XRD analysis would be required to confirm this). Very finely crystalline gypsum/anhydrite occurs throughout. In an sample of more fractured (?weathered) material from this formation, coarsely crystalline gypsum/anhydrite occurs within the fractures. The sample from the *Barnstone Limestone Member* (Barnstone; J449) is typical of this member and is dominated by fine-grained calcite with minor clay and dolomite. The sample from the *Frodingham Ironstone Member* (Conesby-I; J451) is a goethitic oolitic ironstone with well-developed early calcite cement, typical of this Member.

### 4.1.3 Blue Lias Formation

*Basins: E. Midlands Shelf (south only; 1); Worcester (3); Wessex (4).* In the Basins within which this formation occurs, it is confirmed to be highly calcareous, with abundant micro-rhombic and micritic calcite and minor rhombic dolomite. In detail, fabrics are typically massive, and the mudrocks are hard and dense with low surface areas (particularly in the samples from the Wessex Basin). However, some lamination is seen within the more clay-rich samples from Bishops Sutton (H593) and Bishop's Cleeve (H414). Minor framboidal and euhedral pyrite is present.

Variations in surface area (Appendix Table 1.1) broadly correspond to variations in the relative proportions of carbonate and clay, with SEM analysis indicating that the samples from Wessex Basin with relatively low surface areas have lower clay and higher carbonate contents than those from the Worcester Basin and East Midlands Shelf. This variation matches a general regional trend in calcite content reported by Kemp and M$^c$Kervey (2001) for the Lias Group.

In addition to the variation in total clay-content, clay mineral assemblages in the two southernmost samples of this formation (Station [H599] and Lake View [H598]) contain major illite, with minor kaolinite, chlorite and illite/smectite, whereas in the samples from further north (South Wales, the Worcester Basin and the East Midlands Shelf), illite tends to be less dominant of the clay mineral assemblage and smectite and/or illite-smectite become more significant. This variation suggests either a difference in the primary makeup of the sediment, or that the smectite to illite transformation is more advanced in the more southerly samples.

### 4.1.4 Charmouth Mudstone Formation

*Basins: E. Midlands Shelf (2 from north); Worcester (6 from weathering profile); Wessex (4 + 9 from weathering profile).* This formation is characterised in all the studied areas by well-laminated mudrocks, with flat-lying clay platelets and generally only minor amounts of silt and sand-grade material. EDXA analysis suggests a predominance of K-bearing (illitic) clays in the Worcester and Wessex Basins, although XRD indicates that the clay mineral assemblages comprise major kaolinite, with minor illite, chlorite and possible illite-smectite (no XRD data is available for the samples from the north East Midlands Shelf or from the Dorset Coast [Black Ven and Seatown; J093-J087]). EDXA of the samples from the northern end of the East Midlands Shelf indicate kaolinite and illite dominated mineralogies (although XRD analysis would be required to confirm this). Minor smectite is also present in the samples from the Worcester basin. These observations are broadly in line with the results reported by Kemp and M^c^Kervey (2001) for the formation in Southern England and Kemp and Hards (2001) for the formation in the Worcester Basin.

In the samples from the Dorset Coast well-developed lamination-parallel calcite veining with cone-in-cone (beef) fabrics is present. Gypsum/anhydrite is locally developed along lamination surfaces and early framboidal pyrite is present.

The samples through weathering profiles at Dimmer and Blockley reveal development of locally abundant gypsum/anhydrite, nodularisation, rootleting and oxidation towards the surface as seen in hand specimen, but these features are poorly defined on the scale of SEM stubs. No appreciable, systematic differences in clay mineralogy are noted through the weathering profiles.

### 4.1.5 Dyrham Formation

*Basins: E. Midlands Shelf (south only; unsampled); Worcester (1); Wessex (1).* These two samples both represent well-laminated mudstones. SEM analysis suggests a varied clay mineral assemblage of kaolinite, illite, and/or illite/smectite, which is supported by the single XRD analysis available (Robin's Wood Hill, H419), and by the earlier work of Kemp and M^c^Kervey (2001).

### 4.1.6 Cleveland Ironstone Formation

*Basins: Cleveland (1).* The single SEM sample (Kettleness, H591) from this formation represents a hard, red-purple ferruginous concretion and is probably not representative of the formation as a whole

### 4.1.7 Marlstone Rock Formation

*Basins: E. Midlands Shelf (3); Worcester (1).* The samples of this formation from the East Midlands Shelf are peloidal/ooidal with thick coatings of clay on well-rounded grains in a fine clay matrix. SEM and EDXA analysis suggests the clays are chloritic or glauconitic. Cone-in-cone calcite cement is locally present. The single sample of this formation from the Worcester Basin (Robin's Wood Hill, H418) is more closely akin to the material described above for the Dyrham Formation, suggesting it may have been ascribed to the wrong formation.

### 4.1.8 Whitby Mudstone Formation

*Basins: Cleveland (3); E. Midlands Shelf (2 from south); Worcester (unsampled).* In both the Cleveland Basin and the East Midlands Shelf this formation is confirmed as a typically well-laminated mudrock with minor silty material. EDXA suggests a predominance of illite and/or illite-smectite (K and K-Ca-bearing) compositions, consistent with earlier, quantitative, XRD data on samples from the Cleveland Basin by Kemp and M$^c$Kervey (2001) which indicates that the smectite to illite transformation is well advanced. Qualitative XRD on these samples indicates major kaolinite with minor illite, illite-smectite and chlorite. No samples of the Whitby Mudstone from the Worcester Basin were available for analysis, although Kemp and M$^c$Kervey (2001) report that the smectite-illite transformation is less well advanced than in the northerly basins.

### 4.1.9 Bridport Sandstone Formation

*Basins: Worcester (unsampled); Wessex (1).* This formation is only represented by a single sample (Hamden Hill, Yeovil; H597), of fine-grained sandstone/wackestone with spongy interstitial and recrystallised hexagonal clay suggestive of berthierine/chlorite.

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Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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# Appendix 1 XRD Data Tables

| Site | Formation | SampleID | Code of equiv. SEM stub | MPL Code ("B" used for some clay fraction analyses) | WHOLE ROCK DATA quartz | calcite | albite | K-feldspar | 'mica' | chlorite | kaolinite | smectite | goethite | gypsum | dolomite | ankerite | pyrite | hematite | illite/smectite | Siderite | Oligonite | Surface Area (n | CLAY FRACTION DATA smectite | illite | chlorite | kaolinite | illite/smectite | other component |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CLEVELAND BASIN** | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Runswick Bay** | Whitby Mdst | Runswick | H595 | H606 | **** | ** | ** | | ** | ** | ** | | | | | | ** | | | | | 70 | | ** | ** | **** | ** | quartz |
| **Ravenscar** | Whitby Mudstone (Alum Shale) | Ravenscar (03-03-02) | H592 | H608 | **** | | ** | | ** | tr | ** | | | | | | | | ?tr | | | 116 | | ** | ** | **** | ** | quartz |
| **Kettleness** | Cleveland Ironstone | Kettleness | H591 | H605 | **** | | tr | | ** | ** | ** | | | | | | tr | | ?tr | | | 122 | | ** | ** | **** | ** | quartz |
| **Robin Hood's Bay** | Redcar Mdst | Robin Hood's Bay | H590 | H607 | **** | | ** | | ** | ?tr | ** | | | | | | | | ?tr | | | 64 | | ** | ** | **** | ** | quartz |
| **EAST MIDLANDS SHELF** | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Site Landfill, **Brixworth** | Whitby Mdst | BW1 | H416 | H280 | **** | | ** | ** | ** | ** | ** | | | tr | | | ** | | | | | 98 | | ** | ** | **** | ** | quartz |
| **Sidegate Lane**, Finedon | Whitby Mdst | SL1 | H411 | H281 | **** | | tr | ** | ** | ** | ** | | | tr | | | ** | | tr | | | 126 | | ** | ** | **** | ** | quartz |
| **Sidegate Lane**, Finedon | Whitby Mdst | SL2 | H412 | H282 | **** | | tr | ** | ** | tr | ** | | | tr | | | ** | | | | | 124 | | ** | ** | **** | ** | quartz |
| **Edge Hill**, Banbury | Marlstone Rock | EH1 | H417 | H286(B) | | **** | | | | ?** | ?tr | ?tr | ** | | | | | | | ?** | ?** | 146 | **** | tr | | ** | | goethite (minor) |
| **Hornton Grounds**, Wroxton | Marlstone Rock | HT1 | H409 | H288(B) | ** | ** | | | | ?tr | ?tr | ?tr | **** | | | | | | | | | 199 | **** | ** | ?tr | ** | | goethite (minor) |
| **Alkerton**, Edge Hill | Marlstone Rock | AL1 | H413 | H287(B) | tr | **** | | | | ?** | ?tr | ?tr | ** | | | | | | | ?** | ?** | 129 | ?** | | ** | ** | | goethite (major) |
| Southam Cement, **Southam** | Blue Lias | SH1 | H410 | H283 | **** | **** | ** | ** | ** | tr | ** | ?** | | tr | | ?** | ** | | ?tr | | | 208 | ** | ** | ** | ** | ?** | quartz |

Appendix Table 1.1 XRD and surface area data, listing for samples of Lias Group mudrocks (data from M[c]Kervey 2002).

| Site | Formation | SampleID | Code of equiv. SEM stub | MPL Code ("B" used for some clay fraction analyses) | WHOLE ROCK DATA: quartz | calcite | albite | K-feldspar | 'mica' | chlorite | kaolinite | smectite | goethite | gypsum | dolomite | ankerite | pyrite | hematite | illite/smectite | Siderite | Oligonite | Surface Area (m | CLAY FRACTION DATA: smectite | illite | chlorite | kaolinite | illite/smectite | other component |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **WORCESTER BASIN** | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Tufley, **Robin's Wood Hill** | Marlstone Rock | RW2 | H418 | H289 | **** | | ** | tr | ** | ?** | ** | ** | | ** | | | | | | | | 132 | ** | ** | ** | **** | ?** | quartz |
| Tufley, **Robin's Wood Hill** | Dyrham | RW3 | H419 | H290 | **** | | ** | tr | ** | ?** | ** | | | | | | | | | | | 73 | ?** | ** | ** | **** | ?** | quartz |
| Wellacre, **Blockley** | Charmouth Mdst | B1 | H265 | H265 | **** | **** | ** | ** | ?tr | ?tr | ** | | ** | | | | | | | | | 137 | ** | ** | ** | **** | ?** | quartz, ?goethite |
| Wellacre, **Blockley** | Charmouth Mdst | B2 | H266 | H266 | **** | ** | ** | ?tr | ** | ?** | ** | ?** | | | | | | | | | | 152 | ** | ** | ** | **** | ?** | quartz |
| Wellacre, **Blockley** | Charmouth Mdst | B3 | H267 | H267 | **** | | ** | | ** | ?** | ** | ?** | ** | | | | | | | ?tr | | 140 | ** | ** | ** | **** | ?** | quartz, ?goethite |
| Wellacre, **Blockley** | Charmouth Mdst | B4 | H268 | H268 | **** | ** | ** | ** | ** | ?** | ** | ?** | | | | | ** | | | | | 92 | ** | ** | ** | **** | ?** | quartz |
| Wellacre, **Blockley** | Charmouth Mdst | B5 | H269 | H269 | **** | ** | ** | ** | ** | ?** | ** | ?** | | | | | ** | | | | | 93 | ** | ** | ** | **** | ?** | quartz |
| Wellacre, **Blockley** | Charmouth Mdst | B6 | H270 | H270 | **** | ** | ** | ?tr | ** | ?** | ** | ?** | | | | | ** | | | | | 103 | ** | ** | ** | **** | ?** | quartz |
| Wingmoor, **Bishops Cleeve** | Blue Lias | BC1 | H414 | H284 | **** | ** | ** | ** | ** | ?tr | ** | | | | | ?** | tr | | | | | 140 | | ** | ** | ** | ** | quartz |
| Wingmoor, **Bishops Cleeve** | Blue Lias | BC2 | H415 | H285 | **** | **** | ** | ** | ** | ** | ** | | | | | ?** | ** | | | | | 88 | | ** | ** | ** | ** | quartz |
| **Stowey,** Bishops Sutton | Blue Lias | Stowey | H593 | H609 | **** | **** | | tr | ** | ** | ?tr | **** | | | | | ** | | | | | 355 | **** | **** | tr | tr | | quartz |

Appendix Table 1.1 XRD and surface area data, listing for samples of Lias Group mudrocks (data from M$^c$Kervey 2002). Continued.

| Site | Formation | SampleID | MPL Code ("B" used for some clay fraction analyses) Code of equiv. SEM stub | | WHOLE ROCK DATA quartz | calcite | albite | K-feldspar | 'mica' | chlorite | kaolinite | smectite | goethite | gypsum | dolomite | ankerite | pyrite | hematite | illite/smectite | Siderite | Oligonite | Surface Area (n | CLAY FRACTION DATA smectite | illite | chlorite | kaolinite | illite/smectite | other component |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **WESSEX BASIN** | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Hamdon Hill**, Yeovil | Bridport Sand | Homdon | H597 | H603 | **** | ** | ** | ** | tr | | | ?tr | | | ?tr | | | tr | | | | 53 | ** | ** | ** | ** | ** | goethite (minor) |
| **Dimmer** | Charnmouth Mdst | D7 | H271 | H271 | **** | **** | ** | ?tr | ** | ?** | ** | ?** | | tr | | ?** | ** | | | | | 138 | | ** | ** | **** | ?** | quartz |
| **Dimmer** | Charnmouth Mdst | D8 | H272 | H272 | **** | **** | ** | ?tr | ** | ?** | ** | ?** | | ** | | ?** | ** | | | | | 126 | | ** | ** | **** | ?** | quartz |
| **Dimmer** | Charnmouth Mdst | D9 | H273 | H273 | **** | **** | ** | ?tr | ** | ?** | ** | ?** | | ** | | ?** | ?tr | | | | | 124 | | ** | ** | **** | ?** | quartz, ?goethite |
| **Dimmer** | Charnmouth Mdst | D10 | H274 | H274 | **** | **** | ** | ?tr | ** | ?** | ** | ?** | | | | | ?tr | | | | | 175 | | ** | ** | **** | ?** | quartz, ?goethite |
| **Dimmer** | Charnmouth Mdst | D11 | H275 | H275 | **** | **** | ** | ** | ** | ?** | ** | ?** | | | ?tr | | ?tr | | | | | 149 | | ** | ** | **** | ?** | quartz, ?goethite |
| **Dimmer** | Charnmouth Mdst | D12 | H276 | H276 | **** | **** | ** | ** | ** | ?** | ** | ?** | | | | ** | ** | | | | | 122 | | ** | ** | **** | ?** | quartz |
| **Dimmer** | Charnmouth Mdst | D13 | H277 | H277 | **** | **** | ** | ?tr | ** | ?** | ** | ?** | | ** | | ** | ** | | ?tr | | | 121 | | ** | ** | **** | ?** | quartz, ?goethite |
| **Dimmer** | Charnmouth Mdst | D14 | H278 | H278 | **** | **** | ** | ** | ** | ?** | ** | ?** | | | ?** | ?** | | | | | | 144 | | ** | ** | **** | ?** | quartz, ?goethite |
| **Dimmer** | Charnmouth Mdst | DM1 | H279 | H279 | **** | **** | ** | ** | ** | ** | ** | | | | ** | | | ?tr | ?** | | | 141 | | ** | ** | ** | ** | quartz, ?goethite |
| Lliswerry, **Rhoose** | Blue Lias (Pothkerry) | Rhooose | H594 | H601(B) | **** | **** | | | ** | ?tr | ?tr | | | | | | | | | | | 40 | **** | **** | | | ** | quartz (minor) |
| **Aberthaw,** Barry | Blue Lias (Pothkerry) | Aberthaw | H596 | H604 | **** | **** | tr | | ** | tr | ?tr | | | | ?tr | ?tr | ** | | | | | 124 | ?** | **** | tr | ?tr | **** | quartz, ?feldspar |
| **Station**, Somerton | Blue Lias | Station | H599 | H602 | ** | **** | | | ** | | | | | | | | ** | | | | | 48 | | **** | ** | ** | ** | quartz, ?feldspar |
| **Lake View**, Street | Blue Lias | Lake View | H598 | H600 | ** | **** | | | ** | ?tr | ?tr | | | | ?tr | | ** | | | | | 45 | | **** | ** | ** | ** | quartz |

| | |
|---|---|
| **** | major constituent |
| ** | minor constituent |
| tr | trace |
| nd | not detected |

Appendix Table 1.1 XRD and surface area data, listing for samples of Lias Group mudrocks (data from M[c]Kervey 2002). Continued.

# Appendix 2 SEM Descriptions

## CLEVELAND BASIN

| | | | |
|---|---|---|---|
| Site: | **Runswick Bay** | SampleID: | **Runswick** |
| Basin: | **Cleveland** | Formation: | **Whitby Mudstone** |
| MPL Sample Code: | **H595S1** | Preparation: | **Freeze dried, fresh fracture surface** |

A dense, laminated, but otherwise homogenous mudstone, with minor silt-grade particles. Clay particles are predominantly flat lying, commonly crenulated, and have locally well developed webby, and fibrous margins. EDXA indicates predominantly K-Al-Silicate compositions (possibly illite), but minor Ca- and Mg- bearing Al-silicates are also present (possible smectite). In addition, rare patches (20 microns diameter) of webby/honeycombed clay with a Ca-Mg-Al-Silicate composition (possible smectite) are present. Minor $CaCO_3$ and pyrite framboids are noted. XRD indicates major kaolinite, with minor illite, chlorite and illite/smectite) in the clay fraction .

This sample is cut by a approx. 1mm wide veinlet containing intergrown, $CaCO_3$ and sphalerite (ZnS), with minor kaolinite and pyrite. This vein is parallel to lamination in the sample, and is straight sided with no obvious signs of host rock alteration adjacent to it.

Photomicrographs:

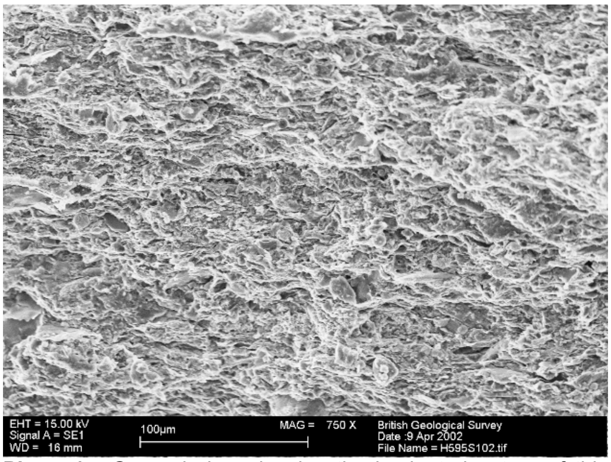


**Photo 1:** General view showing the laminated nature of this sample.

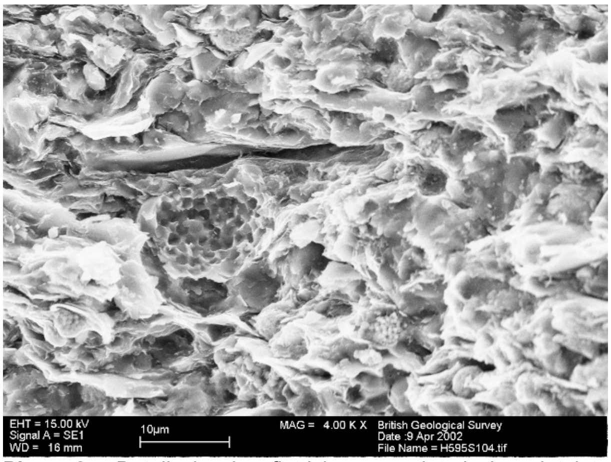


**Photo 2:** Detail showing flat-lying, crenulated clay platelets with irregular margins. Also present is a small patch of webby clay.

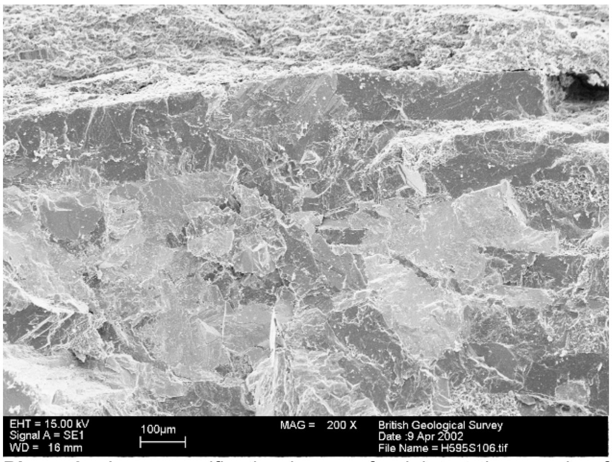


**Photo 3:** Low magnification image of veinlet at the margin of this stub. The darker grey phase is $CaCO_3$, the brighter phase is sphalerite (ZnS).

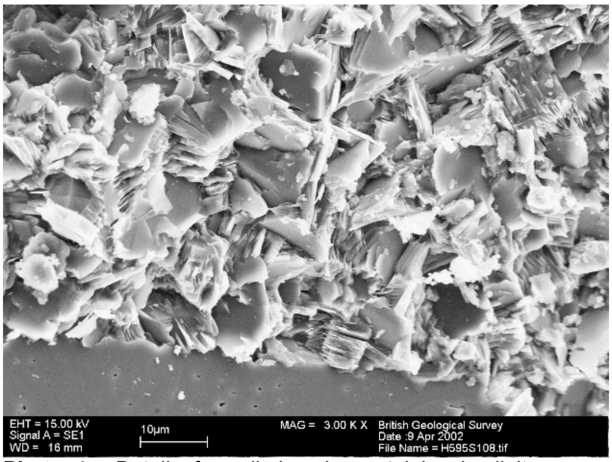


**Photo 4:** Detail of small domain containing kaolinite verms within the main body of the veinlet shown in Photo 3.

| | | | |
|---|---|---|---|
| Site: | **Ravenscar** | SampleID: | **Ravenscar 03-03-02** |
| Basin: | **Cleveland** | Formation: | **Whitby Mudstone (Alum Shale Member)** |
| MPL Sample Code: | **H592S1** | Preparation: | **Freeze dried, fresh fracture surface** |

A well laminated mudstone, which is well cleaved along the lamination. Flat lying micas are abundant with minor amounts of silt-grade quartz and feldspar grains are also evident. Clay particles are flat lying, and curve around more rigid detrital grains. In detail the clay particles are seen to be platy, with irregular wispy margins, with EDXA indicating predominantly K-bearing (illitic?) compositions. However, XRD indicates a predominance of kaolinite in the clay fraction. Minor pyrite framboids (up to 10 microns diameter) occur within some elongate pores. Porosity is minor, and pores are typically <10 microns diameter, occur between clay platelets, and tend to be elongate parallel to lamination.

Photomicrographs:

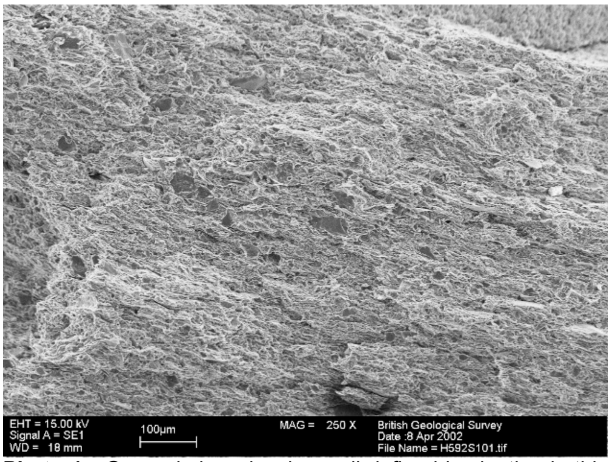


**Photo 1:** General view showing well defined lamination in this sample.

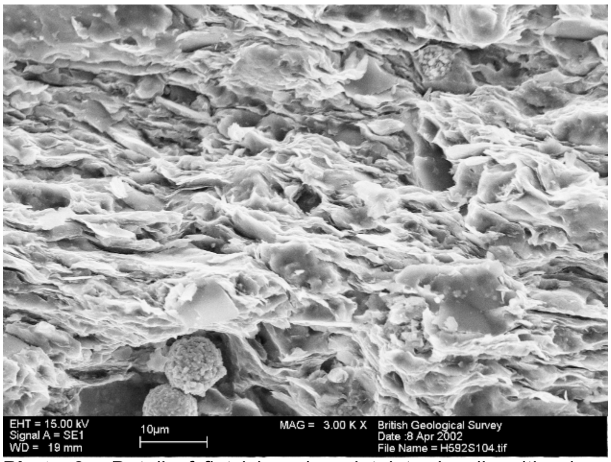


**Photo 3:** Detail of flat lying clay platelets, locally with wispy emanations. Minor framboidal pyrite is present within an elongate pore at the bottom of the image.

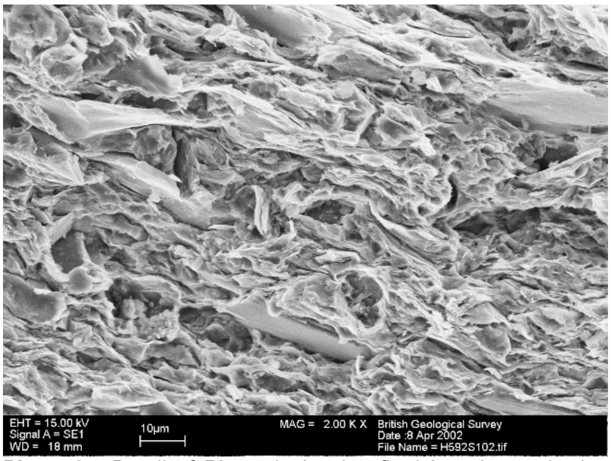


**Photo 2:** Detail of Photo 1 showing flat-lying clay and mica platelets.

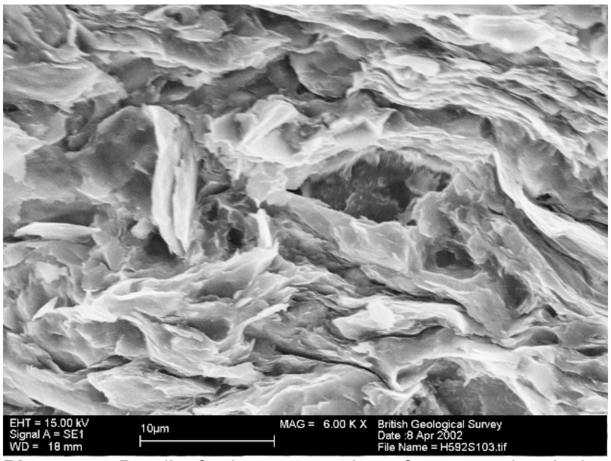


**Photo 4:** Detail of wispy emanations from crenulated clay platelets.

| | | | |
|---|---|---|---|
| Site: | **Ravenscar** | SampleID: | **Ravenscar 15-04-02** |
| Basin: | **Cleveland** | Formation: | **Whitby Mudstone (Alum Shale Member)** |
| MPL Sample Code: | **J088S1** | Preparation: | **Freeze dried, fresh fracture surface** |

This sample is cut by numerous fractures, and readily breaks into mm-cm-scale lumps. Weathering along the fractures is noted by the presence of paler-brown clayey material within this otherwise dark green-grey to black mudrock.

In spite of the weathering/fracturing, the sample can be seen to locally contain a reasonably well-defined lamination, although domains with more massive fabrics are also observed. EDXA indicates that the clay is K-bearing (?illite).

Photomicrographs:

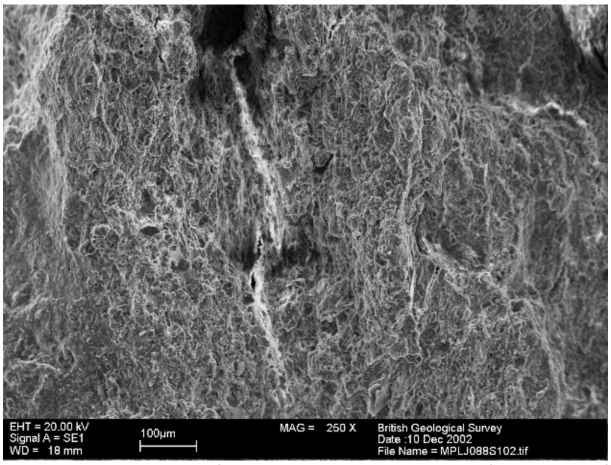


**Photo 1:** Low magnification image showing two fragments of this sample separated by a thin-fracture (which appears "bright" due to charging of the specimen).

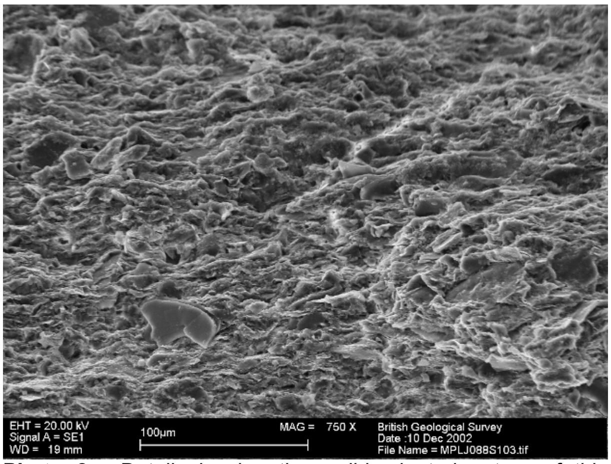


**Photo 2:** Detail showing the well-laminated nature of this sample, with tightly packed, flat-lying, crenulated clay particles.

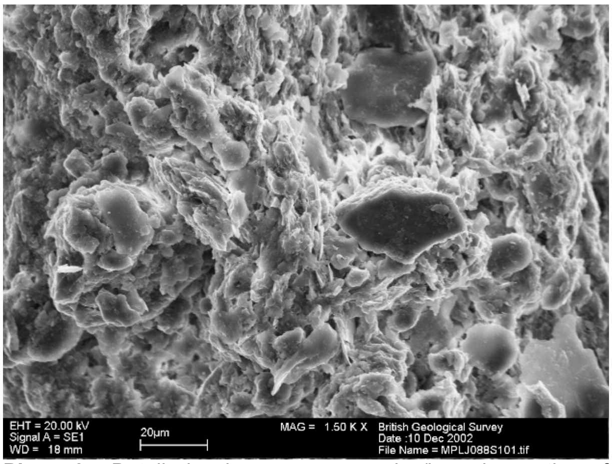


**Photo 3:** Detail showing a more massive/irregular portion of the sample with irregularly aligned particles.

| | | | |
|---|---|---|---|
| Site: | **Kettleness** | SampleID: | **Kettleness** |
| Basin: | **Cleveland** | Formation: | **Cleveland Ironstone** |
| MPL Sample Code: | **H591S1** | Preparation: | **Air dried, fresh fracture surface** |

This sample displays significant colour variations in hand specimen, and these are mirrored by changes in character of the sample at the fine scale. In both black and grey-red portions of the sample porosity is very low, and poorly connected.

**Black portion in hand specimen**

This portion of the sample is tightly packed and comprises sub-circular, aligned platelets (in places almost botryoidal in appearance due to the orientation of the sample surface being approximately parallel to lamination). EDXA indicates Al >> Si = Fe concentrations, with no significant K, Ca or Mg in this material. This composition may be suggestive of chlorite/berthierine, but the high Al/Si ratio is anomalous. Numerous, microfractures criss-cross across this material suggesting that it has fractured slightly during preparation (possible shrinkage cracks).

**Grey-red portion in hand specimen**

This portion of the sample is more chaotic in appearance than that exposed in the black area. Here the sample is seen to comprise very closely packed, irregular platelets with variable Fe-K-Ca-Mg-Na-Al-Silicate compositions. Fe-oxides are abundant and occur as clay-sized platelets (which are difficult to differentiate texturally from clays). Minor pyrite euhedra (< 10 microns diameter) are also noted.

Photomicrographs:

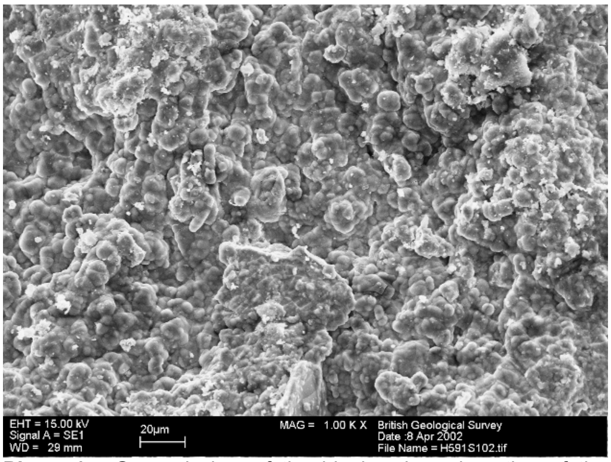


**Photo 1:** General view of the black coloured portion of the sample showing poorly porous material made up of amorphous, almost botryoidal material.

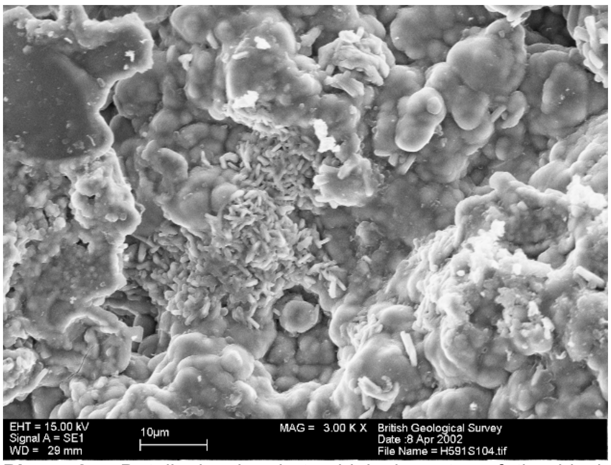


**Photo 2:** Detail showing botryoidal character of the black portions of the sample. The rod-shaped crystals near the centre of the image are Fe-Al-Silicate (possible chlorite?).

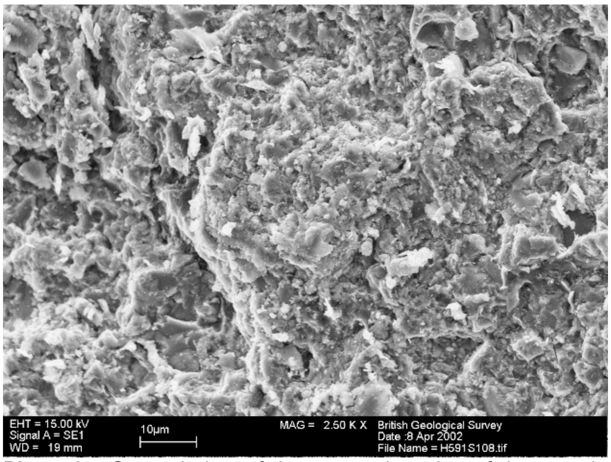


**Photo 3:** General view of the grey-red portion of the sample showing a mass of fine clay platelets.

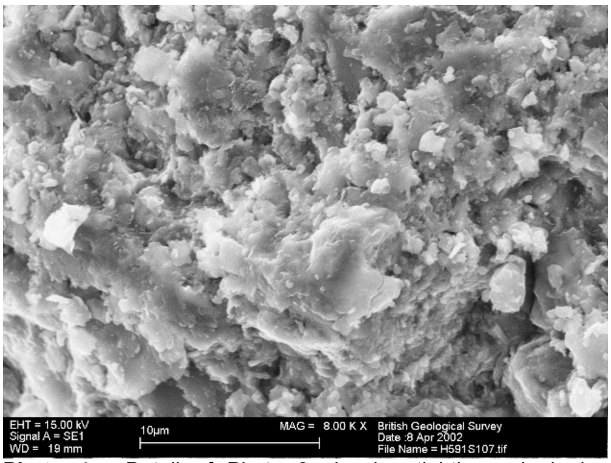


**Photo 4:** Detail of Photo 3 showing tightly packed clay platelets with highly irregular margins.

| | | | |
|---|---|---|---|
| Site: | **Robin Hood's Bay** | SampleID: | **Robin Hood's Bay** |
| Basin: | **Cleveland** | Formation: | **Redcar Mudstone** |
| MPL Sample Code: | **H590S1** | Preparation: | **Freeze dried, fresh fracture surface** |

This sample is essentially homogeneous and contains widespread grains (typically <100 microns diameter) of quartz (EDXA response masked by grain-coating clay and matrix clay), in a predominantly K-Al-silicate (+/- Fe, Ca and Mg-bearing; illite +/- smectite) and Al-silicate (kaolinitic) matrix (mineralogy supported by XRD data). Minor, euhedral quartz overgrowths are developed, and engulf authigenic grain-rimming clay. Crystals in clays grain coating are tangential to the grain surface and commonly have platy authigenic crystals emanating from them. Matrix clay occurs as amorphous masses within which individual crystals are evident and as lineaments, locally meniscus-style, of aligned particles. This sample is only poorly porous, with most porosity occurring at the margins of detrital grains.

Photomicrographs:

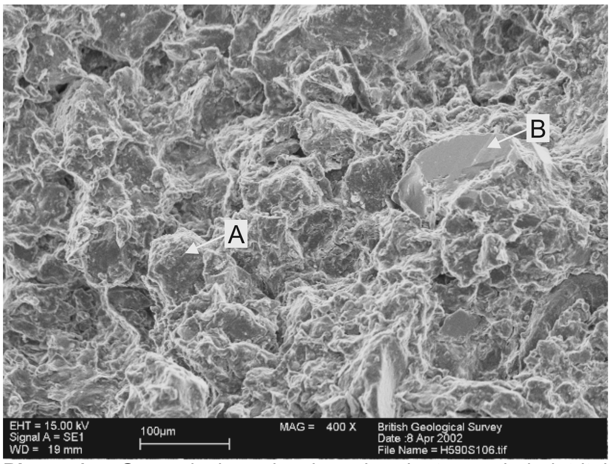


**Photo 1:** General view showing abundant rounded detrital grains, commonly with tangential grain coatings (A). Minor authigenic quartz is also evident (B).

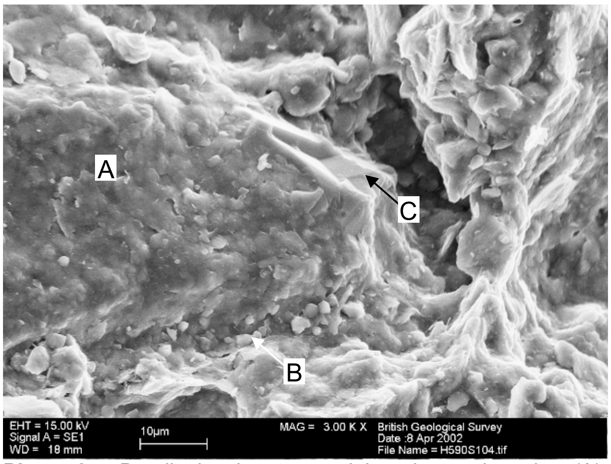


**Photo 3:** Detail showing tangential grain coating clay (A), authigenic platy clay crystals (B), and minor quartz cement (C).

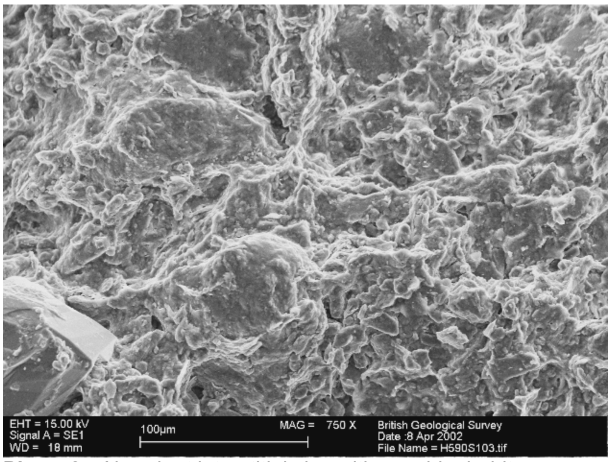


**Photo 2:** Abundant interstitial clay with a webby habit.

## EAST MIDLANDS SHELF (NORTHERN)

| | | | |
|---|---|---|---|
| Site: | **Conesby Quarry** | SampleID: | **Conesby S2** |
| Basin: | **East Midlands Shelf** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **J452S1** | Preparation: | **air dried, fresh fracture** |
| | **J452S2** | | **air dried, fresh fracture/cut surface** |

This sample has a well defined horizontal lamination, with flat laying flakes of clay. The surface of the sample that has been cut with a scalpel indicates relatively low porosity. EDXA indicates that the clay contains sub-equal amounts of K and Ca (?illite-smectite). Disseminated, finely crystalline pyrite euhedra occur throughout (crystals typically 2µm diameter), and minor gypsum/anhydrite occurs as fine crystallites on clay platelets.

The sample is cut by a number of fractures in various orientations. Most of these fractures are closed, but two features are observed which have apertures of approximately 0.2mm which are filled with framboidal pyrite.

Photomicrographs:

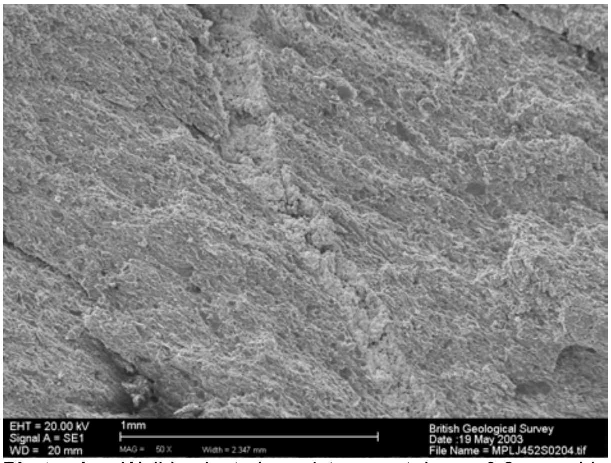


**Photo 1:** Well-laminated mudstone cut by a 0.2mm wide fracture filled with pyrite framboids.

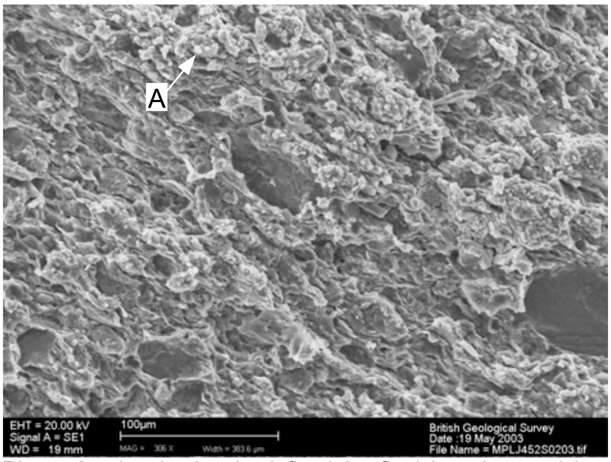


**Photo 2:** Lamination is defined by flat-lying clay particles. Minor disseminated pyrite (2 microns diameter, A) occurs throughout.

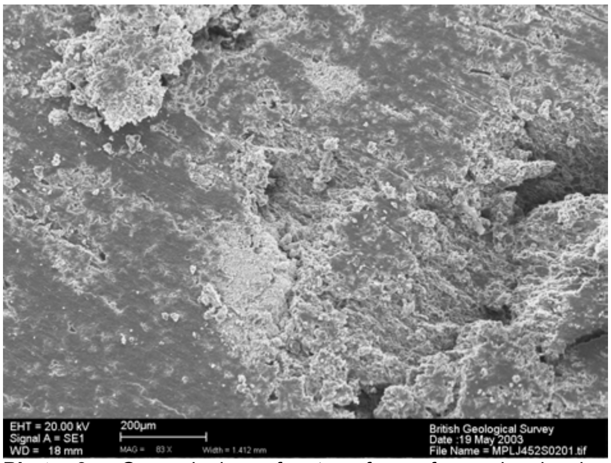


**Photo 3:** General view of cut surface of sample showing relatively low porosity. The centre of the image contains a fracture filled with pyrite framboids.

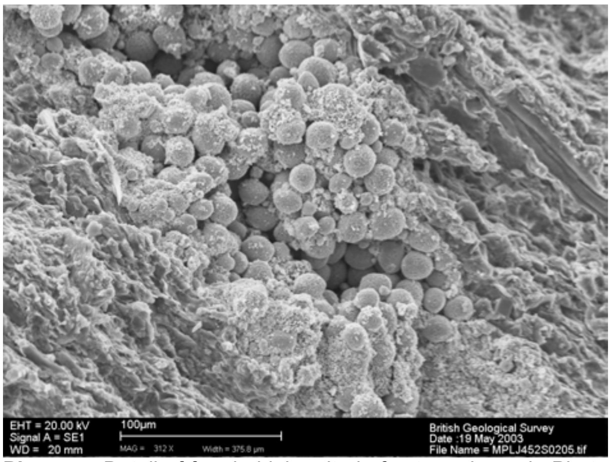


**Photo 4:** Detail of framboidal pyrite in fracture shown in Photo 1.

| | | | |
|---|---|---|---|
| Site: | **Conesby Quarry** | SampleID: | **Conesby S1** |
| Basin: | **East Midlands Shelf** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **J450S1** | Preparation: | **air dried, fresh fracture/cut surface** |

The surface of the sample cut with a scalpel reveals the presence of moderately porous domains within a predominantly poorly porous mudstone. The more porous domains are up to 1 cm in extent and contain pores of approximately 10 microns diameter. In comparison to sample Conesby S2 (J452), this sample is possibly slightly coarser grained (contains silt-grade particles of feldspar and kaolinite) with a less well defined lamination. EDXA analysis indicates a predominance of probable kaolinitic and ?illitic clays. In addition the sample also contains a number of aggregates (possible pellets/clasts?) containing silica (?quartz), gypsum/anhydrite and an unidentified K-Al-Si phase (?clay).

Photomicrographs:

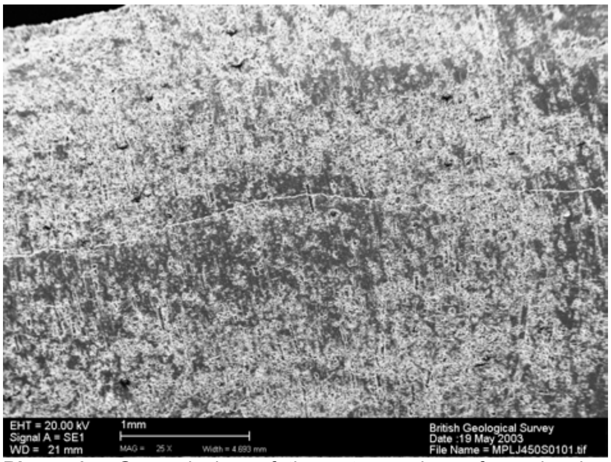


**Photo 1:** General view of the cut sample surface showing variations in porosity. the areas which appear brighter in this image contain greater proportions of pores with diameters at the 10 micron scale. The sample is also cut by a horizontal fracture. The near vertical striations are an artefact of sample preparation.

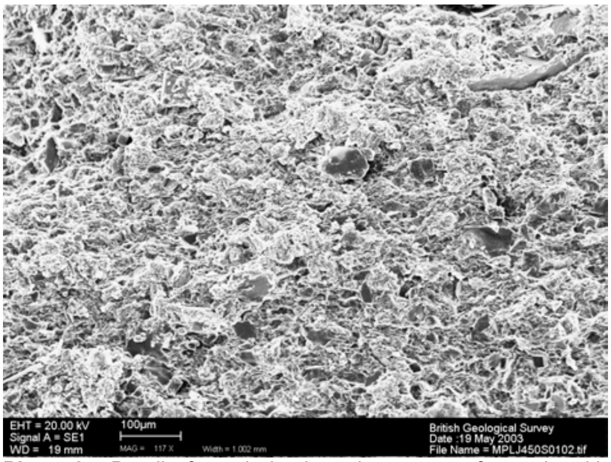


**Photo 2:** Detail of poorly laminated structure of sample with flat-lying platy material.

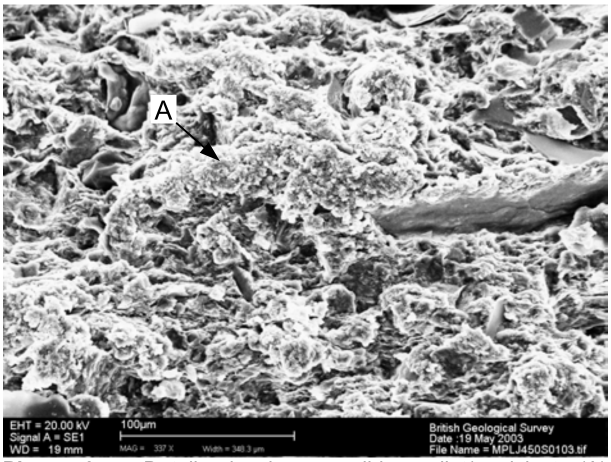


**Photo 3:** Detail showing possible pellet/mudclast (A) containing very fine silica, gypsum/anhydrite and possible clay phase.

| | | | |
|---|---|---|---|
| Site: | **Conesby Quarry** | SampleID: | **Conesby I** |
| Basin: | **East Midlands Shelf** | Formation: | **Scunthorpe Mudstone (Frodingham Ironstone Member)** |
| MPL Sample Code: | **J451S1**<br>**J451S2** | Preparation: | **air dried, fresh fracture (oolitic)**<br>**air dried, fresh fracture (calcite cement)** |

This sample is highly distinctive and contains oblate, well-rounded ooids and peloids, and rare micas which have been replaced by probable goethite (FeO.OH). This observation is based on hand specimen colour and previous work on the Frodingham Ironstone Member; Aggett 1990; Taylor and Curtis 1995). Calcite forms a near-pervasive, coarsely crystalline cement between these grains, which supports a high intergranular volume The green-grey nodules within calcite cemented horizon comprise finely crystalline probable Fe-rich chlorite/berthierine or glauconite which is replaced to variable extent by rhombic siderite and/or calcite. The margin of the calcite-cemented domain is gradational with the calcite-cemented oolitic sediment.

Photomicrographs:

**Photo 1:** Photograph of hand specimen showing oolitic grainstone (top of sample), with domain of coarse calcite cement within which clay-rich green-clay clasts or nodules are floating (lower part of sample).

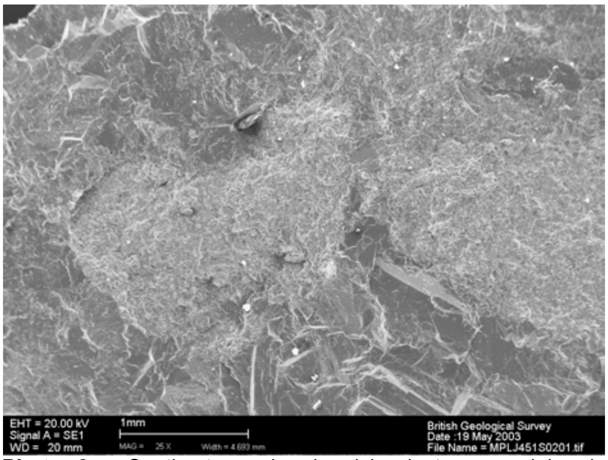


**Photo 3:** Centimetre-scale clay-rich clasts or nodules in coarsely crystalline calcite-dominated domain.

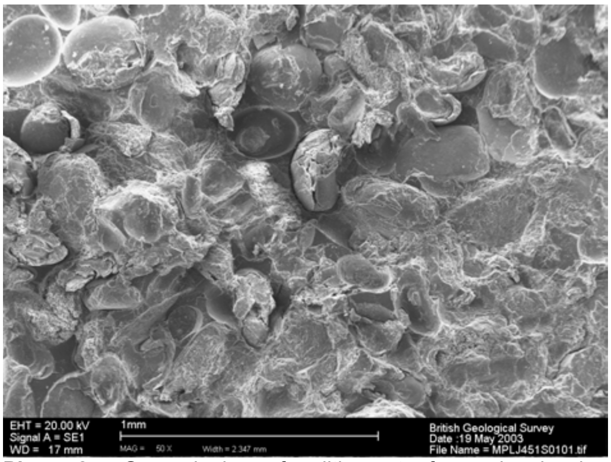


**Photo 2:** General view of oolitic part of sample showing relatively loosely packed ooids and peloids in a pervasive calcite cement.

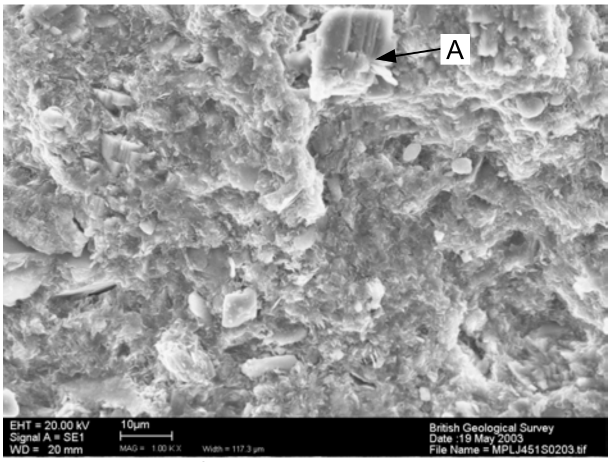


**Photo 4:** Detail of clay-rich clast or nodule within calcite-cemented domain, showing finely crystalline clay (probable chlorite) being replaced by fine rhombs of siderite (A).

| | | | |
|---|---|---|---|
| Site: | **Flixborough Quarry** | SampleID: | **Flixborough** |
| Basin: | **East Midlands Shelf** | Formation: | **Scunthorpe Mudstone** |
| MPL Sample Code: | **J453S1** | Preparation: | **air dried, fresh fracture/cut surface** |
| | **J453S2** | | **air dried, fresh fracture** |

The cut surface of stub S1 reveals a poorly porous mudstone containing small (up to 0.5 mm), lamination-parallel patches of finely crystalline pyrite. The fresh fracture surface indicates that the sample has a well-defined lamination with flat-lying micas and clay particles. EDXA indicates that the clay has a K-Ca-Mg-Al-Si + minor Fe bearing composition (illite/smectite?). Gypsum/anhydrite is well-developed throughout the sample as a finely crystalline encrustation on the detrital material. Stub S2 confirms the observations on stub S1, but also contains a phosphatic shell fragment.

Photomicrographs:

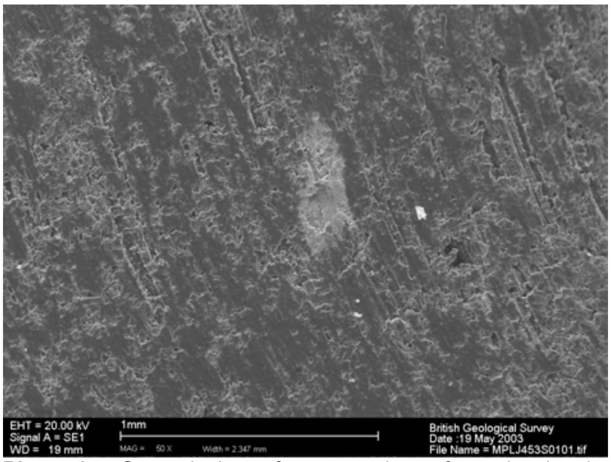


**Photo 1:** General view of cut sample surface showing its poorly-porous nature and a small patch of finely crystalline pyrite (bright feature in centre of image). Sample is rotated and tilted so lamination runs approximately North-South, the curved striations are an artefact of sample preparation. (B).

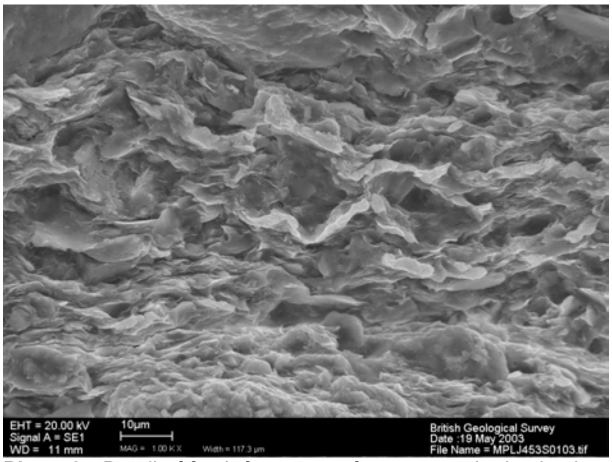


**Photo 3:** Detail of fresh fracture surface across the lamination, showing the well-defined nature of the lamination with flat lying clay particles.

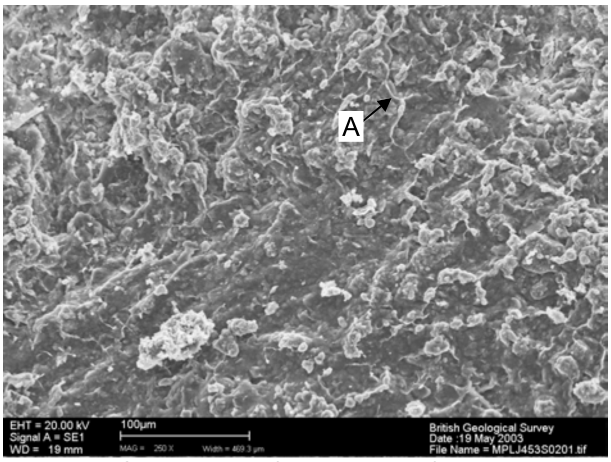


**Photo 2:** General view of lamination surface. The poorly porous nature of the sample is confirmed. The webby clays (A) may represent authigenic clay, or more likely are an artefact of sample preparation.

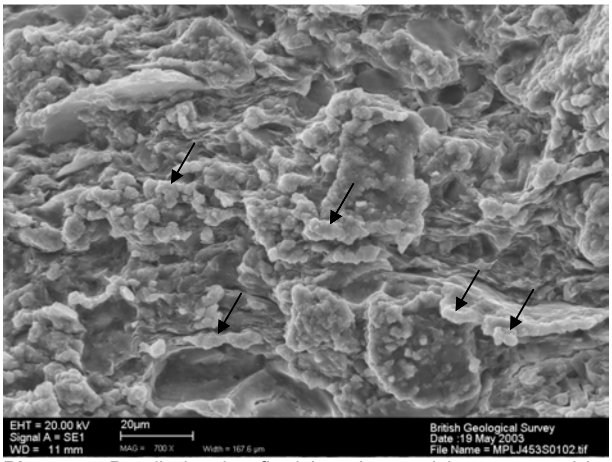


**Photo 4:** Detail showing flat-lying clay particles encrusted by finely crystalline gypsum/anhydrite (arrowed).

| | | | |
|---|---|---|---|
| Site: | **Norton Bottoms** | SampleID: | **Norton Bottoms** |
| Basin: | **East Midlands Shelf** | Formation: | **Scunthorpe Mudstone** |
| MPL Sample Code: | **J454S1** | Preparation: | **air dried, fresh fracture/cut surface** |

The cut surface of this sample reveals a poorly porous, faintly laminated mudstone. EDXA indicates a Ca-K-Al-Si (+minor Mg + Fe) bearing composition for the clay (illite-smectite?). The clay is patchily replaced by calcite and very rare rhombic Fe-rich carbonate (?siderite). Bioclastic material is relatively abundant and bioclasts typically have finely crystalline overgrowths.

Photomicrographs:

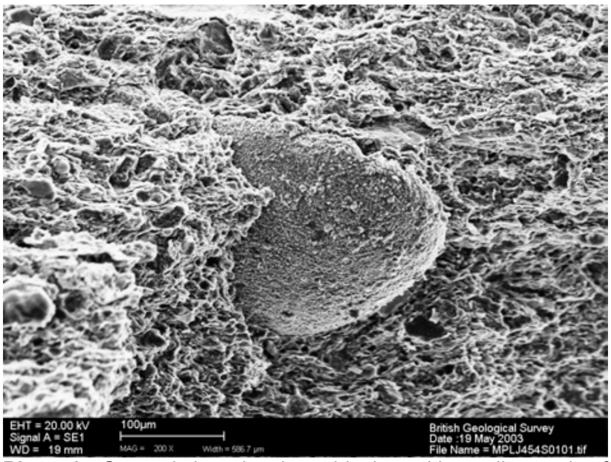


**Photo 1:** General view showing a bioclast with small crystals of calcite overgrowth, sitting in a laminated matrix of clay particles.

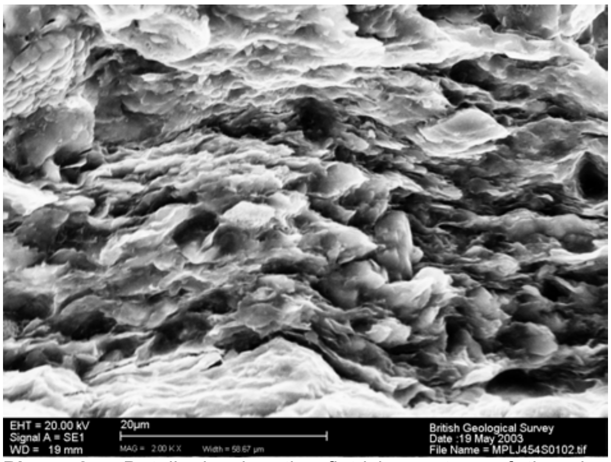


**Photo 2:** Detail showing the flat-lying nature of the clay particles.

| | | | |
|---|---|---|---|
| Site: | **Whisby Quarry** | SampleID: | **Whisby** |
| Basin: | **East Midlands Shelf** | Formation: | **Scunthorpe Mudstone** |
| MPL Sample Code: | **J455S1** | Preparation: | **air dried, fresh fracture/cut surface** |
| | **J455S2** | | **air dried, fresh fractured concretion** |

The cut surface of stub S1 reveals a poorly porous sample cut by numerous fractures parallel to a poorly defined horizontal lamination. The sample contains abundant gypsum/anhydrite making it difficult to meaningful EDXA data for the clays, however, where this is possible a K-(Mg)-Al-Si-bearing (illitic?) composition is indicated. The gypsum/anhydrite occurs in similar manner to that seen in sample J453, but is also well develop adjacent to and on natural fractures within the sample as a fine encrustation and as coarser euhedra.

Stub S2 represents a fresh fracture surface through a cm-scale nodule picked from the mudstone. SEM analysis indicates that this is an apatite-dominated concretion which also contains fine particle of quartz, kaolinite and minor clays. The apatite ranges from very coarsely to very finely crystalline.

Photomicrographs:

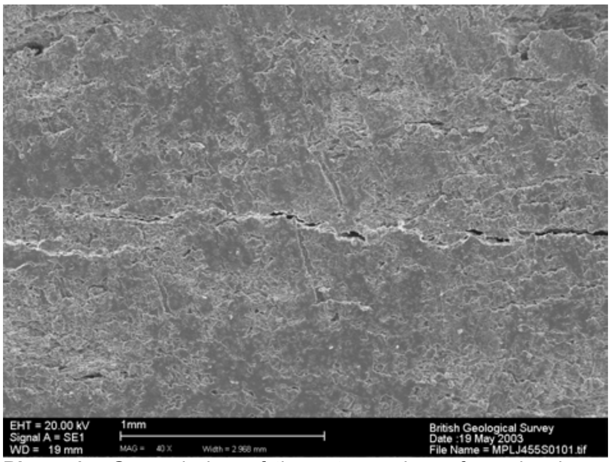


**Photo 1:** General view of the cut sample surface showing a poorly porous mudstone cut by a number of fine horizontal fractures. The vertical striations are an artefact of sample preparation.

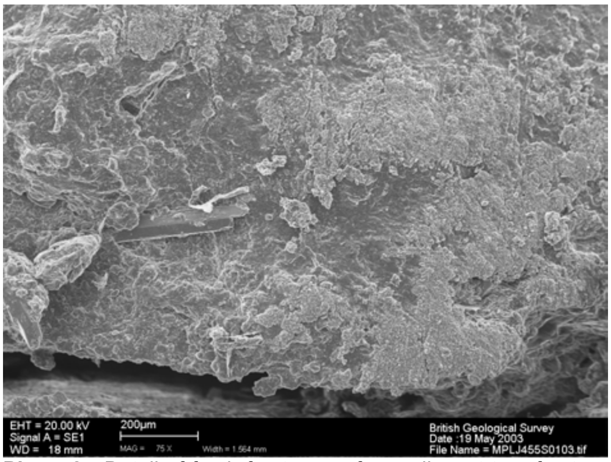


**Photo 2:** Detail of fresh fracture surface adjacent to a fracture within the sample. The sample surface is encrusted with finely crystalline and rarer coarse crystals of gypsum/anhydrite.

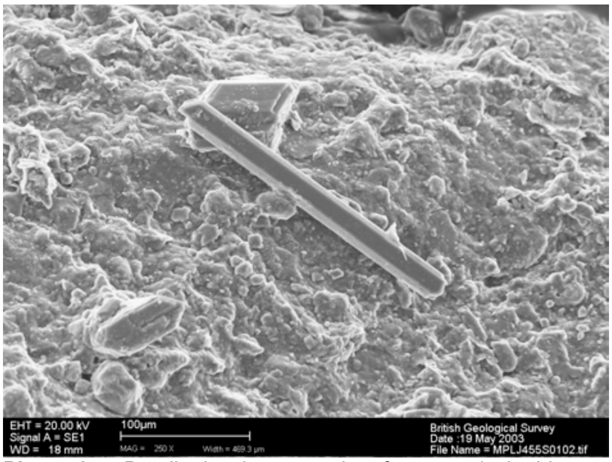


**Photo 3:** Detail showing crystals of gypsum/anhydrite on natural fracture surface within sample.

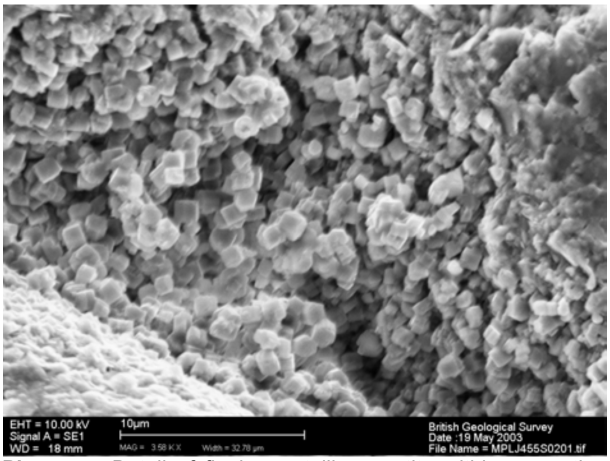


**Photo 4:** Detail of finely crystalline apatite within concretion removed from the sample.

| | | | |
|---|---|---|---|
| Site: | **Barnestone Quarry** | SampleID: | **Barnestone** |
| Basin: | **East Midlands Shelf** | Formation: | **Scunthorpe Mudstone (Barnstone Limestone Member)** |
| MPL Sample Code: | **J449S1** | Preparation: | **air dried, fresh fracture** |
| | **J449S2** | | **air dried, fresh fracture** |

Although lamination is clearly defined in this sample at hand specimen scale, at a finer scale this lamination is less well defined, with thin laminae. The sample is dominated by fine grained calcite, with isolated very fine (<10 micron diameter) rhombic dolomite crystals. Clay occurring on and between the calcite crystals is a relatively minor component, with EDXA indicating a K-Ca-Al-Si bearing composition (Al:Si = 3:4; illite/ smectite?).

Photomicrographs:

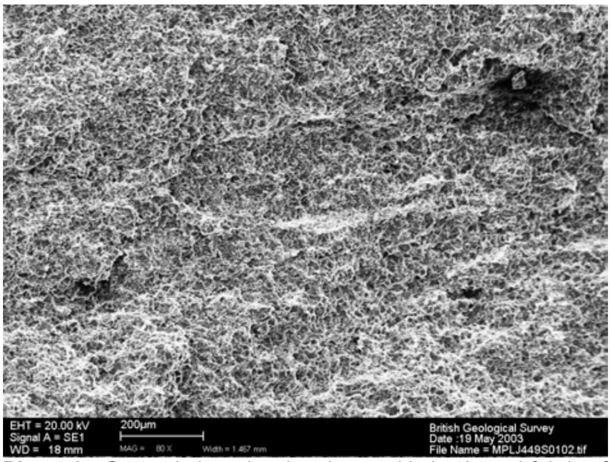


**Photo 1:** General view showing the weakly laminated fabric of the sample.

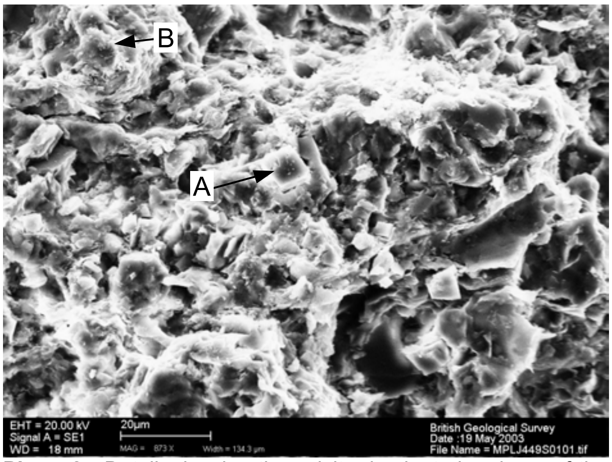


**Photo 2:** Detail, showing the calcite-dominated makeup of the sample. Within the calcite, small (10 micron) rhombs of dolomite are developed (A). Clay is a minor component (B).

## EAST MIDLANDS SHELF (SOUTHERN)

| | | | |
|---|---|---|---|
| Site: | Site Landfill, **Brixworth** | SampleID: | **BW1** |
| Basin: | **East Midlands Shelf** | Formation: | **Whitby Mudstone** |
| MPL Sample Code: | **H416S1** | Preparation: | **Freeze dried, fresh fracture/cut surface** |

The surface of this stub comprises a fresh fracture surface which has been partially cut with a scalpel.

The fresh fracture surface is sub-parallel to lamination, and is highly irregular with a stepped/terraced appearance. Clay particles occur in small aggregates, a few 10's of microns in diameter. The clay in these aggregates appears relatively amorphous, although at higher magnification minor crenulations and individual platelets are evident within and emanating from the amorphous clay.

The cut surface indicates no compositional variability, and moderate amounts of evenly distributed, poorly connected porosity. Although XRD analysis suggests a predominantly kaolinitic mineralogy, EDXA suggests predominantly K-bearing, and local Ca-Mg-bearing clays (predominantly illite, with subordinate smectite?).

Photomicrographs:

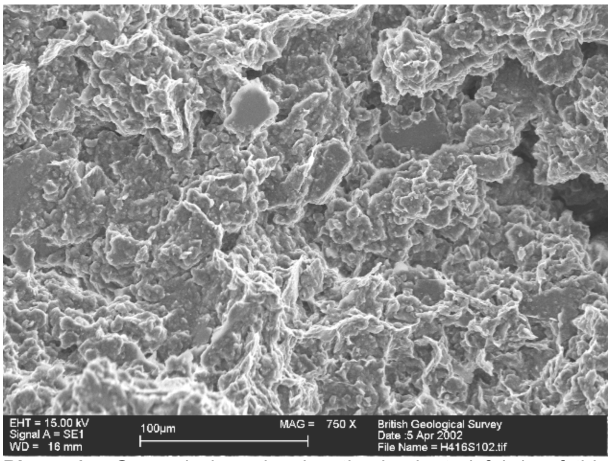


**Photo 1:** General view showing the laminated fabric of this sample. Because the sample surface is approximately parallel to lamination, lamination manifests itself as a series of steps/terraces.

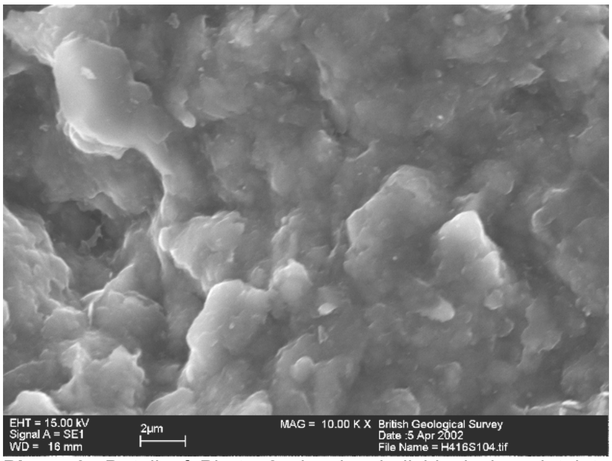


**Photo 3:** Detail of Photo 2 showing individual clay platelets within clay which appears relatively homogeneous at lower magnifications.

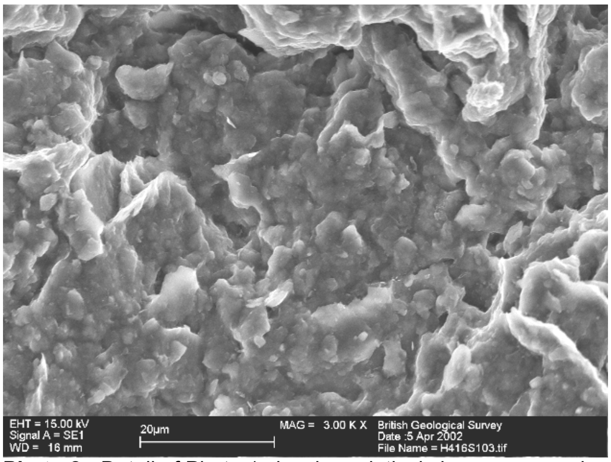


**Photo 2:** Detail of Photo 1 showing relatively homogenous clay within which minor platelets are evident.

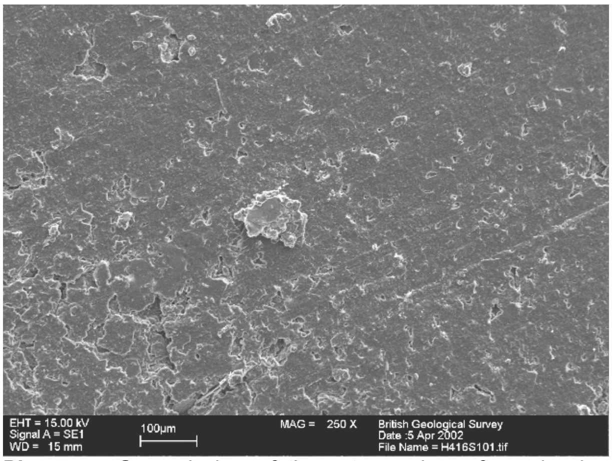


**Photo 4:** General view of the cut sample surface showing compositional homogeneity and minor amounts of poorly connected micropores.

| | | | |
|---|---|---|---|
| Site: | **Sidegate Lane**, Finedon | SampleID: | **SL1** |
| Basin: | **East Midlands Shelf** | Formation: | **Whitby Mudstone** |
| MPL Sample Code: | **H411S1** | Preparation: | **Freeze dried, fresh fracture surface** |
| | **H411S2** | | **Freeze dried, cut surface** |

**H411S1** Fresh fracture surface

At moderate magnification, clay in this sample has a relatively "smooth" appearance with relatively poorly differentiated clay particles/platelets. The sample surface is characterised by fine webby crenulations, which may represent an artefact of preparation or authigenic clays (probably the former). In more detail however, within this "smooth" clay distinct "lumps" are evident. EDXA indicates variable compositions, but suggests a predominance of K-bearing clay (?illite). Also noted are locally significant Ti concentrations within the clays (these probably represent discrete Ti-oxide particles). Microporosity is localised appearing as circular features approx. 10 microns diameter at the sample surface (could be spherical or tubular in 3-dimensions). Larger pores (>100 microns) are also noted in the sample, and tend to occur as elongate features of variable orientation. Minor patches of gypsum/anhydrite, with radiating prismatic crystals are present. Filamentous, strands of an unidentified material (<1 micron wide and 100-200 microns long) are irregularly distributed on the sample surface.

**H411S2** Cut surface

Low magnification imaging indicates no compositional variations inferred from grey-scale variations on the cut surface. This preparation mechanism also seems to confirm the observations from H411S1 that the pores are elongate, and also gives an indication of their size and distribution - this sample is more porous than stub H411S1 would suggest. EDXA confirms a predominantly K-bearing composition for the clay (?illite), although XRD indicates major kaolinite with minor illite, chlorite and illite/smectite.

Photomicrographs:

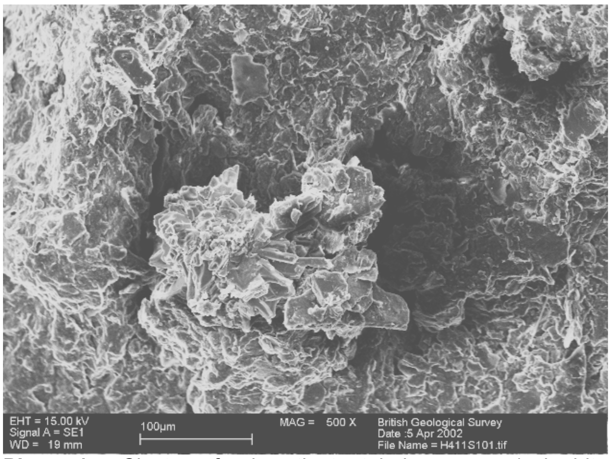


**Photo 1:** Cluster of prismatic to tabular gypsum/anhydrite crystals.

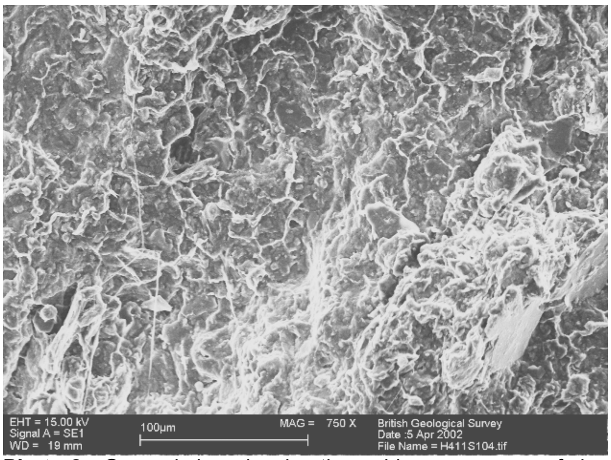


**Photo 2:** General view showing the webby appearance of clay on a fresh fracture surface. Also note the fibres lying on sample surface.

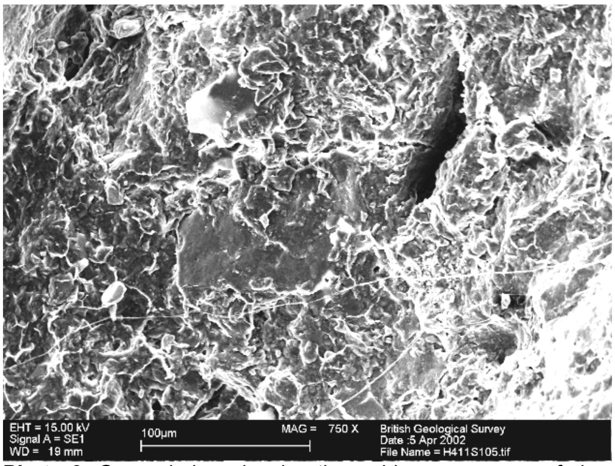


**Photo 3:** General view showing the webby appearance of clay on fresh fracture surface. Also note the fibres lying on the sample surface.

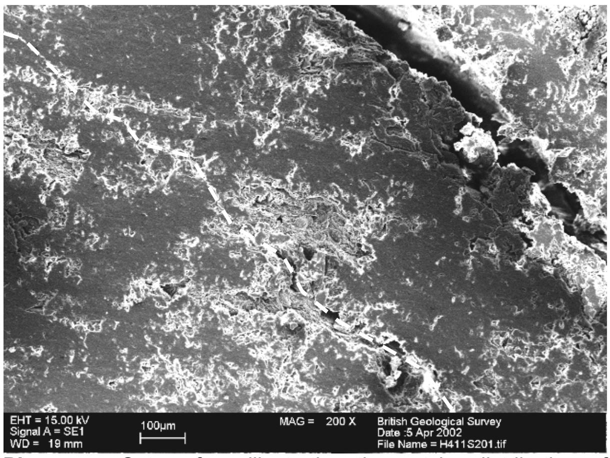


**Photo 4:** Cut surface illustrating the patchy distribution of porosity in this sample. The less well packed, porous domains are oriented parallel to lamination, and along a possible shear surface cuts the field of view.

| | | | |
|---|---|---|---|
| Site: | **Sidegate Lane**, Finedon | SampleID: | **SL2** |
| Basin: | **East Midlands Shelf** | Formation: | **Whitby Mudstone** |
| MPL Sample Code: | **H412S1** | Preparation**:** | **Freeze dried, fresh fracture/cut surface** |

The surface of this stub comprises a fresh fracture surface which has cut over a portion of it's surface using a scalpel.

The cut surface indicates no obvious compositional heterogeneity, and shows relatively limited amounts of porosity (less than observed on cut surface of Sidegate Lane 1 (H411S2). EDXA of the clays indicate a similar composition to that seen in Sidegate Lane sample 1 (H411), being predominantly K-bearing (+Mg + Fe; ?illitic; although XRD indicates a kaolinite dominated, with minor illite, chlorite and illite/smectite clay fraction). Minor Fe-Ti-oxide particles are also noted..

On the fresh fracture surface, a very well defined lamination is apparent, with the sample breaking into elongate fragments. Also evident are relatively abundant flat-lying mica plates, and small patches (<100 microns) of finely crystalline, displacive pyrite framboids. Clay particles are clearly defined on the fresh fracture surface, and appear platy, flat lying and wrap around silt-grade particles. Minor fibrous/ribbon-like emanations are evident growing from some platelets.

Photomicrographs:

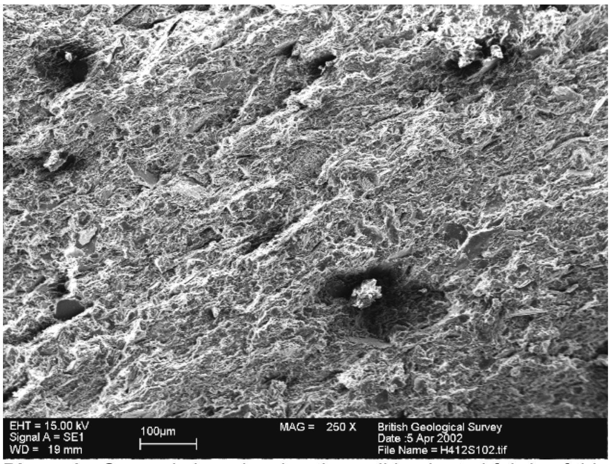


**Photo 1:** General view showing the well laminated fabric of this sample.

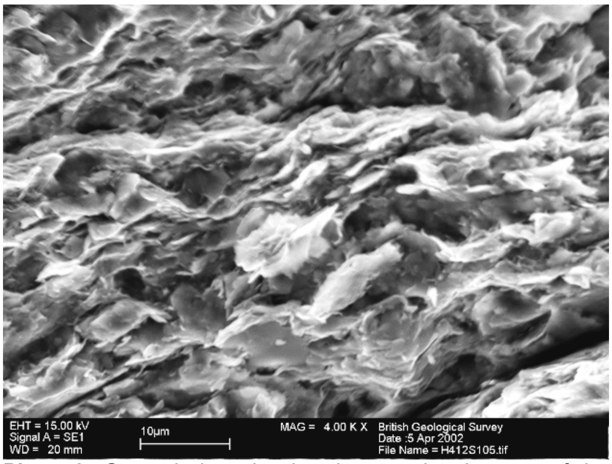


**Photo 3:** General view showing the crenulated nature of the clay platelets and the development of minor rosette structures (centre).

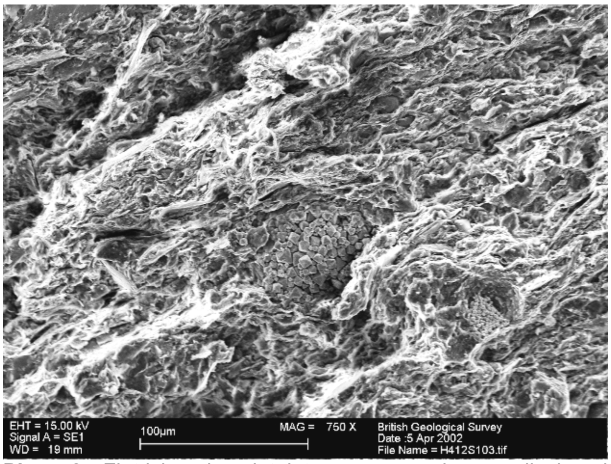


**Photo 2:** Flat lying clay platelets wrap-around or are displaced by framboidal pyrite (centre).

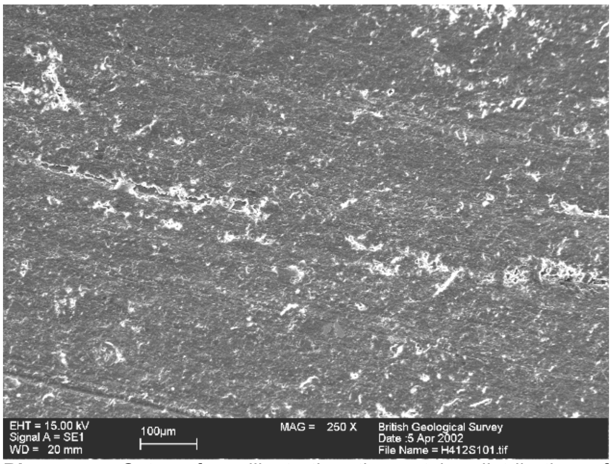


**Photo 4:** Cut surface illustrating the patchy distribution of elongate porosity within this sample.

| | | | |
|---|---|---|---|
| Site: | **Edge Hill,** Banbury | SampleID: | **EH1** |
| Basin: | **East Midlands Shelf** | Formation: | **Marlstone Rock** |
| MPL Sample Code: | **H417S1** | Preparation**:** | **Freeze dried, fresh fracture surface** |
| | **H417S2** | | **Freeze dried, cut surface** |

**H417S1** Fresh fracture surface

This is a highly porous, and in the context of this suite of samples, a permeable sample, comprising loosely packed grains of Fe-Al-Silicate (possible chlorite/berthierine peloids/ooids?), coated with Fe-Al-Silicate (chlorite) with diverse array of morphologies with extensive evidence for recrystallisation of the original clay with development of: skeletal euhedral hexagonal crystals, which may be replaced by finely crystalline platelets, honeycomb-structures, and webby-outgrowths. XRD analysis indicates major smectite and minor kaolinite in the clay-fraction. The interstices between these grains are irregularly packed with spongy to platy clays, locally showing skeletal hexagonal forms also seen on grain coatings. The interstitial clay has a similar Fe-Al-Silicate (?chlorite) composition to the grain coatings. Minor Mn-nodules (approx. 100 microns diameter) are present in the cores of some ooids. Macropores in excess of 100 microns diameter are well connected.

**H417S2** Cut surface

This stub adds little to the observations made on the fresh fracture surface.

Photomicrographs:

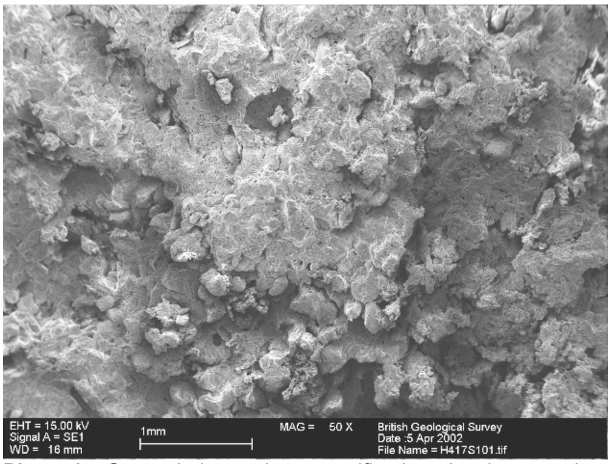


**Photo 1:** General view at low magnification showing massive, loosely packed sample with abundant fine-sand grade grains with interstitial clay.

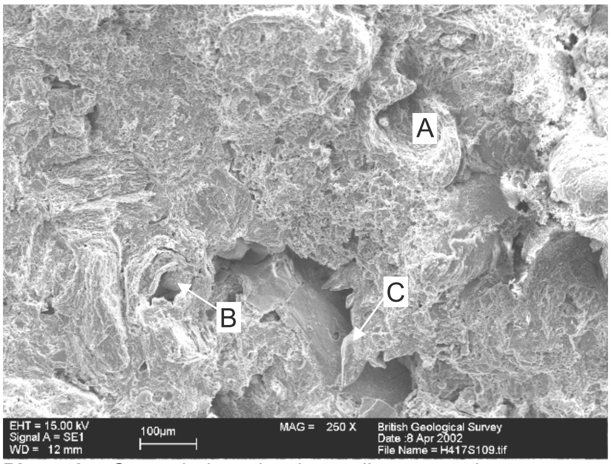


**Photo 2:** General view showing well connected macropores, fractured ooids showing internal concentric lamination (A), Mn-nodule (B), and unusual euhedral Fe-oxide crystals (C).

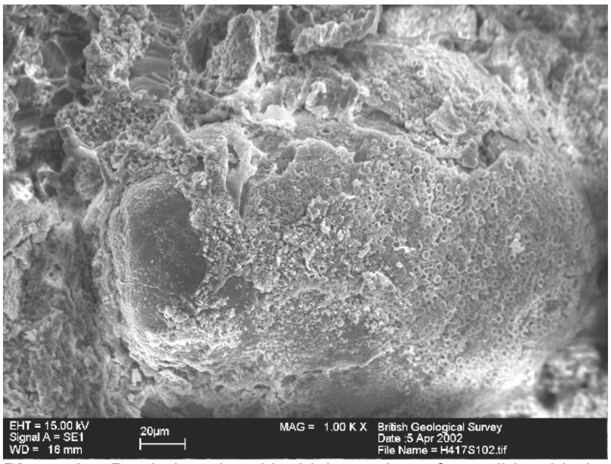


**Photo 3:** Detrital grain with thick coating of possible chlorite crystals displaying a wide range of morphologies.

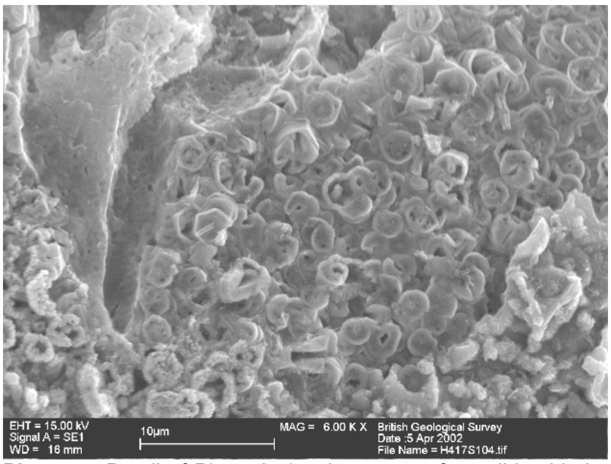


**Photo 4:** Detail of Photo 3 showing range of possible chlorite crystal morphologies.

| | | | |
|---|---|---|---|
| Site: | **Hornton Grounds**, Wroxon | SampleID: | **HT1** |
| Basin: | **East Midlands Shelf** | Formation: | **Marlstone Rock** |
| MPL Sample Code: | **H409S1** | Preparation: | **Freeze dried, disaggregated material** |

Once dried this sample was highly friable and all attempts to prepare a fresh fracture surface failed, with stubs collapsing even with gentlest of handling. Therefore, this sample comprises a few grains, and grain aggregates. As such it largely represents disaggregated material and consequently charges badly under electron bombardment.

The majority of grains preserved on this stub are very well rounded, cracked pellets/beads (200-300micron diameter) of an Fe-rich mineral, which could possibly be berthierine or chlorite?. Interstitial, finely particulate clay occurs in between these pellets/beads and has a similarly Fe-rich composition. Two intact aggregates of the sample are also observed, one of these comprises material of similar character to that described above. However, the other contains finer-grained (100 micron diameter), pellets/beads/nodules of a Mn-oxide in a clay-grade matrix of Fe-rich composition (?berthierine/chlorite?). Clay fraction XRD analysis of this sample suggests a smectite-dominated clay mineralogy with minor illite and kaolinite.

Photomicrographs:

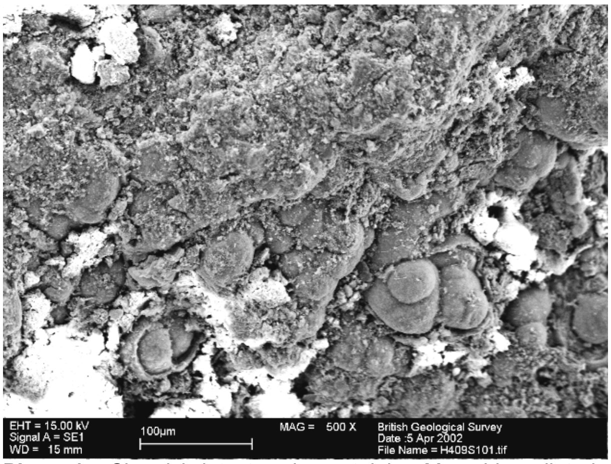


**Photo 1:** Clay-rich intact grain containing Mn-oxide pellets in Fe-Al-Silicate (berthierine/chlorite matrix).

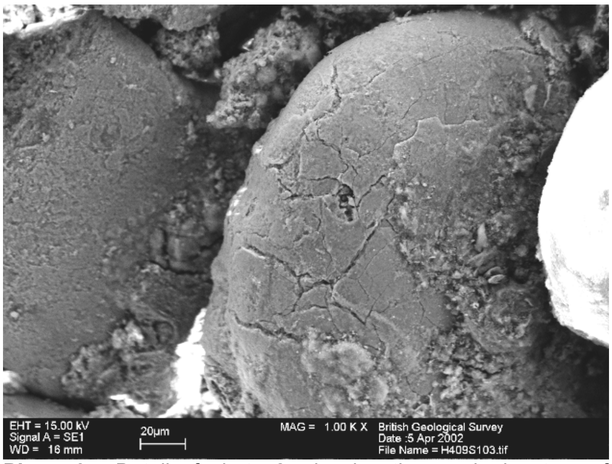


**Photo 3:** Detail of photo 2, showing the cracked nature of berthierine/chlorite pellets.

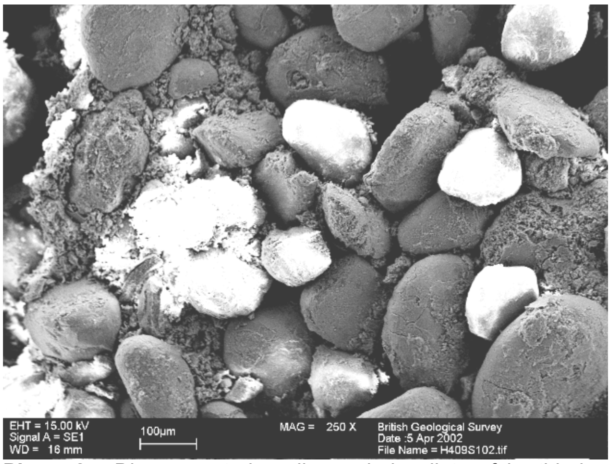


**Photo 2:** Disaggregated, well rounded pellets of berthierine /chlorite. The “bright” grains are charging due to electron bombardment.

| | | | |
|---|---|---|---|
| Site: | **Alkerton**, Edge Hill | SampleID: | **AL1** |
| Basin: | **East Midlands Shelf** | Formation: | **Marlstone Rock** |
| MPL Sample Code: | **H413S1** | Preparation: | **Freeze dried, fresh fracture/cut surface** |

The surface of this stub comprises a fresh fracture surface which has cut over a portion of it's surface using a scalpel.

On the fresh fracture surface, calcite is very prominent and occurs as rhombs, irregular stubby euhedra, and more rarely as cone-in-cone structures. Also evident on the fresh fracture surface is the nature of the larger scale fabric of this sample, which can be seen to comprise discrete clumps of clay particles, which are squashed together. Minor amounts of porosity occur between the clumps. Within clumps clay particles may be laminated/aligned, or irregularly distributed. A single clast, comprising a coarse, degraded verm of kaolinite is observed.

On the cut surface, EDXA indicates predominantly Fe and Ca-bearing compositions for the clay. (?berthierine/chlorite + smectite?). Fe- concentrations are high and account for this samples orange colour in hand specimen. Minor Fe-oxy-hydroxide framboids, and nodules are noted (EDXA indicates high O contents for Fe content). These mineralogical observations are supported by the XRD data, which indicate major calcite (with only trace quartz in the whole-rock sample), with minor chlorite and geothite being minor components of both the whole rock and the clay fraction analyses.

Photomicrographs:

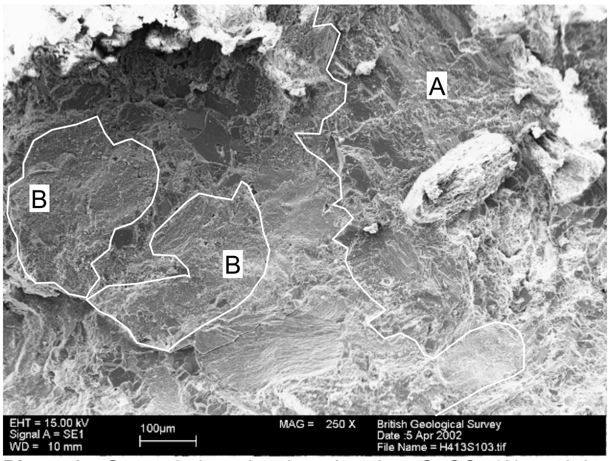


**Photo 1:** General view showing abundant $CaCO_3$ (A), and the presence of distinctly rounded aggregates of clay particles (B).

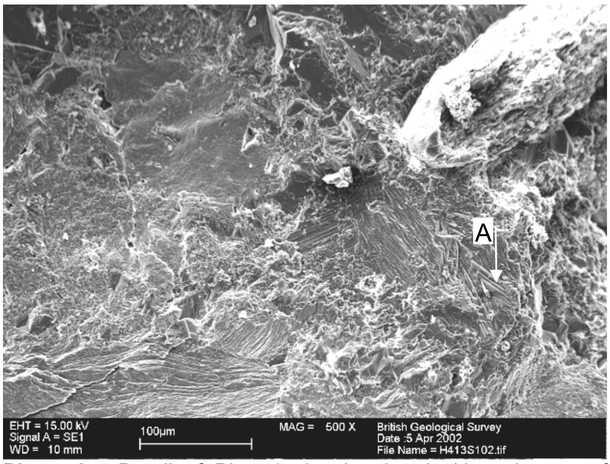


**Photo 2:** Detail of Photo1 showing interlocking clusters of cone-in-cone calcite (A).

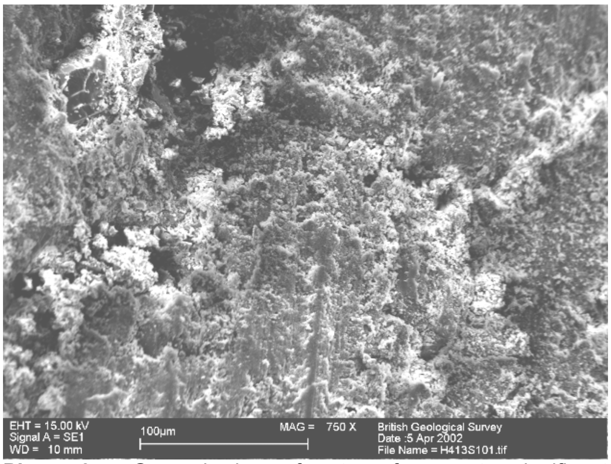


**Photo 3:** General view of cut surface, note significant disruption of fabric in this example.

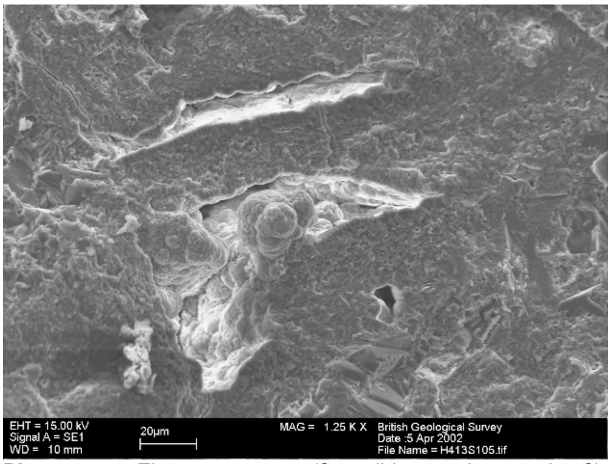


**Photo 4:** Elongate pores (?possible tension gashes?), containing botryoidal Fe-oxy-hydroxides (centre).

| | | | |
|---|---|---|---|
| Site: | **Southam** Cement, Southam | SampleID: | **SH1** |
| Basin: | **East Midlands Shelf** | Formation: | **Blue Lias** |
| MPL Sample Code: | **H410S1** | Preparation**:** | **Freeze dried, fresh fracture surface** |
| | **H410S2** | | **Freeze dried, fresh fracture surface** |

**H410S1** – low angle to lamination

Discrete clay particles are typically evident within this sample, and local crenulations are visible. EDXA suggests approximately equal amounts of kaolinite (Al-Silicate indicated on EDXA spectra) and smectite (variable Ca-Mg-Al (+/-K) ratios indicated on EDXA spectra). Rare K-rich clays are also noted (?possible illite). CaCO3 occurs as fine crystals in patches a few 10microns in diameter, and more rarely as tiny Ca-rich particles (?probably embedded within Ca-bearing clay particles. Micro-porosity occurs throughout as <10 micron pores between clay particles, and also as larger more isolated rounded features up to 20 microns diameter.

**H410S2** – across lamination

There is a notable difference in character of this sub-sample relative to H410S1. Clay here occurs as coarser, blocky particles, with no evidence for development of the fine platelets seen in H410S1. Although lamination is clearly defined at low magnification, at higher magnification it is less clear, with clay particles appearing to be randomly oriented. EDXA also indicates a predominance of kaolinite (Al-silicate) and probable illite (K-Al-silicate), with relatively minor amounts of Ca-bearing clay.

Photomicrographs:

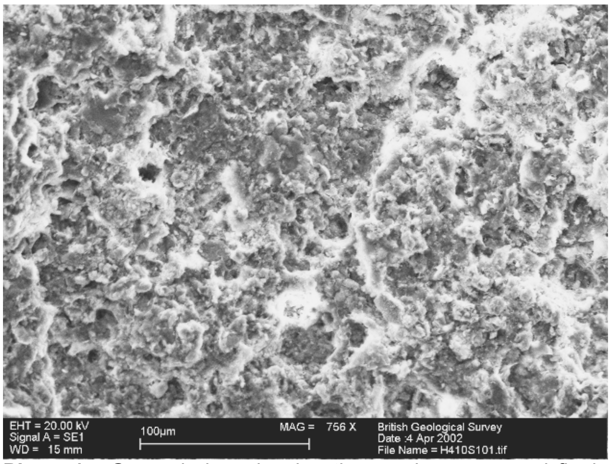


**Photo 1:** General view showing the poorly porous and finely particulate character of H410S1.

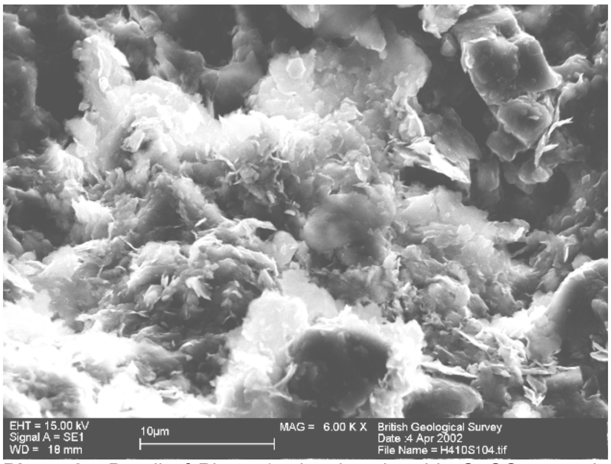


**Photo 2:** Detail of Photo 1, showing rhombic $CaCO_3$ crystals (top right), and fine clay crystals of a range of sizes (1 - >10 microns).

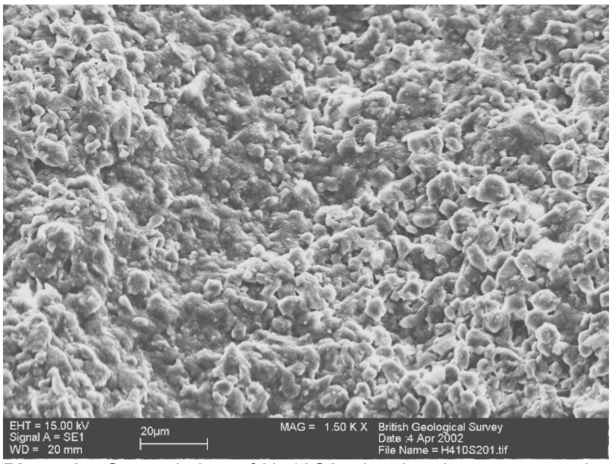


**Photo 3:** General view of H410S2, showing the more granular character of this sub-sample relative to H410S1.

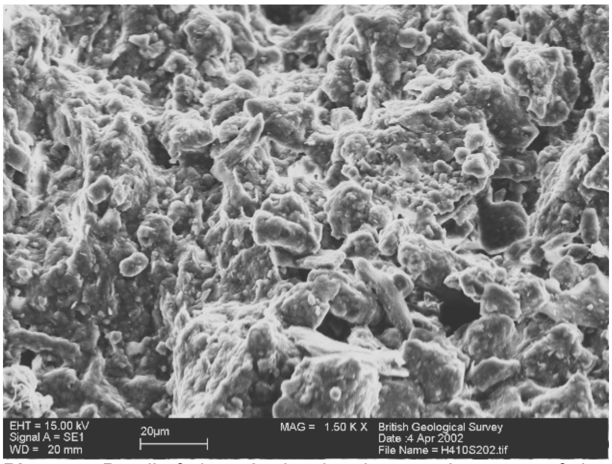


**Photo 4:** Detail of photo 3, showing the granular nature of clay particles.

## WORCESTER BASIN

| | | | |
|---|---|---|---|
| Site: | Tufley, **Robin's Wood Hill** | SampleID: | **RW2** |
| Basin: | **Worcester** | Formation: | **Marlstone Rock** |
| MPL Sample Code: | **H418S1** | Preparation**:** | **Freeze dried, fresh fracture/cut surface** |

The surface of this stub comprises a fresh fracture surface which has cut over a portion of it's surface using a scalpel.

The fresh fracture surface reveals a tightly packed, poorly porous, well-laminated mudstone with some elongate pore/microfractures parallel to a moderately well defined lamination.  Minor wispy/webby emanations are noted on some clay particles.

The cut surface indicates a mottled mudstone containing domains with two distinct textures.  This mottling occurs on a scale of approximately 100-200 microns.  No compositional difference can be inferred using EDXA analysis, with both domains indicating high Al-Si contents, and low but variable contents of K, Ca and Fe.  XRD indicates a kaolinite dominated clay fraction.  Texture A appears darker, but this could relate to bright "edges" in more porous patches of Texture B:

- Texture A (40% of cut surface) - tightly packed,, low porosity mottles, commonly elongate parallel to lamination (relict of depositional lamination), within which individual crystals are poorly resolved.
- Texture B (60% of cut surface)- loosely packed, highly porous (pores approx. 1-10 microns diameter), within which individual blocky to platy (?recrystallised) clay particles/crystals are evident.

Photomicrographs:

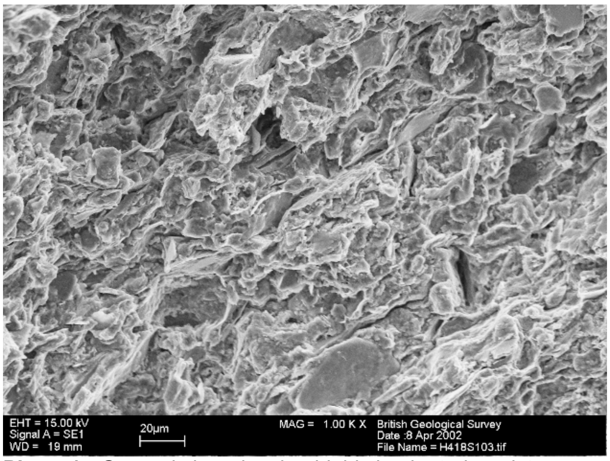


**Photo 1:** General view showing highly laminated mudstone.

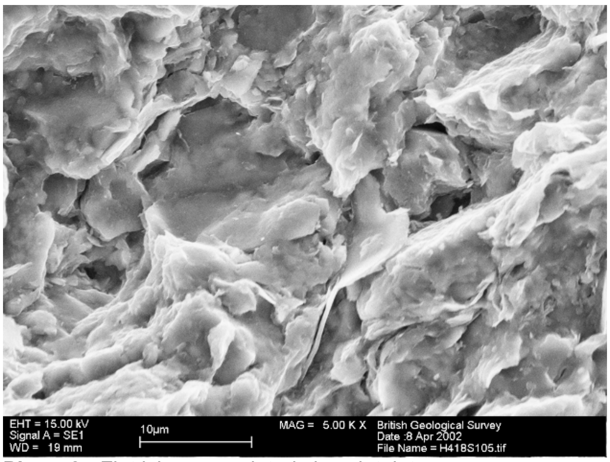


**Photo 2:** Flat lying, crenulated clay platelets.

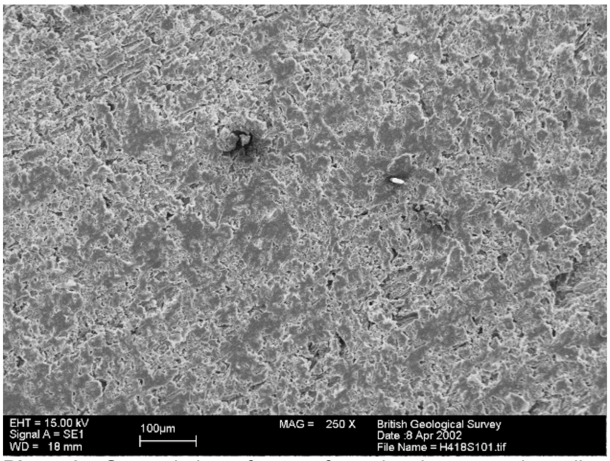


**Photo 3:** General view of cut surface showing textural mottling with low and high porosity domains.

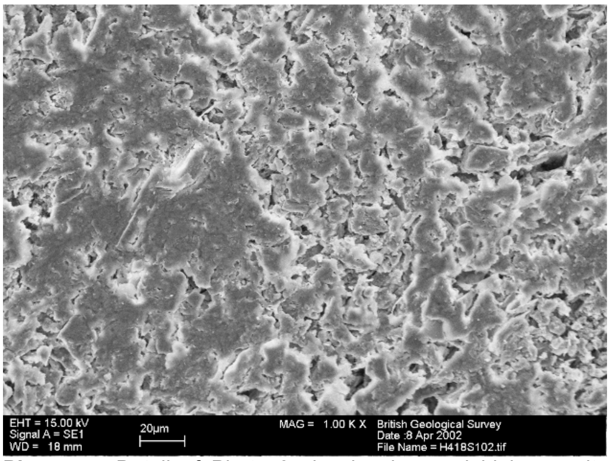


**Photo 4:** Detail of Photo 3 showing low and high porosity domains.

| | | | |
|---|---|---|---|
| Site: | Tufley, **Robin's Wood Hill** | SampleID: | **RW3** |
| Basin: | **Worcester** | Formation: | **Marlstone Rock / Dyrham (?)** |
| MPL Sample Code: | **H419S1** | Preparation: | **Freeze dried, fresh fracture/cut surface** |

The surface of this stub comprises a fresh fracture surface which has cut over a portion of it's surface using a scalpel.

The fresh fracture surface indicates a strongly laminated mudstone of similar appearance to the Robins Wood Hill sample 2 (H418). However, in this sample the platy (?recrystallised) particles are less common Minor bookleted, authigenic kaolinite is present..

The cut surface indicates a loosely packed, homogeneous mudstone, with evenly distributed micropores up to approximately 20 microns diameter. No differences in signal intensity are observed across the sample, suggesting no significant compositional variations. EDXA indicates a variable Fe-Mg-Al-Silicate and K-Al-Silicate (?illite) composition for the clays, with XRD suggesting a kaolinite dominated clay fraction.

Photomicrographs:

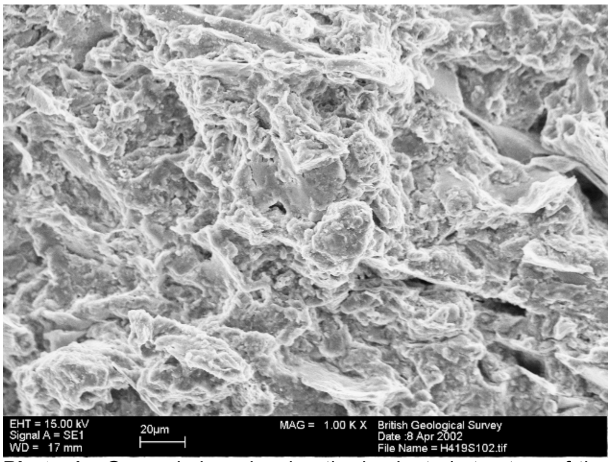


**Photo 1:** General view showing the laminated structure of the sample.

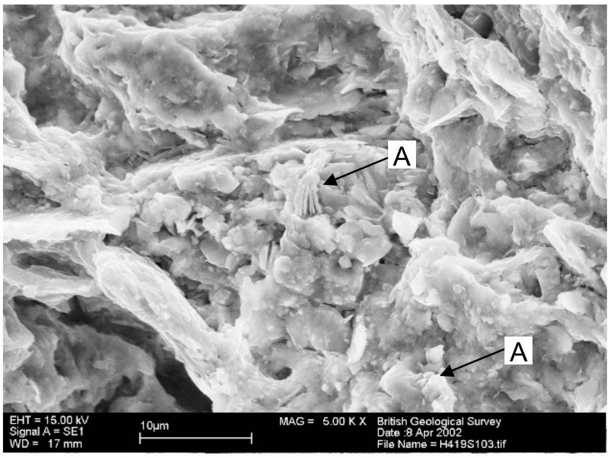


**Photo 3:** detail showing irregularly oriented clay platelets, and small clusters of bookleted kaolinite (A).

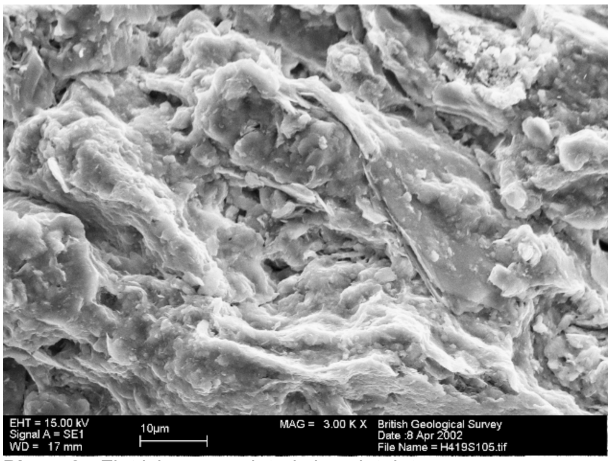


**Photo 2:** Flat lying, crenulated clay platelets.

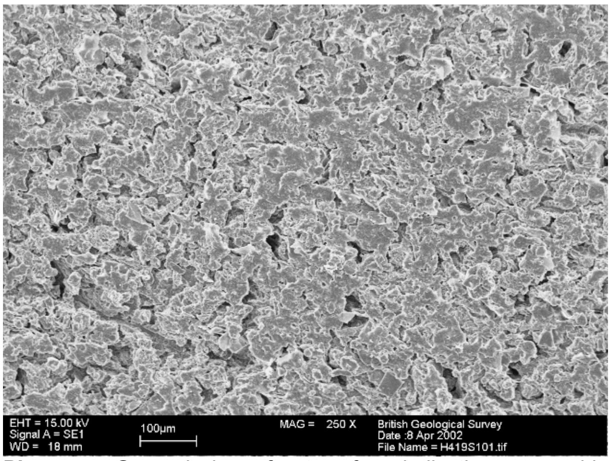


**Photo 4:** General view of cut surface indicating reasonably well-connected pores up to 20 microns in diameter.

# Weathering Profile at Blockley

| | | | |
|---|---|---|---|
| Site: | Wellacre, **Blockley** | SampleID: | **B1** |
| Location ID: | **1a** | Position in Profile: | **0.4m from top of location** |
| Basin: | **East Midlands Shelf** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H265S1** | Preparation: | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

Sample taken near top of profile, from material noted to contain sandy/gravely-lenses. In hand specimen the sample is pale orange-brown in colour, and poorly consolidated. Sandy/gravely material evident.

SEM Description:

- sand grains are typically well rounded, and embedded within the clayey matrix (Photo 1).
- patches containing silt-grade particle are also noted (Photo 3).
- the clay fabrics are variable and include:
  - accumulations of variably shaped clay-grade particles which wrap around silt-grade particles, and
  - meniscus-style bridges between clay-coated grains (Photo1).
- rounded macropores occur throughout the clayey matrix range from a few 10's microns to over 200microns in diameter (Photos 1, 2 and 4).
- clay particles locally have irregular crenulated margins suggesting either fabric disruption during sample preparation and/or minor neomorphism.
- EDXA of the clays indicates variable Al:Si peak ratios (0.75:1 to 1:1), and variable amounts of Ca, K, Mg, Na and Fe.
- microfractures particularly around the margins of grains may be artificially induced,.
- minor filamentous material occurs throughout, some of these may be rootlets, however some of these appear too fine for this (Photo 3).

Photomicrographs:

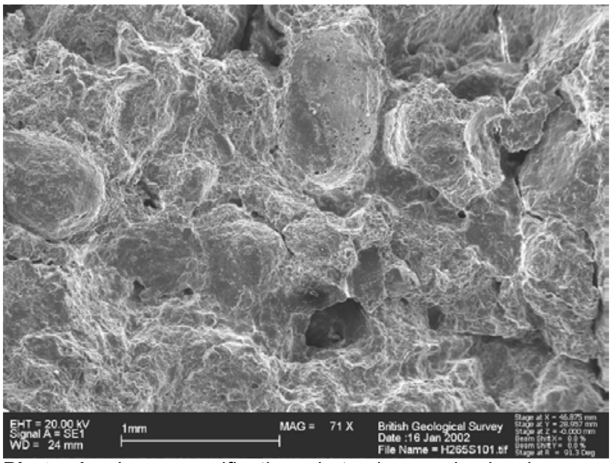


**Photo 1:** Low magnification photomicrograph showing very coarse sand grade grains within clayey matrix. Note the presence of relatively large and well connected pores and the meniscus-style habit of the clay between the grains.

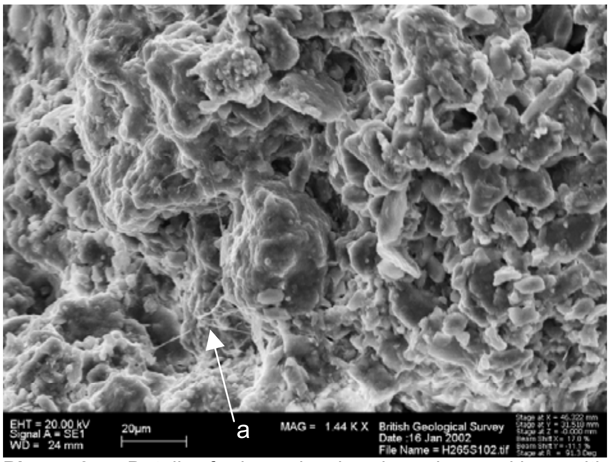


**Photo 3:** Detail of clay, showing irregular packing, with significant microporosity between particles. Also note the filamentous material between particles (a).

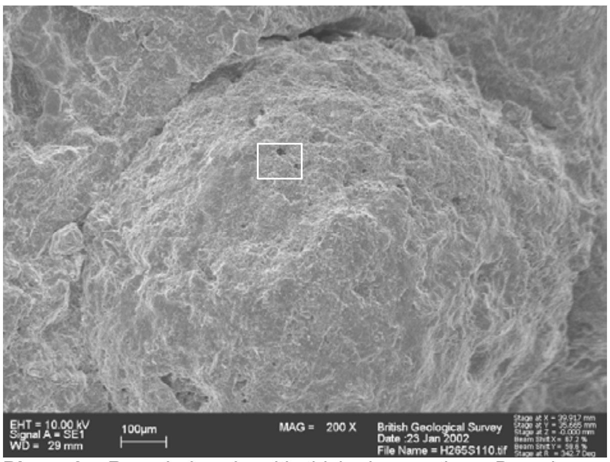


**Photo 2:** Rounded grain with thick clay coating. Boxed area shown in detail in Photo 4.

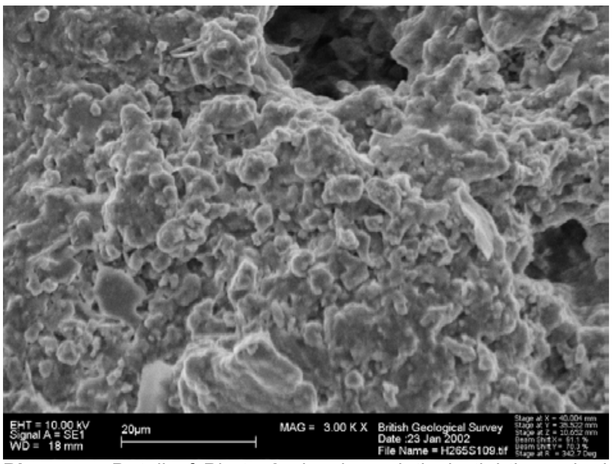


**Photo 4:** Detail of Photo 2 showing relatively tightly packed clay particles.

| | | | |
|---|---|---|---|
| Site: | Wellacre, **Blockley** | SampleID: | **B2** |
| Location: | **1b** | Position in Profile: | **0.4m from top of location** |
| Basin: | **East Midlands Shelf** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H266S1** | Preparation: | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

Sample is mottled orange and green-grey with ferruginous nodules and more porous red-brown patches. A well defined horizontal lamination is preserved.

SEM Description:

- this sample is more homogeneous than sample 01A (H265), and lacks the sand-grade particles.
- low magnification indicates well defined horizontal lamination (as seen in HS; Photos 1, 2 and 3), and that this sample is breaking along microfractures into lumps up to 5mm in size.
- relatively large elongate pores occur throughout (Photo 1) as noted in hand specimen.
- EDXA indicates variable clay composition (variable Na, K, Ca and Fe content).
- small crenulations, and wispy projections are evident on some clay flakes possibly indicating some authigenic clay (and/or recrystallisation/neomorphism; Photo 4).

Photomicrographs:

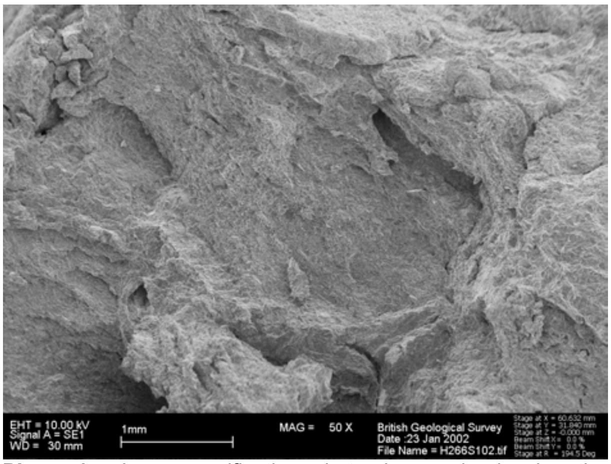


**Photo 1:** Low magnification photomicrograph showing the presence of large elongate pores within the sample.

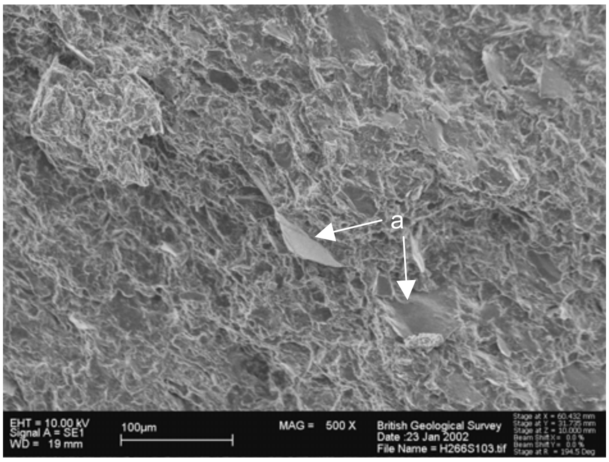


**Photo 3:** Detailed photomicrograph showing abundant mica platelets within laminated clay fabric (a).

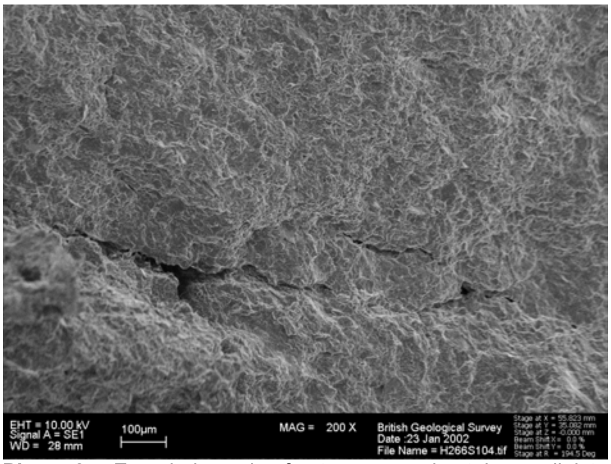


**Photo 2:** En-echelon microfracture approximately parallel to laminated fabric of sample.

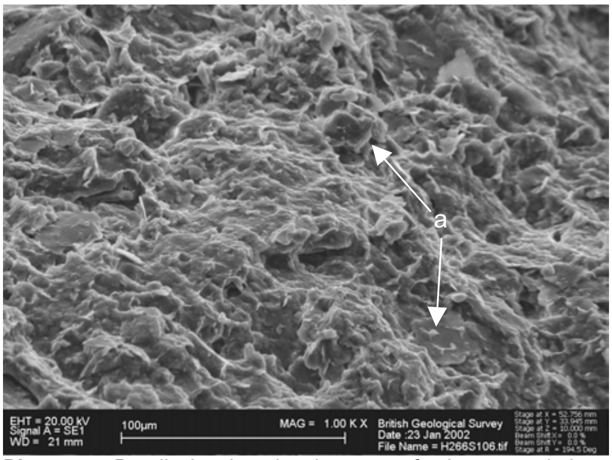


**Photo 4:** Detail showing development of minor crenulations and wispy projections from clay platelets (a), indicating possible clay authigenesis/ neomorphism.

| | | | |
|---|---|---|---|
| Site: | Wellacre, **Blockley** | SampleID: | **B3** |
| Location ID: | **2** | Position in Profile: | **0.2m from top of location** |
| Basin: | **East Midlands Shelf** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H267S1** | Preparation: | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

Variably oxidised material, (orange and green-grey mottling). Some variations in oxidation state relate to microfractures (reduced directly adjacent to microfractures).

SEM Description:

- at low magnifications the sample appears to be relatively homogeneous with a moderately well defined lamination (see in oblique view in Photo 1), although it is locally fragmented into up to 5mm-sized pieces.
- the sample surface is characterised by the presence of crenulated clay, this clay could represent:
  - "real" clay squeezed between coarser aggregates of clay particles (Photos 2 and 3),
  - authigenic clay (Photo ), or
  - an artefact of sample preparation (Photo 4), possibly due to the sample being slightly damp when the fresh fracture surface was prepared. Attempts to generate a fresh fracture surface on small fragment of freeze-dried sample proved impossible (samples proved to be too hard and brittle to generate fracture in 1cm^3 sample without destroying the entire fragment).
- as in other samples, EDXA indicates variable compositions for the clay with variations in Al:Si ratio, and in Ca, K, Na and Fe content.

Photomicrographs:

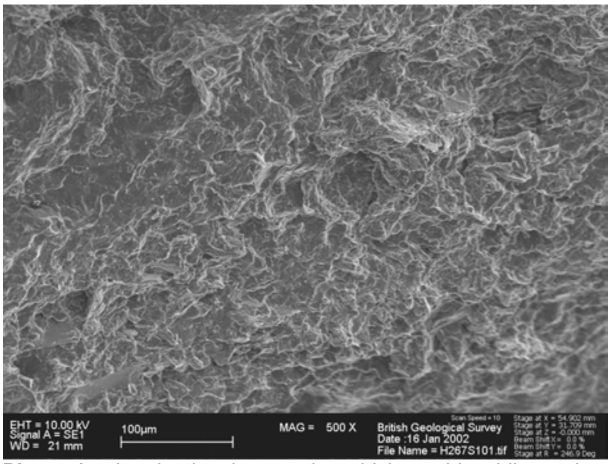


**Photo 1:** Lamination in sample, which at this oblique view manifests itself as a series of “terraces” and “steps”.

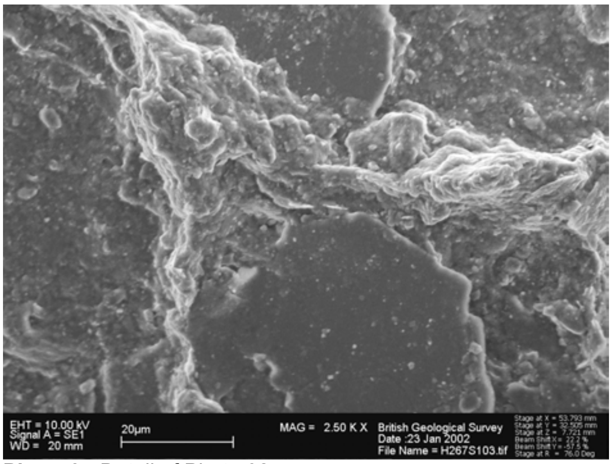


**Photo 3:** Detail of Photo 02.

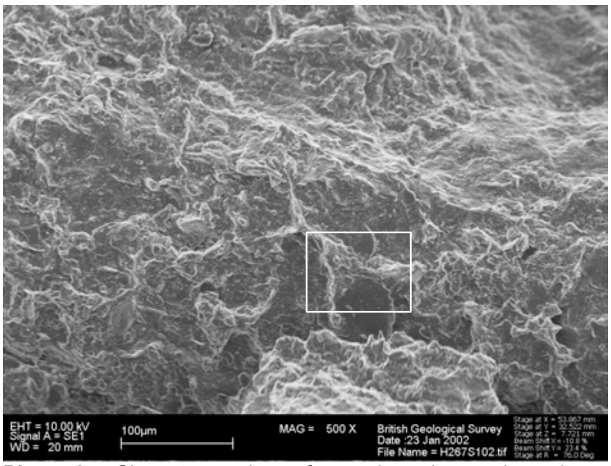


**Photo 2:** Clay at sample surface, where it may have been squeezed between aggregates of clay particles. Boxed area shown in detail in Photo 3.

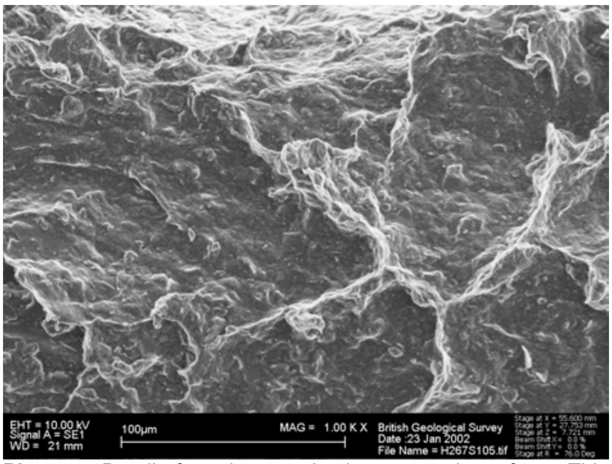


**Photo 4:** Detail of meniscus-style clay at sample surface. This could either represent authigenic clay or an artefact of sample preparation.

| | | | |
|---|---|---|---|
| Site: | Wellacre, **Blockley** | SampleID: | **B4** |
| Location ID: | **3** | Position in Profile: | **0.4m from base of location** |
| Basin: | **East Midlands Shelf** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H268S1** | Preparation: | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

Grey coloured, laminated mud, with abundant mica.

SEM Description:

- this sample has a well-defined laminated structure evident at low-moderate magnification (Photo 1).
- comprises aggregates of clay platelets (Photo 1), with common mica platelets (20 to >200microns diameter; Photo 1).
- minor possible authigenic clay platelets are noted (Photo 4).
- EDXA indicates that the detrital clay is K and Ca-bearing, whereas the possible authigenic clay shown in Photo 4 is Al-Si-bearing only (kaolinite?).
- this sample is locally highly microporous, with 10micron-scale pores between aggregates of clay particles (Photo 1).

Photomicrographs:

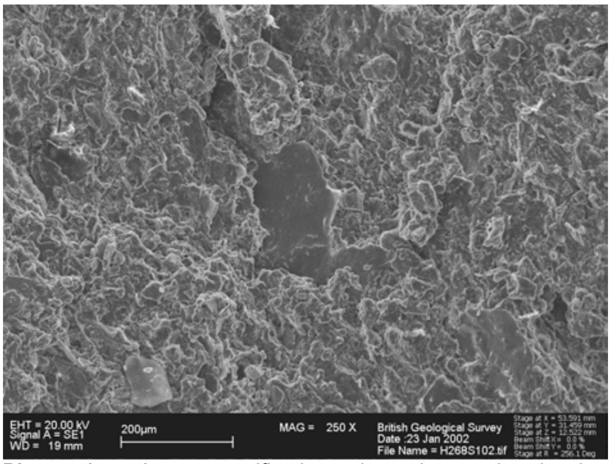


**Photo 1:** Low magnification photomicrograph showing laminated structure of sample.

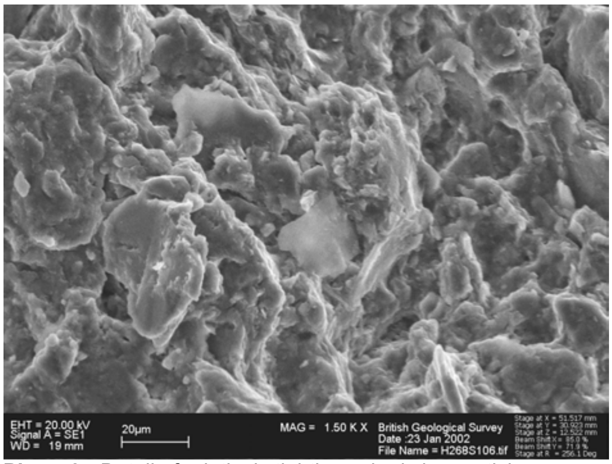


**Photo 3:** Detail of relatively tightly packed clay particles.

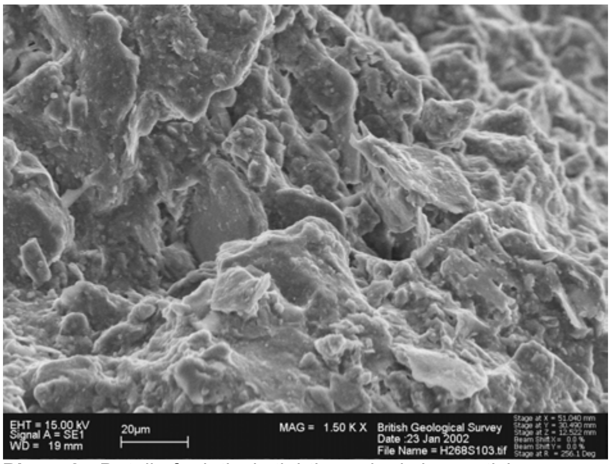


**Photo 2:** Detail of relatively tightly packed clay particles.

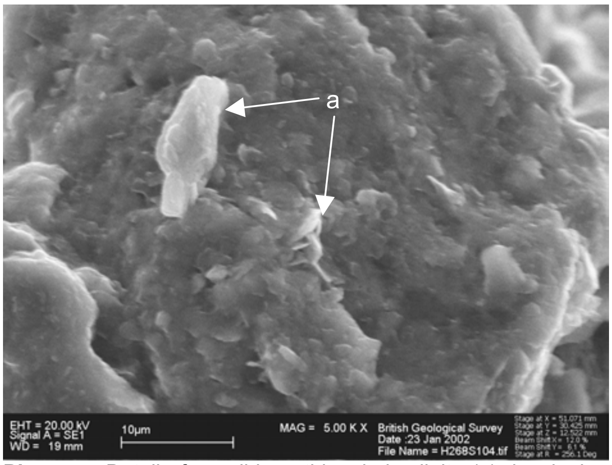


**Photo 4:** Detail of possible authigenic kaolinite (a) developing on an aggregate of ?detrital clay-particles.

| Site: | Wellacre, **Blockley** | SampleID: | **B5** |
|---|---|---|---|
| Location ID: | **4** | Position in Profile: | **0.4m from base of location** |
| Basin: | **East Midlands Shelf** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H269S1** | Preparation: | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

Similar in character to B4 (H268), dark grey laminated mudrock with some small shell fragments, and some lath-shaped crystals noted at the SEM stub fracture surface.

SEM Description:

- the sample retains a well developed primary lamination as seen in hand specimen, which is evident at a range of scales (H269S103 and H269S104).
- the particles in this sample occur as discrete clay/silt-grade particles, in contrast to earlier samples which comprise aggregates of particles (compare Photo 4 of this sample with Photo 4 of sample B3; [H267]).
- EDXA of the lathe-shaped crystals, presumed to be gypsum in hand specimen, only detects Ca and O, and no S. This suggests that the phase is calcite/aragonite.
- this sample only contains limited volumes of micropores, which are elongate parallel to lamination and poorly connected (Photo 4).
- as noted elsewhere, EDXA indicates that the clays have variable composition, and contain variable amounts of Na, Ca, Mg and K. However, there is a possible tendency towards more K-rich compositions in this sample than noted in shallower samples.

Photomicrographs:

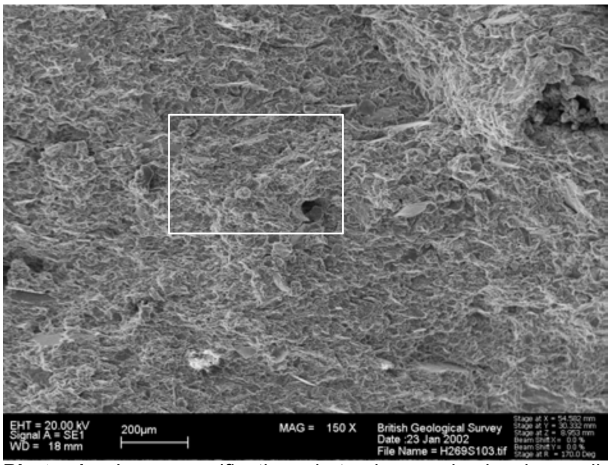


**Photo 1:** Low magnification photomicrograph showing well-defined horizontal lamination (boxed area shown in detail in Photo 2).

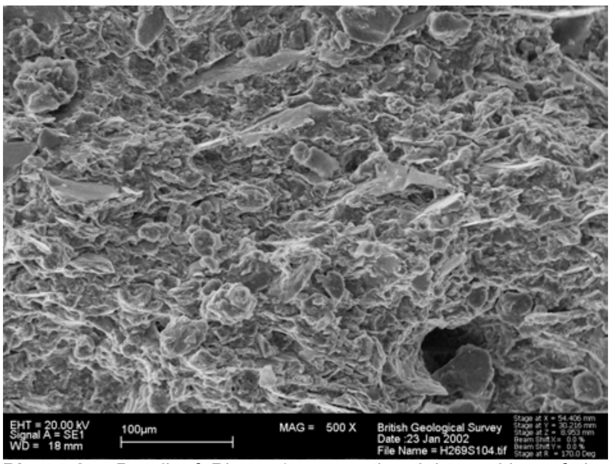


**Photo 2:** Detail of Photo 1, note the tight packing of the individual clay-silt-grade particles and the relatively low volumes of microporosity.

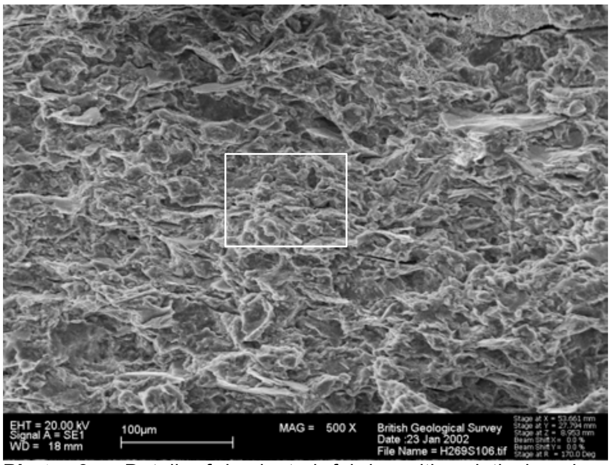


**Photo 3:** Detail of laminated fabric, with relatively minor volumes of microporosity. (boxed area shown in detail in Photo 4)

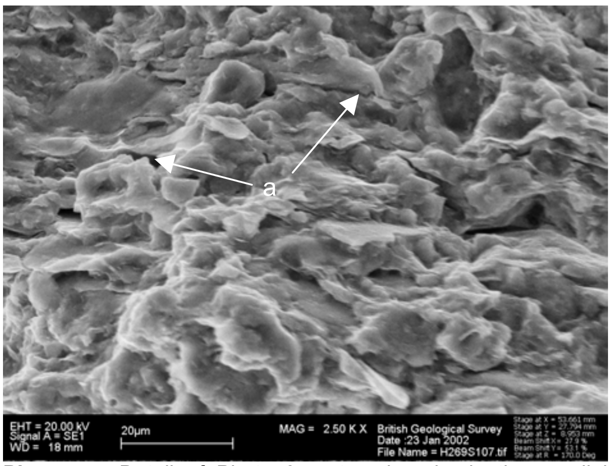


**Photo 4:** Detail of Photo 3, note minor lamination-parallel elongate micropores and microfractures (a).

| | | | |
|---|---|---|---|
| Site: | Wellacre, **Blockley** | SampleID: | **B6** |
| Location ID: | **5** | Position in Profile: | **0.6m from base of location** |
| Basin: | **East Midlands Shelf** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H270S1** | Preparation: | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

Similar in character to H268, Grey, hard, laminated mudrock.

SEM Description:

- this sample also has a well defined horizontal lamination (Photos 1 to 4), defined by flat-lying clay platelets and relatively common mica (predominantly Mg-bearing ?biotite).
- bioclasts are abundant and occur throughout (Photos 1 and 2).
- clay particles occurs as small discrete particles rather than in relatively large aggregates (Photo 4).
- this sample is very poorly microporous, with minor micropores (a few microns), elongate parallel to lamination.
- as noted elsewhere, EDXA indicates that the clay has variable K, Ca, Mg and ?Na content.
- rare meniscus/crenulated clay is locally noted at the sample surface (as described in H267).

Photomicrographs:

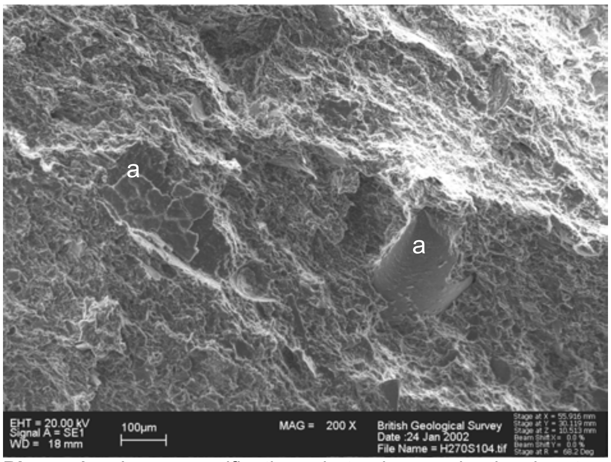


**Photo 1:** Low magnification photomicrograph showing two large calcitic/aragonitic bioclasts (a) within laminated clay matrix.

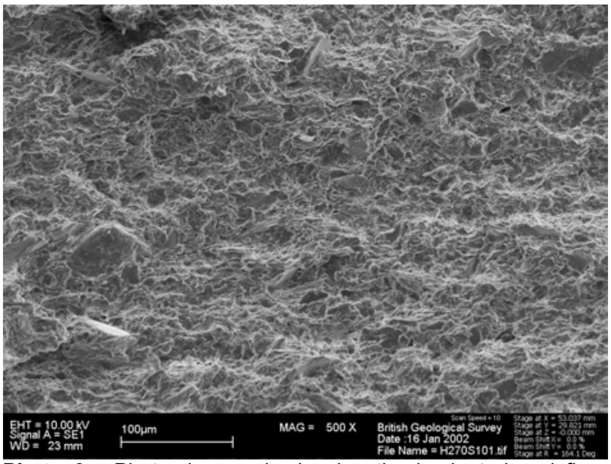


**Photo 3:** Photomicrograph showing the laminated and fine-grained character of this sample.

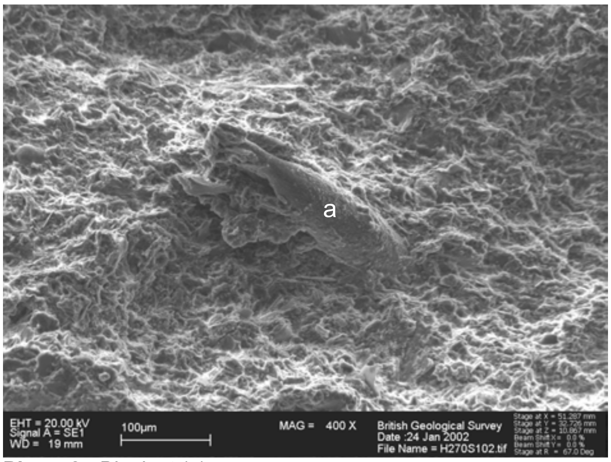


**Photo 2:** Bioclast (a).

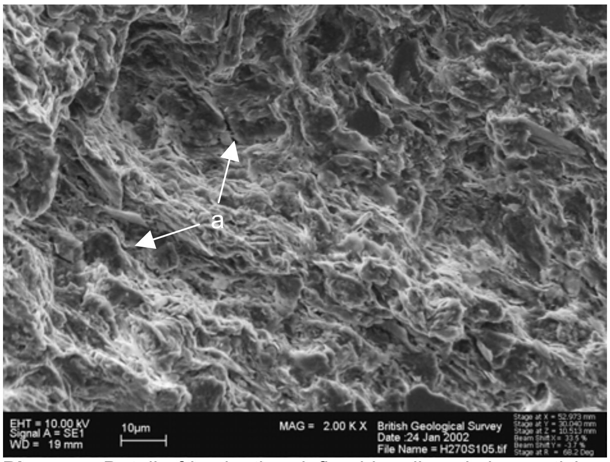


**Photo 4:** Detail of lamination defined by aligned clay particles. Note the tight packing of the individual particles and the relatively minor amounts of very poorly connected micropores (a).

| | | | |
|---|---|---|---|
| Site: | Wingmoor, **Bishops Cleeve** | SampleID: | **BC1** |
| Basin: | **Worcester** | Formation: | **Blue Lias** |
| MPL Sample Code: | **H414S1** | Preparation: | **Freeze dried, fresh fracture/cut surface** |

The surface of this stub comprises a fresh fracture surface which has cut over a portion of it's surface using a scalpel.

The fresh fracture surface indicates a high content of 10 micron sized $CaCO_3$ grains, which are generally sub-spheroidal but otherwise featureless (?microfossils), in a matrix of mixed K-, Ca-, +/-Mg bearing clay (possible illite-smectite; supported by the XRD data which indicates a mixture of illite, kaolinite, chlorite and illite/smectite), which wraps around the $CaCO_3$ spherules, with a generally laminated fabric. The matrix clay comprises a mixture of amorphous clay and discrete crystals, with individual platelets typically of approximately 1 micron in diameter. Also evident are coarser, $CaCO_3$ particles (up to 200 microns) made up of tiny (5-10 micron) individual crystals. Furthermore, some plucked voids on the sample surface are suggestive of plucking of platy ?bioclastic material (i.e. small shell fragments) during sample preparation.

The cut surface indicates a compositionally homogeneous sample with minor amounts of fairly evenly distributed porosity. There is possible evidence for rounded clay aggregates locally.

Photomicrographs:

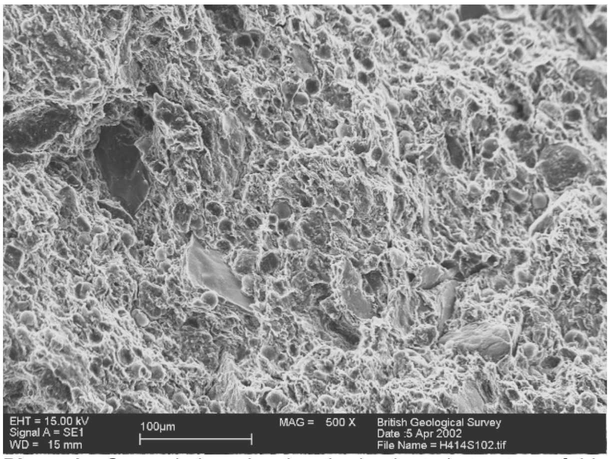


**Photo 1:** General view showing the laminated structure of this sample, with flat lying clay particles wrapping around abundant spheroidal $CaCO_3$ grains (?microfossils).

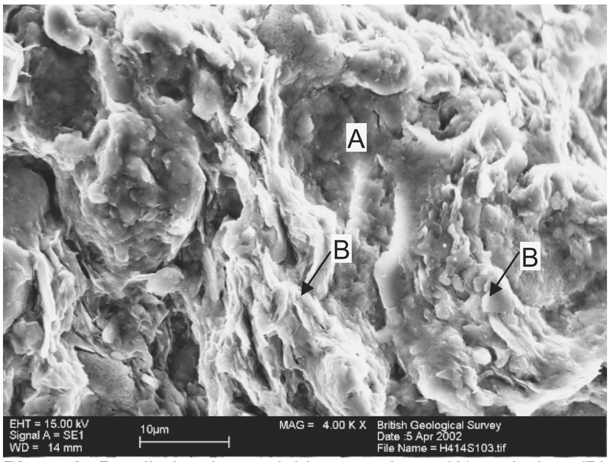


**Photo 3:** Detail showing variably amorphous (A) and platy (B) nature of clay particles.

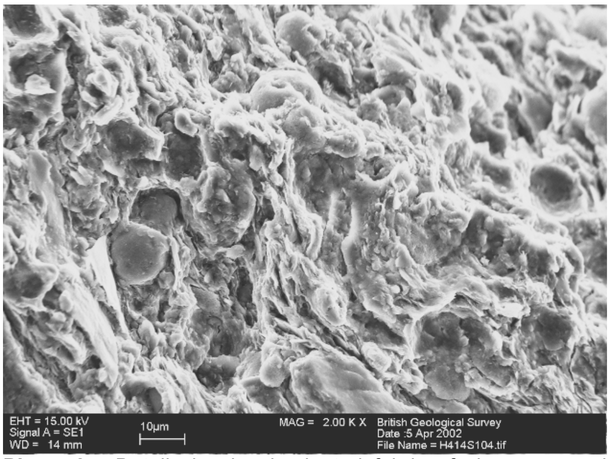


**Photo 2:** Detail showing laminated fabric of clays wrapped around $CaCO_3$ spherules.

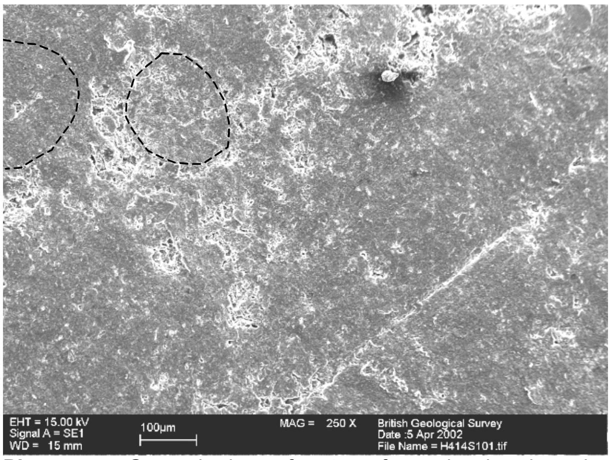


**Photo 4:** General view of cut surface showing irregular distribution of pores, and possible evidence for larger-scale rounded clay-aggregates (marked with dashed lines).

| | | | |
|---|---|---|---|
| Site: | Wingmoor, **Bishops Cleeve** | SampleID: | **BC2** |
| Basin: | **Worcester** | Formation: | **Blue Lias** |
| MPL Sample Code: | **H415S1** | Preparation**:** | **Freeze dried, fresh fracture/cut surface** |

The surface of this stub comprises a fresh fracture surface which has cut over a portion of it's surface using a scalpel.

The fresh fracture surface indicates that this sample is mineralogically similar to Bishop's Cleeve BC1 (H414S1), with $CaCO_3$ spherules (?microfossils), and interstitial clay of variable, mixed Ca, K +/- Mg composition (XRD indicates mixed illite, chlorite, kaolinite and illite/smectite). However, this sample is texturally distinct, as the interstitial clay appears less well laminated (this could partially reflect a different orientation of the sample surface relative to the orientation of the lamination), and has a generally more open fabric. A similar mix of amorphous and finely crystalline clay is evident.

The cut surface indicates a relatively granular texture for this sample, and reveals significant amounts of evenly distributed and relatively well-connected porosity. No compositional heterogeneity is inferred from the grey-scale intensity of this surface.

Photomicrographs:

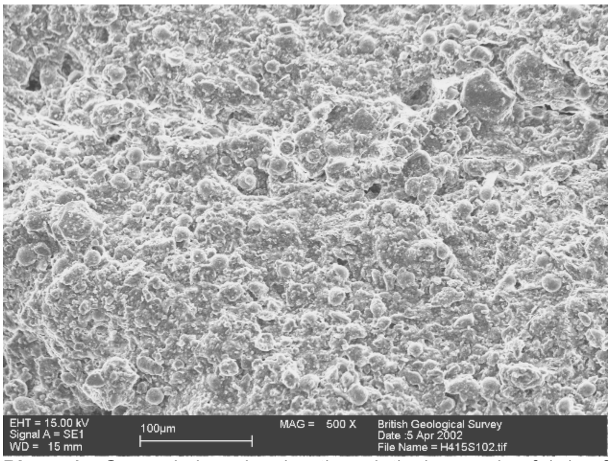


**Photo 1:** General view showing the relatively massive fabric of this sample.

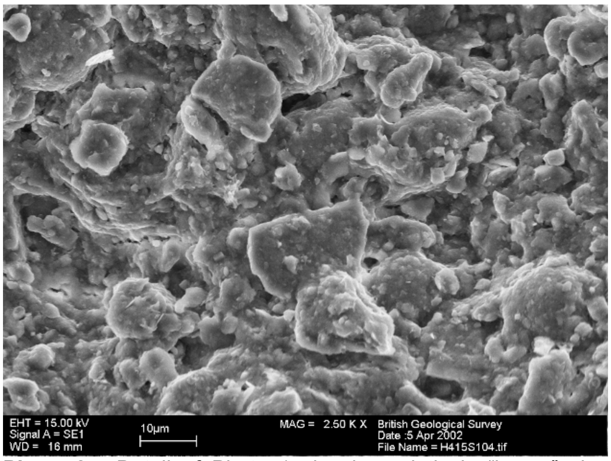


**Photo 2:** Detail of Photo 1 showing relatively "lumpy" clay particles with appreciable Interparticle microporosity.

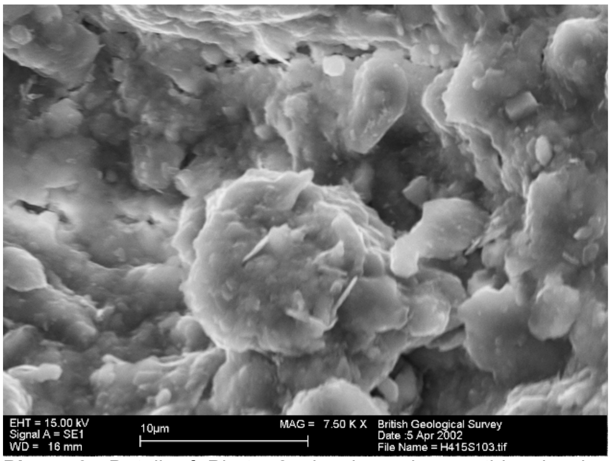


**Photo 3:** Detail of Photo 2 showing minor authigenic clay platelets.

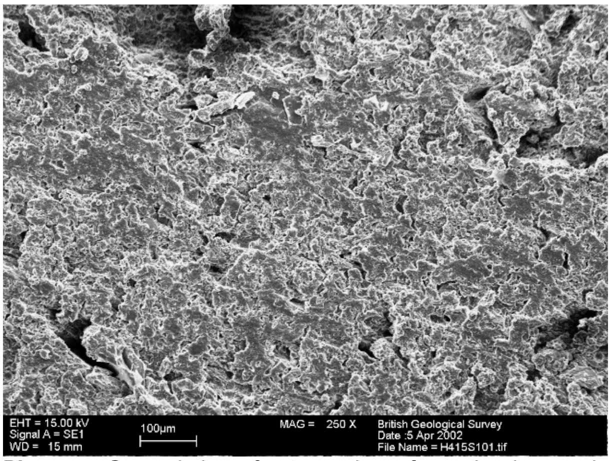


**Photo 4:** General view of cut sample surface, showing poorly laminated structure and abundant, moderately well connected pores of up 10 microns diameter.

| | | | |
|---|---|---|---|
| Site: | **Stowey**, Bishops Sutton | SampleID: | **Stowey** |
| Basin: | **Worcester (?)** | Formation: | **Blue Lias** |
| MPL Sample Code: | **H593S1** | Preparation**:** | **Freeze dried, fresh fracture/cut surface** |

The majority of the sample comprises a well laminated mudstone, with irregular cracks developed approximately parallel to lamination. Within the laminated mudstone, silt-grade grains are rare, and minor porosity (<10 micron diameter pores elongate parallel to lamination) occurs between flat lying clay particles. In detail the clay platelets are crenulated with wispy outgrowths. EDXA indicates K and Mg- (+minor Ca-) bearing Al-silicate composition (possible illite; supported by XRD analysis).

In a more porous, pyritised domain of the sample (approximately 2 mm in extent, elongate parallel to lamination), pyrite is unusually abundant, and occurs as small (<10 micron) euhedra and framboids. Within this domain, the clay has a more webby structure with well connected micropores. As elsewhere in this sample, the clay has a predominantly K-bearing (?illitic) composition.

Photomicrographs:

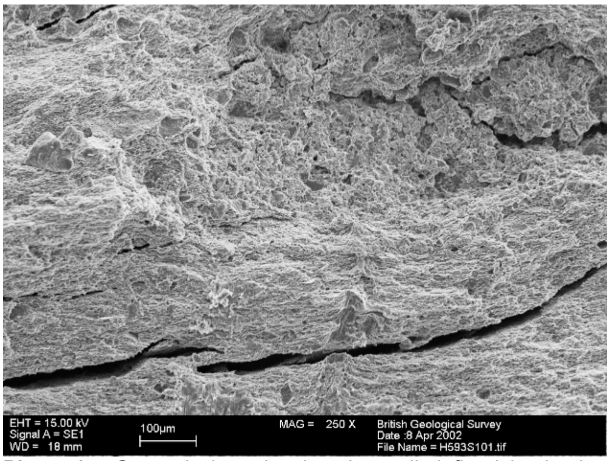


**Photo 1:** General view showing the well defined lamination present in the bulk of the sample, but also note the presence of a mm-scale domain containing more granular, massive material.

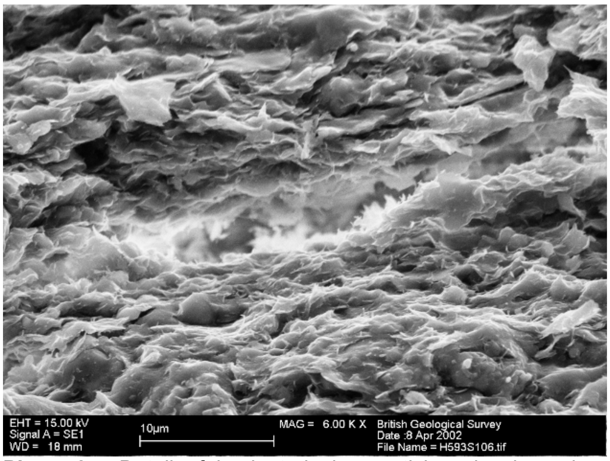


**Photo 3:** Detail of laminated clay particles showing minor development of ribboned clay lining an elongate pore.

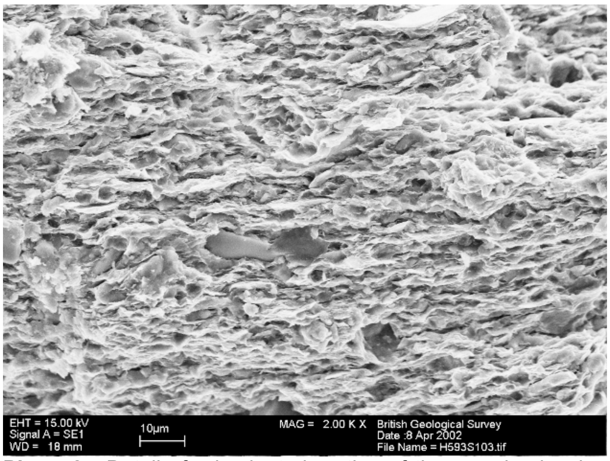


**Photo 2:** Detail of a laminated portion of the sample showing tightly packed, flat lying clay particles.

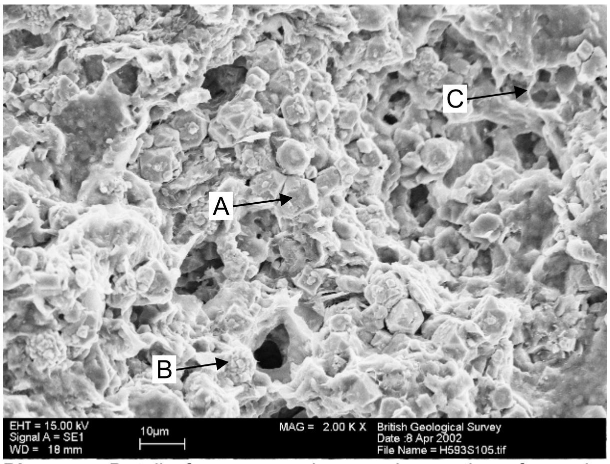


**Photo 4:** Detail of more granular massive portion of sample. This domain is dominated by pyrite euhedra (A) and framboids (B), with some webby clay (C).

## WESSEX BASIN

| | | | |
|---|---|---|---|
| Site: | **Hamdon Hill**, Yeovil | SampleID: | **Hamdon** |
| Basin: | **Wessex** | Formation: | **Bridport Sand** |
| MPL Sample Code: | **H597S1** | Preparation: | **Freeze dried, fresh fracture surface** |

This sample is effectively a fine-grained sandstone/wackestone with well rounded quartz and more blocky/tabular feldspar grains of 70-120 microns diameter. Clay grade material is abundant with grain-rimming and pore-filling varieties present. The sample retains a appreciable well connected macro-pore system with pores between 10-30 microns diameter, although this is significantly occluded by clay. EDXA indicates Fe-Mg-Al-Silicate composition for the clay (possible chlorite/berthierine) and a diverse range of crystal habits are observed - predominantly webby, with some development of plates and rod, and minor "beehive" structures. Also evident are some skeletal forms as seen in the Edge Hill sample (H417).

Photomicrographs:

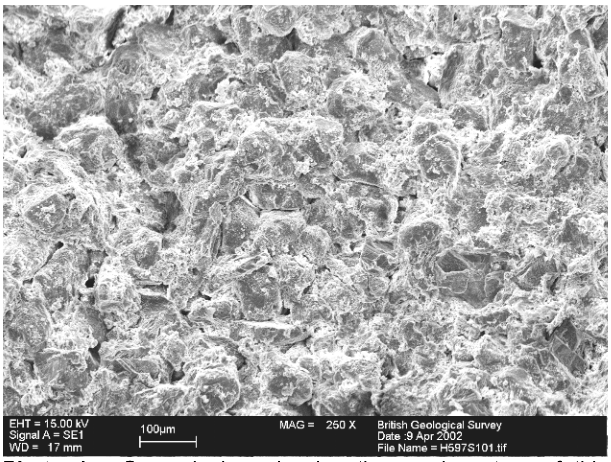


**Photo 1:** General view showing the sandy nature of this sample with grains of detrital quartz and feldspar of between 70-120 micron diameter in a clay-rich matrix.

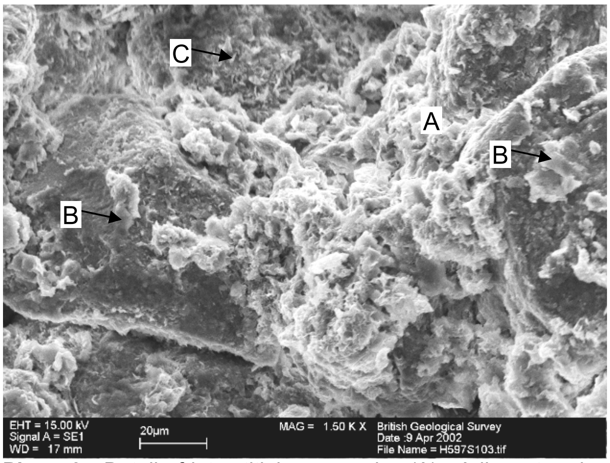


**Photo 3:** Detail of interstitial spongy clay (A). Adjacent grains have tangential clay coats (B), and minor authigenic platelets of possible chlorite are also observed (C).

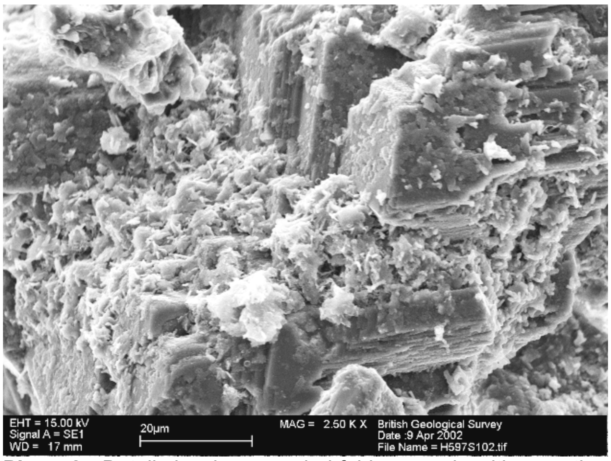


**Photo 2:** Detail showing corroded feldspar grain with a coating of plates and rods of possible chlorite.

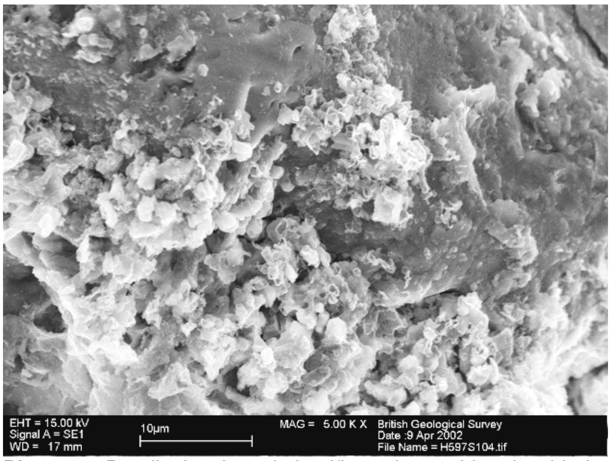


**Photo 4:** Detail showing skeletal/irregular authigenic chlorite crystals.

| | | | |
|---|---|---|---|
| Site: | **Seatown** Cliffs | SampleID: | **Seatown N** |
| Basin: | **Wessex** | Formation: | **Dyrham (Eype Clay Member)** |
| MPL Sample Code: | **J083S1** | Preparation: | **Freeze dried, fresh fracture surface** |

A well-laminated, fossiliferous mudstone, with flat lying mica plates (probably biotite as indicated by Fe-Mg-bearing composition using EDXA). The clays have variable chemistry, with EDXA indicating some pure Al-Silicate (probable kaolinite), and other clays with variable proportions of Ca, K, Na, Mg and Fe (?illite and smectite). Minor gypsum/anhydrite, and pyrite are present.

Photomicrographs:

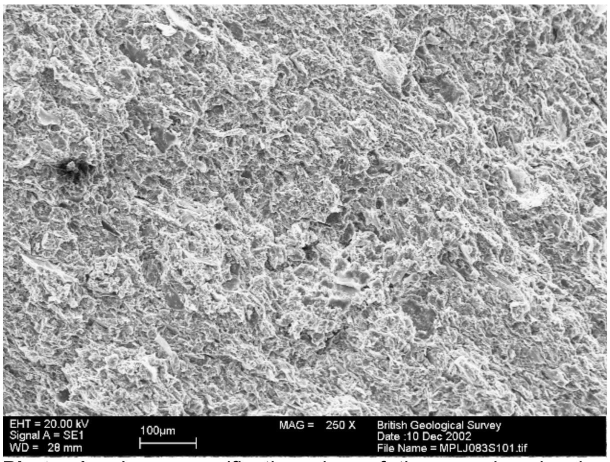


**Photo 1:** Low magnification view of the sample, showing lamination (running NW-SE in this image).

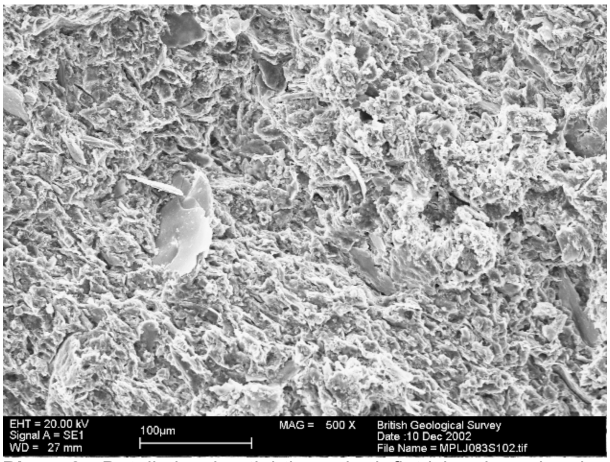


**Photo 2:** Detail showing tightly packed, flat lying, irregular clay platelets, with minor mica flakes.

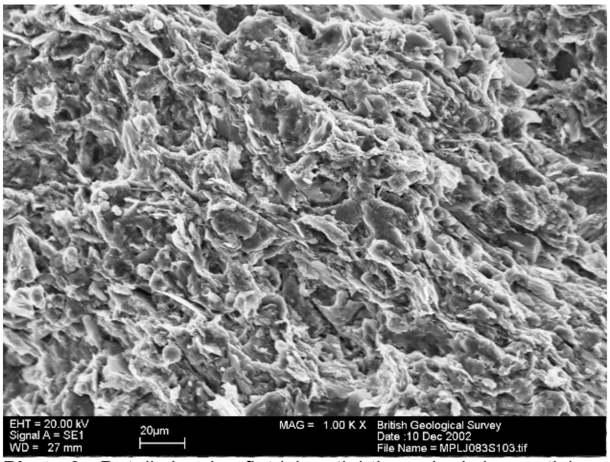


**Photo 3:** Detail showing flat-lying, tightly packed clay particles.

| | | | |
|---|---|---|---|
| Site: | **Seatown** Cliffs | SampleID: | **Seatown** |
| Basin: | **Wessex** | Formation: | **Charmouth Mudstone (Green Ammonite Member)** |
| MPL Sample Code: | **J084S1** | Preparation**:** | **Freeze dried, fresh fracture surface** |

A laminated mudrock containing well-rounded grains of quartz, plagioclase and bioclasts. The clay is flat lying, tightly packed, and appears to predominantly K-bearing (?illite). Wispy to platy emanations at crystal margins suggest some neomorphism/authigenesis of the clay.

Photomicrographs:

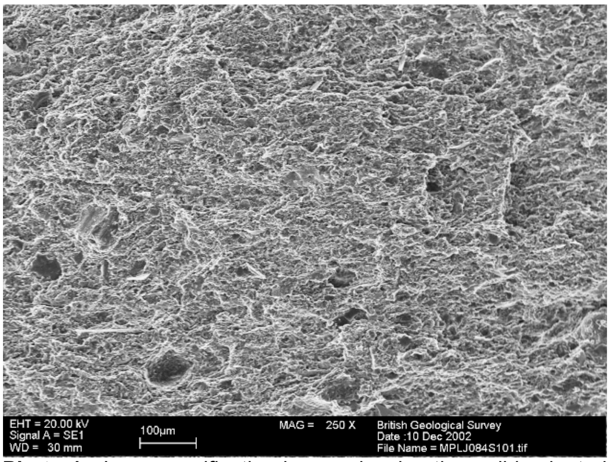


**Photo 1:** Low magnification image showing the well-laminated nature of this sample, and the presence of sub-spherical voids, left by the plucking of spherical grains.

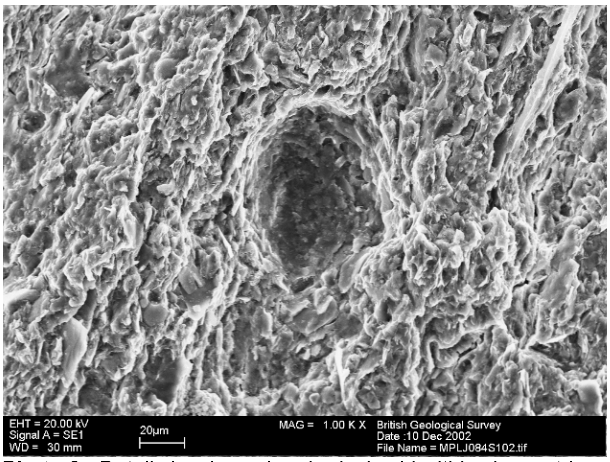


**Photo 2:** Detail showing sub-spherical void within clay matrix.

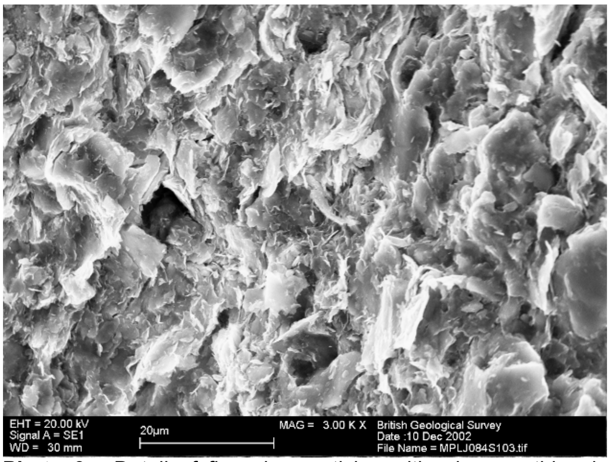


**Photo 3:** Detail of fine clay particles with wispy, authigenic emanations.

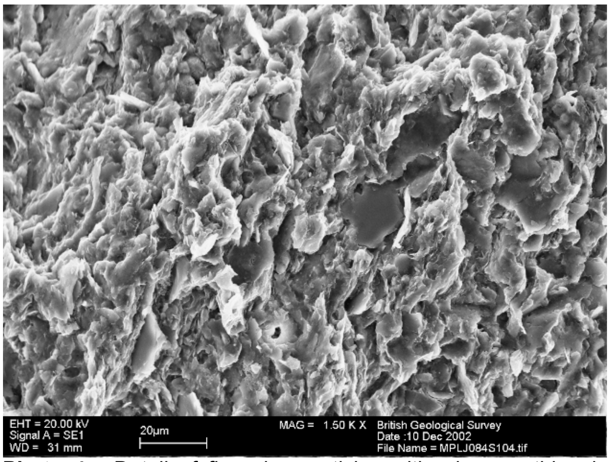


**Photo 4:** Detail of fine clay particles with wispy, authigenic emanations.

| | | | |
|---|---|---|---|
| Site: | **Black Ven** Landslide | SampleID: | **Belemnite Marl** |
| Basin: | **Wessex** | Formation: | **Charmouth Mudstone (Belemnite Marl Member)** |
| MPL Sample Code: | **J086S1** | Preparation: | **Freeze dried, fresh fracture surface** |

This sample appears to be highly calcareous sample, with large Ca-peaks evident on EDXA analyses of clay particles. The centre of the sample includes a number of calcite cement bands. These bands consistently have one clearly defined, sharp margin, and one more diffuse margin. However, the "side" of the cement band with the sharp margin is not consistent (i.e. no "way-up" significance can construed from these features.

The clay within this sample appears to be more finely crystalline than "usual" for this sample set, and apart from the cement bands, lamination in this sample is poorly defined.

Photomicrographs:

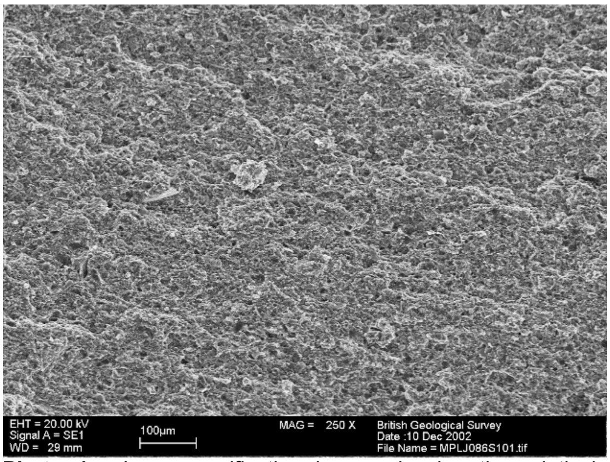


**Photo 1:** Low magnification image showing the relatively massive nature of this sample.

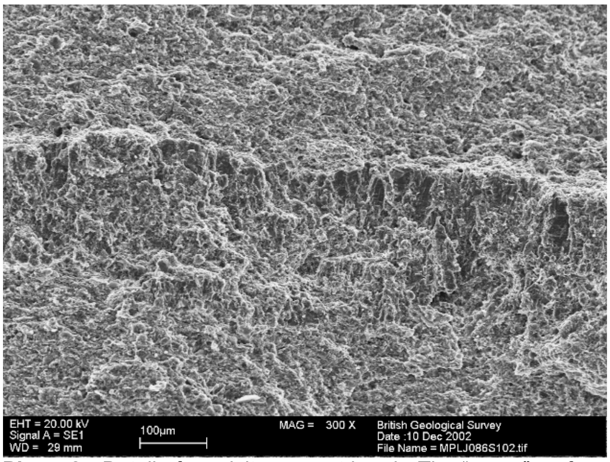


**Photo 2:** Detail of a calcite cement band. The "upper" surface of this band is sharply defined, whereas the lower margin is more diffuse.

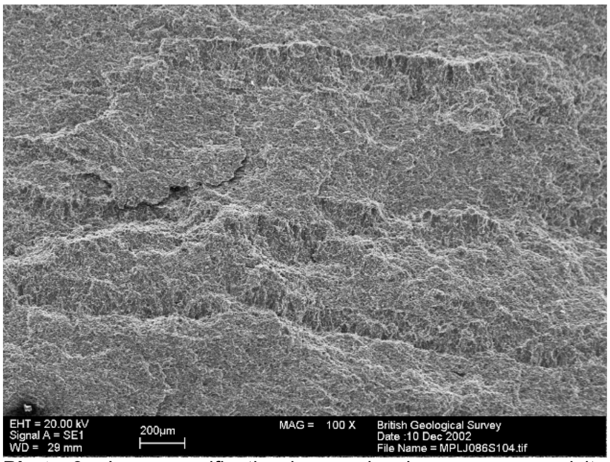


**Photo 3:** Low magnification image showing numerous calcite cement bands. Some bands display sharp contacts on their upper surfaces, others display sharp contacts on their lower surfaces.

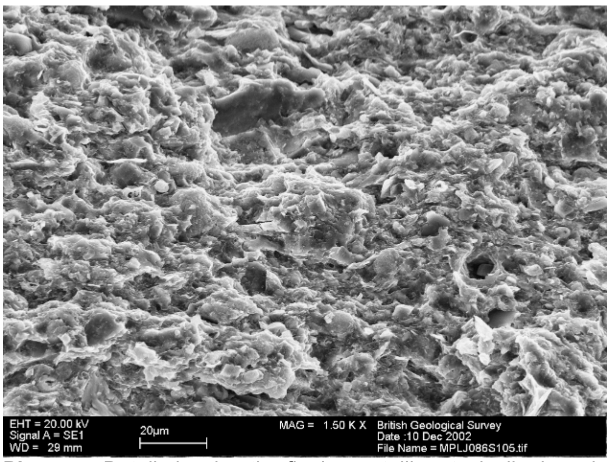


**Photo 4:** Detail showing the finely crystalline, typically densely packed nature of the clay particles in this sample.

| | | | |
|---|---|---|---|
| Site: | **Black Ven** Landslide | SampleID: | **Upper Cement Bed** |
| Basin: | **Wessex** | Formation: | **Charmouth Mudstone (Black Ven Marls)** |
| MPL Sample Code: | **J085S1** | Preparation**:** | **Freeze dried, fresh fracture surface** |

A well-laminated mudstone, containing abundant silt-grade material. EDXA suggests that the clay is K-bearing, suggesting an illitic composition, with minor Ca-K-bearing clay. The clay particles are flat-lying, tightly packed, and have crenulated morphologies. Minor dolomite and framboidal pyrite occur within the sample. One margin of the SEM stub contains a calcite cemented band of similar character to that seen in the sample of Belemnite Marl from this site (J086).

Photomicrographs:

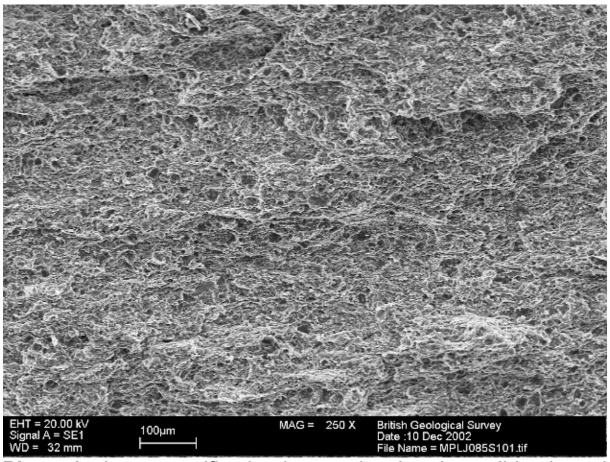


**Photo 1:** Low magnification image showing the well-laminated character of this sample, and the presence of silt-grade particles.

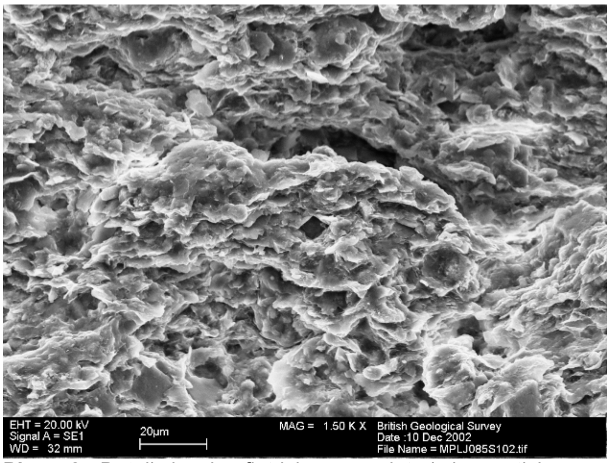


**Photo 2:** Detail showing flat-lying, crenulated clay particles.

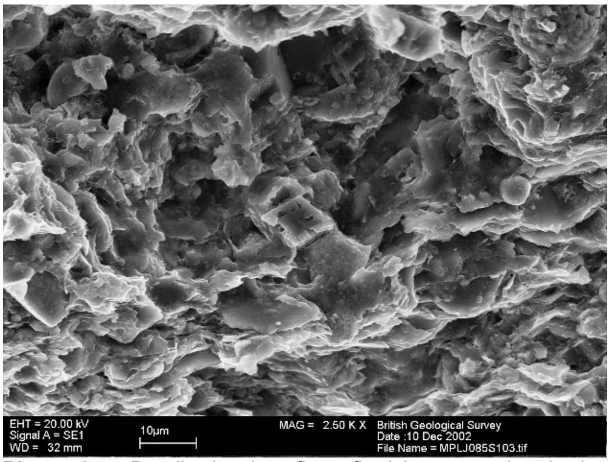


**Photo 3:** Detail showing fine, flat-lying, crenulated clay particles and an incipiently developed, or corroded dolomite rhomb.

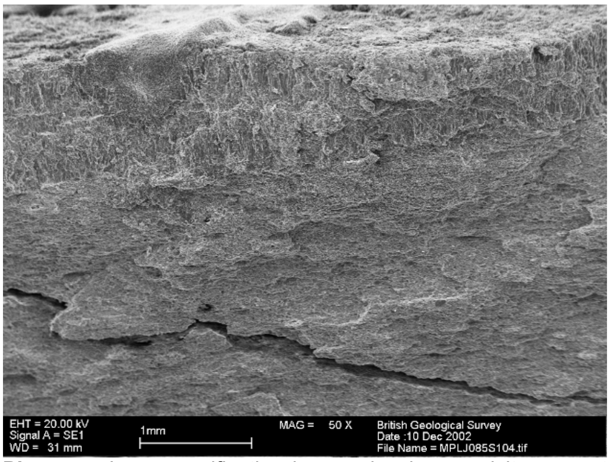


**Photo 4:** Low magnification image showing a calcite cement band at the top of the image. Individual calcite crystals are aligned across the width of the fracture.

| | | | |
|---|---|---|---|
| Site: | **Black Ven** Landslide | SampleID: | **Shales with beef** |
| Basin: | **Wessex** | Formation: | **Charmouth Mudstone (Shales-with-Beef Member)** |
| MPL Sample Code: | **J087S1** | Preparation: | **Freeze dried, fresh fracture surface** |
| | **J087S2** | | **Freeze dried, lamination surface** |
| | **J087S3** | | **Freeze dried, fresh fracture surface** |

**J087S1** – perpendicular to lamination

This sample is very strongly laminated and is made up of flat-lying, very fine, crenulated clay particles with wispy/fibrous emanations. Minor pyrite framboids occur between the clay particles. EDXA indicates Ca-Mg-K-bearing (ambiguous) compositions for the clay.

**J087S2** – lamination surface

This stub presents a lamination surface upon which clusters of very fine gypsum/anhydrite crystals are developed.

**J087S3** – at angle to lamination

As seen in J087S1.

Photomicrographs:

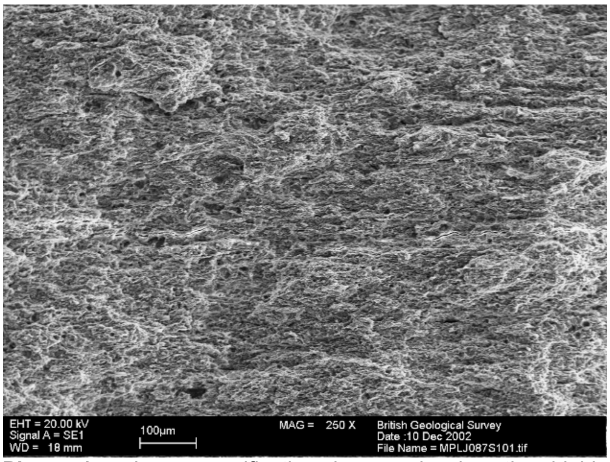


**Photo 1:** Low magnification image showing the highly laminated, very fine-grained nature of this sample.

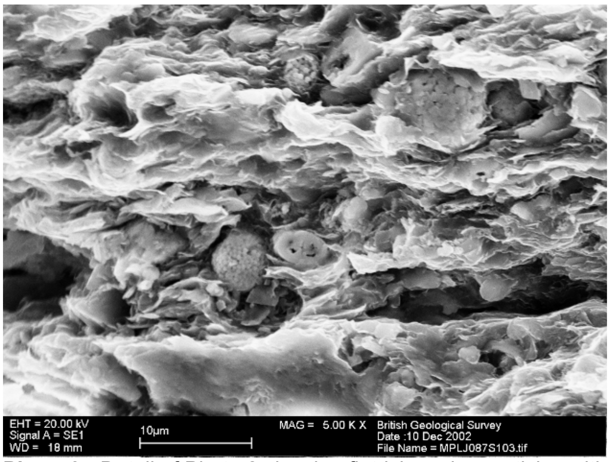


**Photo 3:** Detail of Photo 2 showing flat-lying, clay particles with wispy emanations. Minor framboidal pyrite occurs between the platelets.

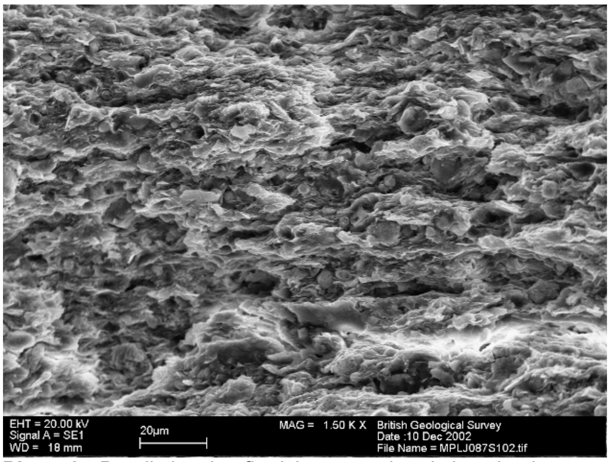


**Photo 2:** Detail showing flat-lying, crenulated clay platelets.

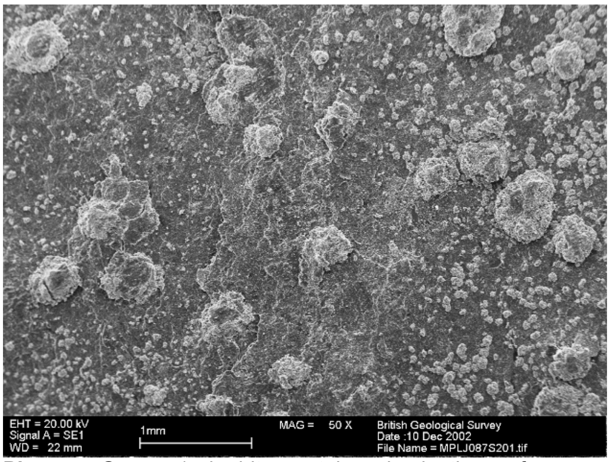


**Photo 4:** Gypsum/anhydrite crystals on lamination surface.

## Weathering Profile at Dimmer

| | | | |
|---|---|---|---|
| Site: | **Dimmer** | SampleID: | **D10** |
| Location ID: | **1** | Position in Profile: | **0.7 m bGL** |
| Basin: | **Wessex Basin** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H274S1** | Preparation: | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

Green-orange faintly laminated with near spherical pores to a couple of mm in diameter. Some oxidised patchy typically associated with porosity.

SEM Description:

- rounded pores of between 100-1000microns occur throughout the sample (Photo 1).
- pores are locally associated with microfractures (Photo 2), and some pores are tubular in character, indicative of decayed rootlets (Photo 3).
- well developed microfracture network, with cracks between rounded "peds".
- actual clay fabrics within peds, much the same as seen and described in other samples.

Photomicrographs:

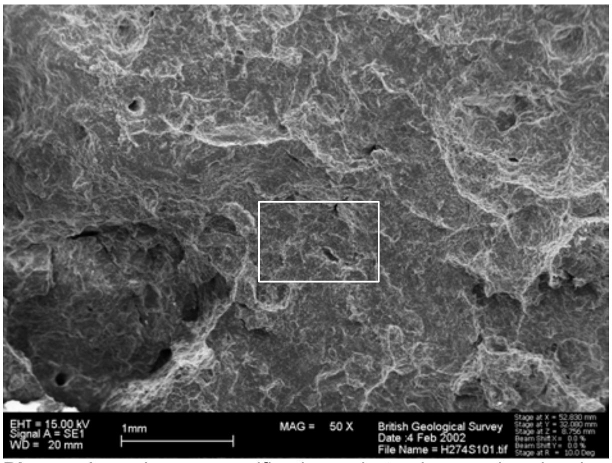


**Photo 1:** Low magnification photomicrograph showing distribution of pores throughout sample (arrowed). Microfractures also clearly evident and some pores noted to be associated with these fractures (boxed area detailed in Photo 2).

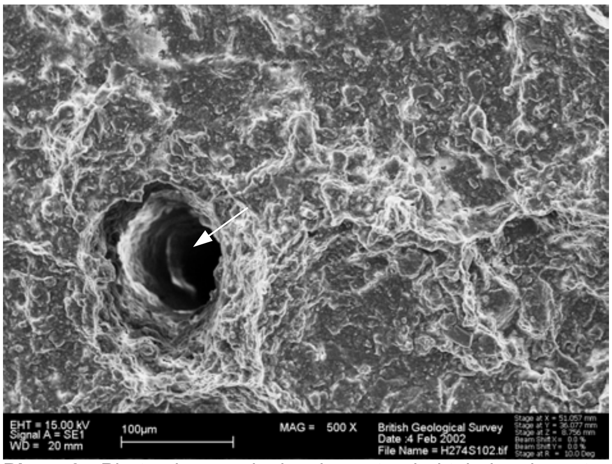


**Photo 3:** Photomicrograph showing extended tubular character of pores (arrowed).

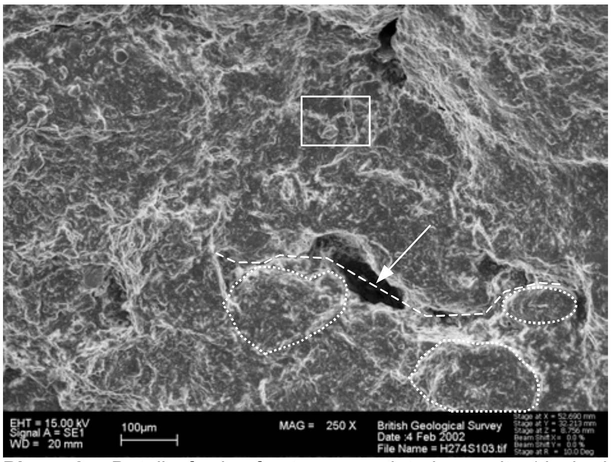


**Photo 2:** Detail of microfracture-associated porosity (dashed line and arrow, boxed area detailed in Photo 4). Brecciated nature of sample also apparent with clay occurring in discrete clumps (dotted lines) bounded by microfractures.

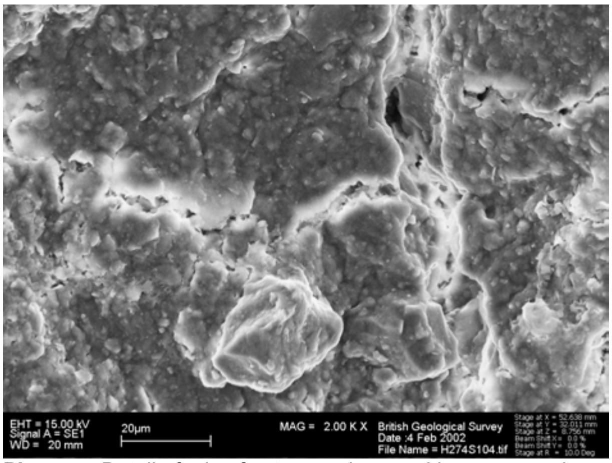


**Photo 4:** Detail of microfracture and general lumpy-amorphous clay fabric.

| | | | |
|---|---|---|---|
| Site: | **Dimmer** | SampleID: | **D15 / DM1** |
| Location ID: | **1** | Position in Profile: | **1.75 m bGL** |
| Basin: | **Wessex Basin** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H279S1** | Preparation: | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

This sample comprises very plastic clay and breaks readily into cm-scale peds. Internally the sample displays variable green-grey orange mottling.

SEM Description:

- this sample is highly fragmented (probably due to sample preparation enhancing the natural characteristics of the sample; see fracture in Photo 1).
- the clay fabric is typically relatively amorphous with some clay platelets evident both within and upon the amorphous clay. These platelets/crystals are locally form rosettes (Photo 3).

Photomicrographs:

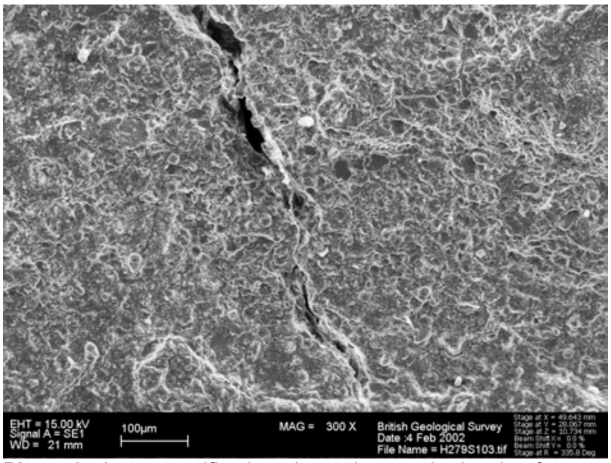


**Photo 1:** Low magnification photomicrograph showing fracture within relatively massive mudstone.

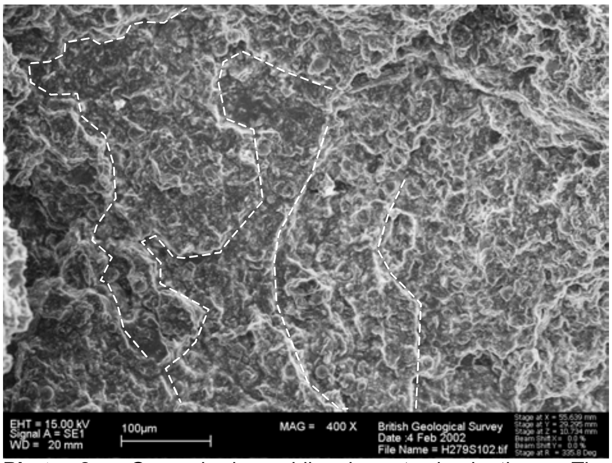


**Photo 2:** General view obliquely onto lamination. The lamination manifests itself as a series of steps (dashed lines).

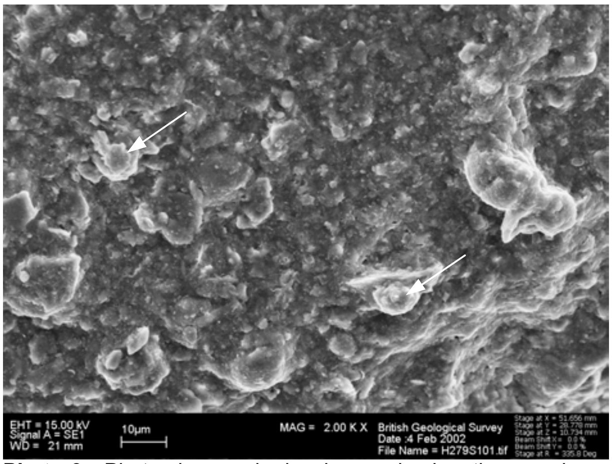


**Photo 3:** Photomicrograph showing predominantly amorphous clay, within and upon which some small clay platelets are evident. These platelets locally form poorly defined rosettes (arrowed).

| | | | |
|---|---|---|---|
| Site: | **Dimmer** | SampleID: | **D9** |
| Location ID: | **2b** | Position in Profile: | **1.7 m bGL** |
| Basin: | **Wessex Basin** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H273S1** | Preparation: | **Freeze dried, fresh fracture surface** |
| | **H273S2** | | **Freeze dried, lamination surface** |

Field / Hand Specimen Observations:

Mottled green/grey and orange, with oxidation typically associated with patchy porosity, and also along microfractures (seen in H273S1). Patchy mm-scale gypsum crystals noted.

SEM Description: H273S1 (across lamination)

- lamination is clearly defined by aligned clay particles and enhanced by microfractures.
- elongate/rounded pores are patchily developed and may represent rootlets (Photo 2).
- clay particles locally have minor fibrous projections and crenulated margins (Photo 4).
- there are no obvious textural differences observed between the oxidised and non-oxidised parts of the sample.

SEM Description: H273S2 (lamination plane surface)

- patch containing large 200micron gypsum/anhydrite crystals is highly porous permeable (Photo 1).
- cellular, organic matter present on lamination surface (Photo 1).
- microfractures noted cutting across lamination.

Photomicrographs:

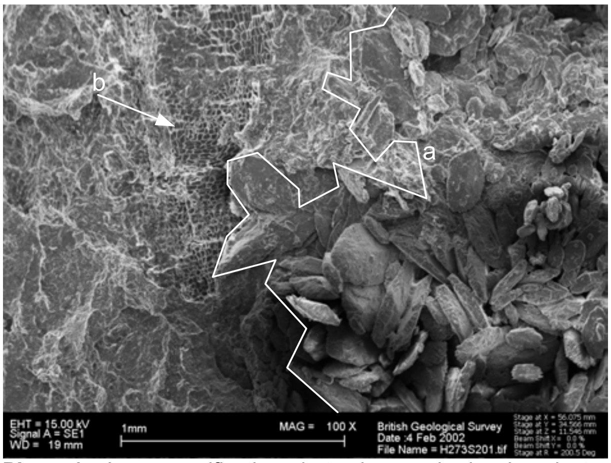


**Photo 1:** Low magnification photomicrograph showing cluster of coarse gypsum crystals (bounded by line a) adjacent to cellular, organic matter lying flat on lamination surface (arrow b).

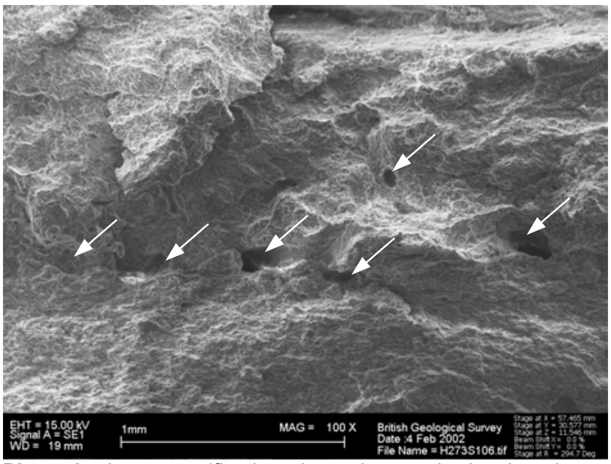


**Photo 2:** Low magnification photomicrograph showing cluster of rounded/tubular pores (arrowed) within the laminated clay. These features are locally interconnected and probably represent decayed rootlets.

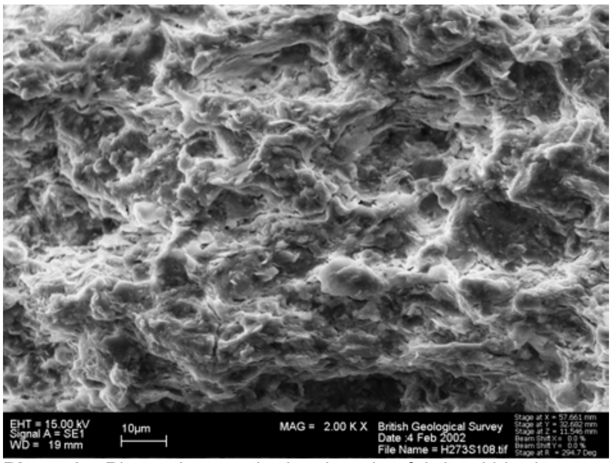


**Photo 3:** Photomicrograph showing clay fabric within the non-oxidised part of sample. Clay fabrics are indistinguishable between the oxidised and non-oxidised parts of the sample.

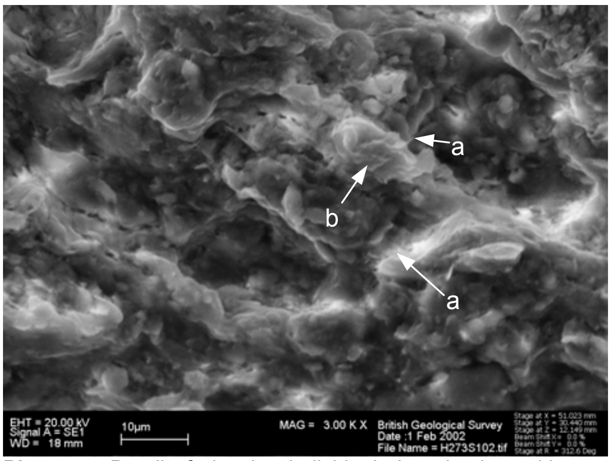


**Photo 4:** Detail of showing individual clay platelets with rare fibrous emanations (arrow a) and possible development of rosettes (arrow b).

| | | | |
|---|---|---|---|
| Site: | **Dimmer** | SampleID: | **D8** |
| Location ID: | **2b** | Position in Profile: | **2.9 m bGL** |
| Basin: | **Wessex Basin** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H272S1** | Preparation: | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

Green-grey coloured mudrock with minor orange mottling, with some mottling related to microfractures and porosity. When the hand-specimen was cut open for SEM stub sample preparation, a near-vertical fracture/shear within the sample was revealed. The fabric is more massive than that of sample 07 (H271), but lamination is still apparent in hand specimen. Some coarse-grained mm-scale clear crystals were included on the SEM stub for purposes of identification.

SEM Description:

- mm-scale clear crystals confirmed as gypsum/anhydrite (Photo 1).
- lamination defined at high magnification by aligned clay-particles and microfractures (Photos 2-4).
- this sample appears to contain notably greater volumes of microporosity than sample 07 (H271), and clay-particles tend to be less strongly aligned.
- sample contains localised sub-spherical $CaCO_3$ bodies (locally plucked), leaving sub-spherical voids (Photos 2 and 3). It is ambiguous if these features represent microfossils or authigenic carbonate (possibly the former given their rounded shapes).

Photomicrographs:

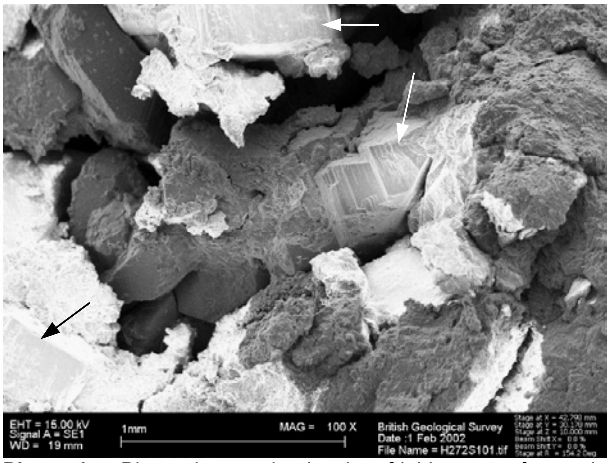


**Photo 1:** Photomicrograph showing friable part of sample (which results in significant sample charging under the electron beam) associated with large amounts of porosity and well developed gypsum/anhydrite crystals (arrowed).

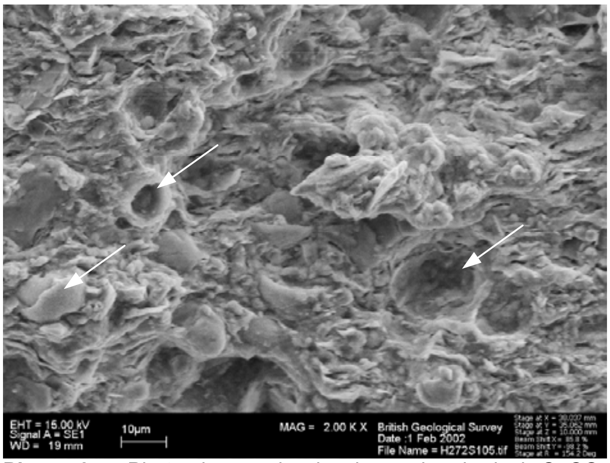


**Photo 3:** Photomicrograph showing sub-spherical $CaCO_3$ bodies which are locally plucked leaving spherical voids within laminated clay (arrowed). ?bioclasts or authigenic carbonate?.

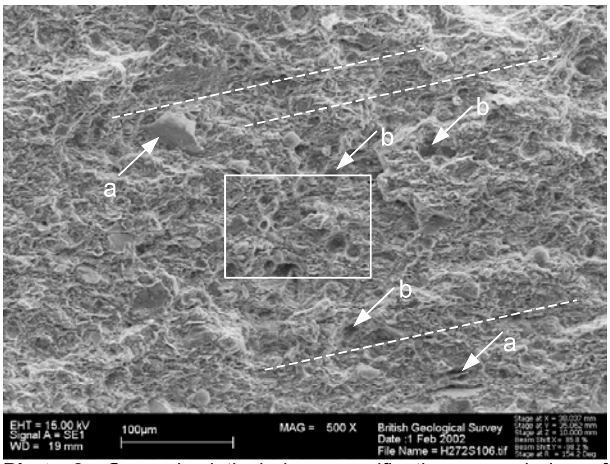


**Photo 2:**. General relatively low magnification general view of this sample. The laminated fabric is clearly evident (dashed lines), as are minor mica flakes (arrowed, a). Note the presence of rounded features which possibly represent plucked microfossils (arrowed, b). Boxed area is detailed in Photo 3.

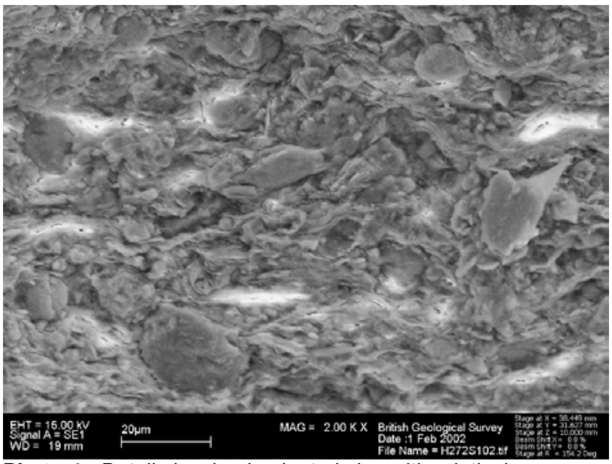


**Photo 4:** Detail showing laminated clay with relatively common silt-grade material. Note the relatively microporous nature of this sample compared with sample 07 (H271). Also note the common lamination-parallel microfractures.

| | | | |
|---|---|---|---|
| Site: | **Dimmer** | SampleID: | **D7** |
| Location ID: | **2b** | Position in Profile: | **4.2 m bGL** |
| Basin: | **Wessex Basin** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H271S1** | Preparation: | **Freeze dried, fresh fracture surface** |
| | **H271S2** | | **Freeze dried, lamination surface** |

Field / Hand Specimen Observations:

Dense, grey, well laminated mudrock. no mottling apparent. Some bioclasts. Microfractures developed parallel to lamination (induced).

SEM Description: H271S1 (across lamination)

- lamination is defined by the common alignment of clay particles (Photos 1 and 2).
- microfractures (probably artificially induced) are well developed parallel to lamination.
- this sample has very limited porosity, comprising tiny, typically elongate, micropores that are only connected by the microfractures (Photo 1).
- minor fibrous emanations are noted from some clay-platelets indicating possible minor neomorphism/authigenesis.
- EDXA indicates that the clay is predominantly K- and Ca- bearing with minor Mg.
- this sample relatively free of silt/sand-grade material.
- at very high magnification clay particles seen to comprise fine aggregates of platelets, commonly having a "lumpy" appearance.

SEM Description: H271S2 (lamination plane surface)

- the lamination plane surface is criss-crossed by irregular crenulated clay. These crenulations appear to emanate from within the sample, rather than just sitting on the sample surface, suggesting that they are "natural" (rather than sample preparation induced) features (Photos 3 and 4).
- also noted are rare "rosettes" of clay platelets - also probably of authigenic origin.

Photomicrographs:

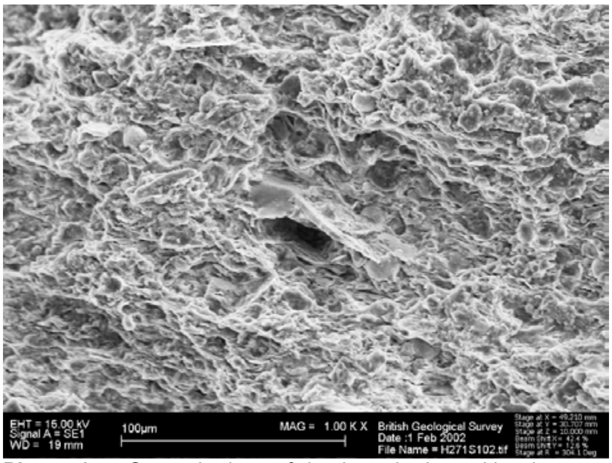

**Photo 1:** General view of laminated clay with elongate, lamination parallel micropores and microfractures.

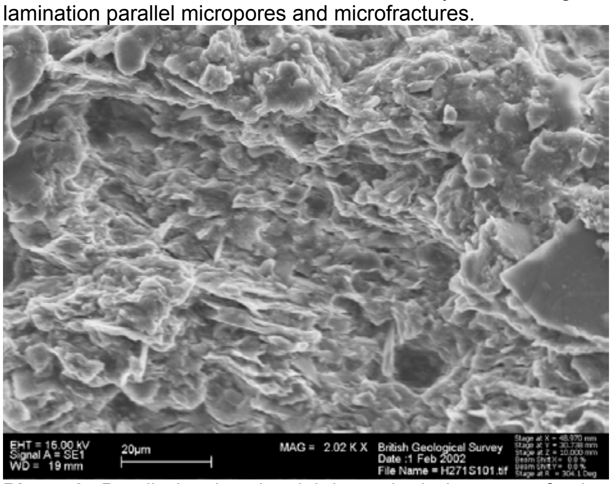

**Photo 2:** Detail showing the tightly packed character of clay platelets. Also note the presence of microfractures and the common alignment of particles/aggregates of particles, parallel to lamination.

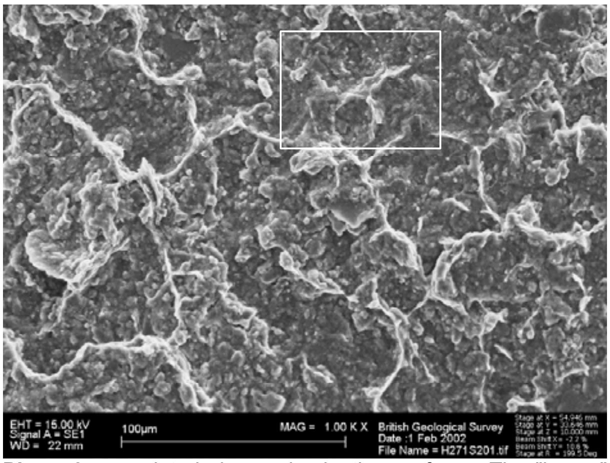

**Photo 3:** crenulated clay on lamination surface. The "lumpy" character of the clay is also clear in this image. Boxed area detailed in Photo 07.4.

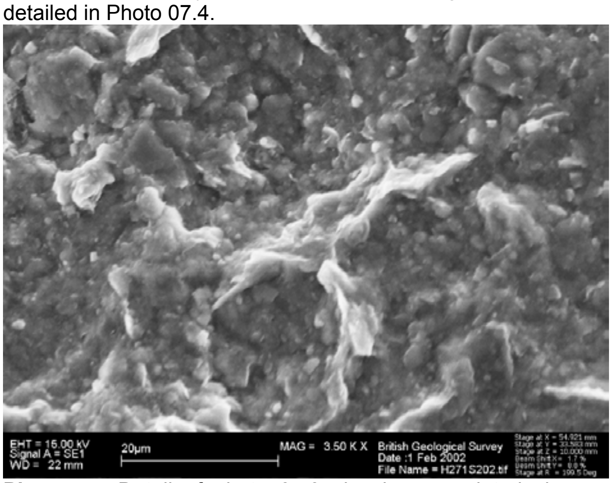

**Photo 4:** Detail of photo 07.3 showing crenulated clay on lamination surface and detailing the “lumpy” character of the clay..

| | | | |
|---|---|---|---|
| Site: | **Dimmer** | SampleID: | **D13** |
| Location ID: | **3** | Position in Profile: | **2.1 m bGL** |
| Basin: | **Wessex Basin** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H277S1** | Preparation: | **Freeze dried, cut surface** |
| | **H277S2** | | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

This sample is pale green-grey with green-orange mottling, and is relatively crumbly with abundant pores and mm-scale dispersed gypsum/anhydrite crystals, and ferruginous nodules to 5mm diameter.

SEM Description:

- the cut surface of stub H277S1 indicates the presence of “bright” nodules/mottles (higher backscattered electron signal) up to 2mm diameter occur within **“**darker matrix" clay (Photo 1). EDXA of areas of different brightness indicates that the “bright” mottles have different bulk chemistry to the “dark matrix" (Photo 2):

| | | |
|---|---|---|
| - ***characteristic*** | ***“bright”*** | ***“dark”*** |
| - Al, Si, Mg, Fe, K peak intensities/ratios | comparable | |
| - Ca peak intensity | low | high |
| - Ca:Al ratio | low (1:3) | high (2:3) |
| - Ca:K ratio | low (1:0.7) | high (4:1). |

- within the “bright” mottles clay platelets are notably better defined and microporosity is more abundant than in the “dark” matrix which has a more amorphous, lumpy appearance (as seen in other samples; Photo 3). This suggests that the clay has recrystallised within the “bright” mottles.
- some large gypsum/anhydrite crystals noted.
- H277S2 is highly fragmented/nodularised (Photo 4).

Photomicrographs:

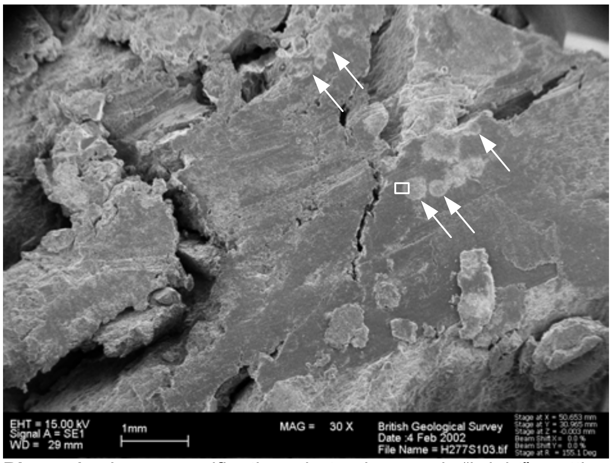


**Photo 1:** Low magnification photomicrograph “bright” mottles (arrowed) within “darker” clay matrix. (Boxed area detailed in Photo 13.2.)

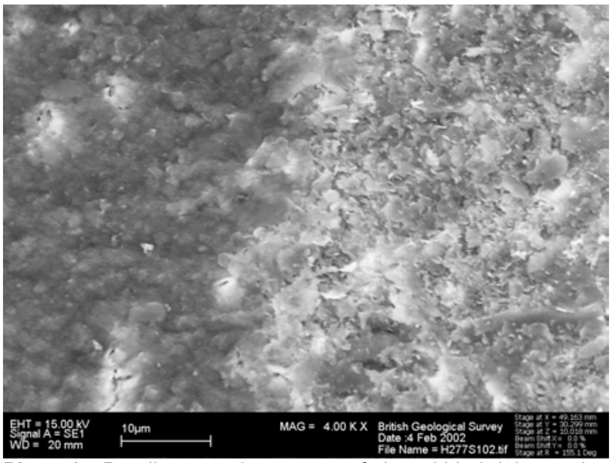


**Photo 3:** Detail contrasting texture of clay within bright mottles (finely crystalline platelets with wispy emanations, highly microporous) with dark matrix clay (amorphous to lumpy texture, poorly microporous).

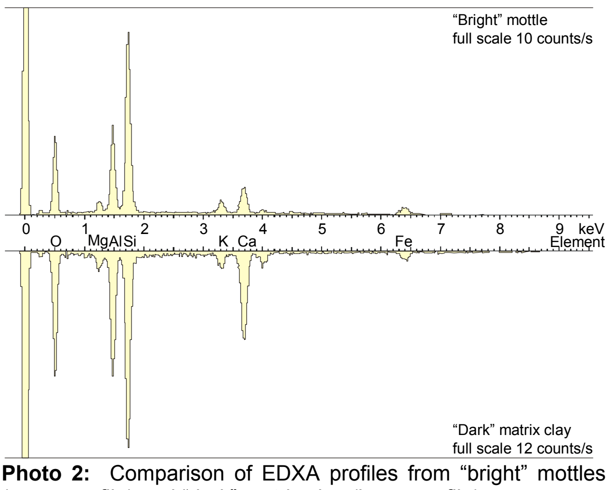


**Photo 2:** Comparison of EDXA profiles from “bright” mottles (upper profile) and “dark” matrix clay (lower profile).

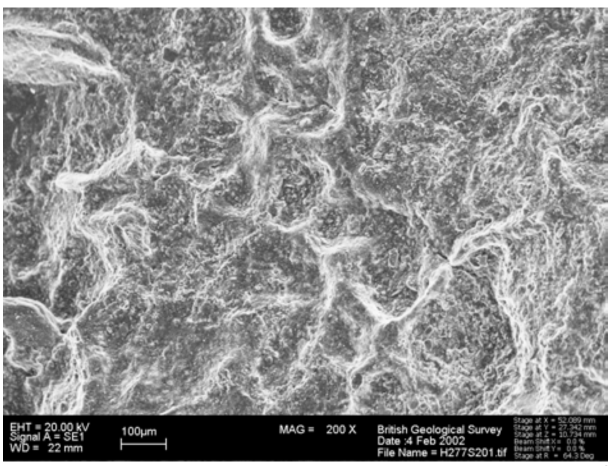


**Photo 4:** general view showing the nodularised texture of S277S2.

| | | | |
|---|---|---|---|
| Site: | **Dimmer** | SampleID: | **D12** |
| Location ID: | **3** | Position in Profile: | **3.5 m bGL** |
| Basin: | **Wessex Basin** | Formation: | **Charmouth Mudstone** |
| MPL Sample Code: | **H276S1** | Preparation: | **Freeze dried, fresh fracture surface** |

Field / Hand Specimen Observations:

A dark-grey, well laminated mudstone with no obvious mottling, taken 1.2 m below a horizon containing large (up to 50 cm diameter) calcareous, septarian nodules. Minor small <<1mm pores are evident.

SEM Description:

- pores up to *c*.50microns diameter are fairly evenly distributed throughout this sample, and tend to be elongate parallel to lamination (enhancing lamination-parallel microfractures; Photo 1).
- the SEM stub is cut by a possible high angle shear, across which some microfractures are discontinuous, which may imply that some fractures were present prior to shear (Photo 1).
- patchy euhedral Fe-sulphide crystals up to *c*.40microns diameter are present (Photo 2). EDXA suggests Fe:S ratios of 1:2.
- wispy emanations noted on some clay platelets (Photo 3).
- minor patchy, poorly formed carbonate noted (Photo 4). This carbonate has a skeletal appearance and it is ambiguous whether this is of corroded detrital or poorly formed authigenic origin. EDXA indicates that this is predominately calcite, but minor dolomite is also noted.

Photomicrographs:

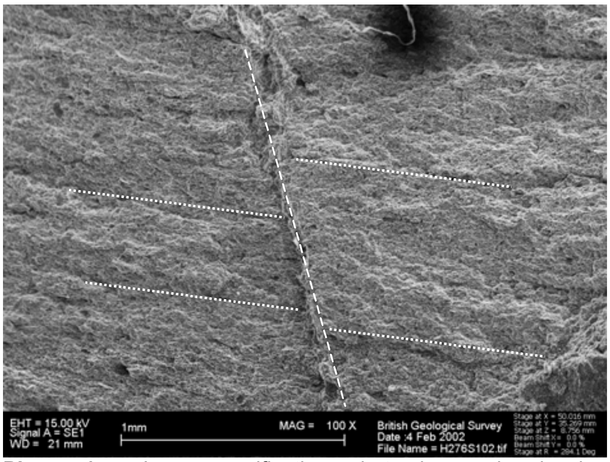


**Photo 1:** Low magnification photomicrograph showing laminated structure of this sample, with lamination-parallel microfractures (dotted lines) truncated at high angle shear (dashed line).

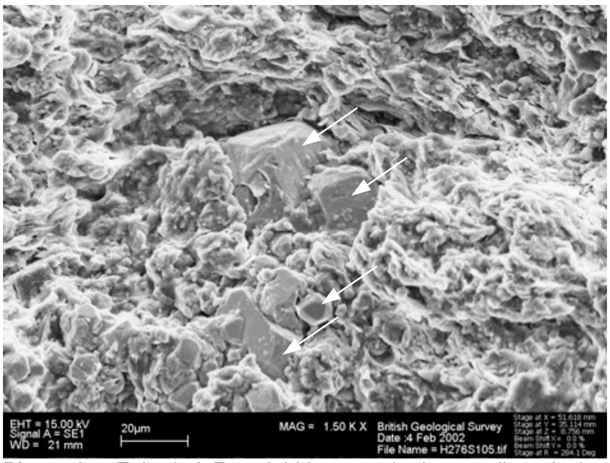


**Photo 2:** Euhedral Fe-sulphide crystals (arrowed) replacing laminated clay.

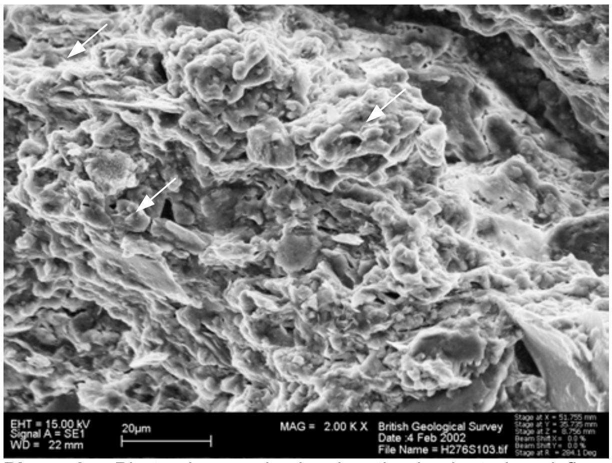


**Photo 3:** Photomicrograph showing the laminated and fine-grained character of this sample. Minor wispy emanations from clay platelets are arrowed.

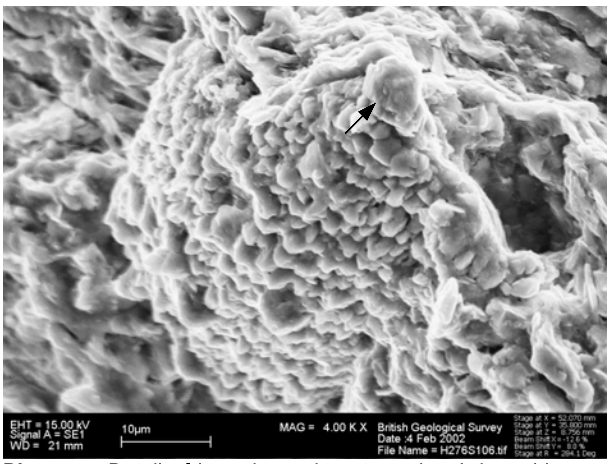


**Photo 4:** Detail of irregular carbonate grain. It is ambiguous whether this texture is crystallisation or dissolution-related. The rhombic grain at the "top" of the grain is dolomite (arrowed), the remainder is calcite.

| | | | |
|---|---|---|---|
| Site: | Lliswerry, **Rhoose** | SampleID: | **Rhoose** |
| Basin: | **Wessex** | Formation: | **Blue Lias** |
| MPL Sample Code: | **H594S1** | Preparation**:** | **Air dried, fresh fracture surface** |

A homogeneous, apparently massive, dense sample, with relatively minor porosity. $CaCO_3$ is patchily abundant with carbonates occurring as small disseminated euhedra commonly "buried" beneath clays at the sample surface making acquisition of "clean" EDXA spectra and morphological characterisation difficult. Clay particles display variably well developed crystal shapes, and only locally have obvious wispy/ribbon-like outgrowths. EDXA indicates K-Ca-Mg-bearing compositions (variable Ca/Mg/K ratios) for the clay (?smectite?). These mineralogical interpretations are supported by XRD analysis, which suggests that the clay fraction is dominated by illite and smectite with minor illite/smectite.

Photomicrographs:

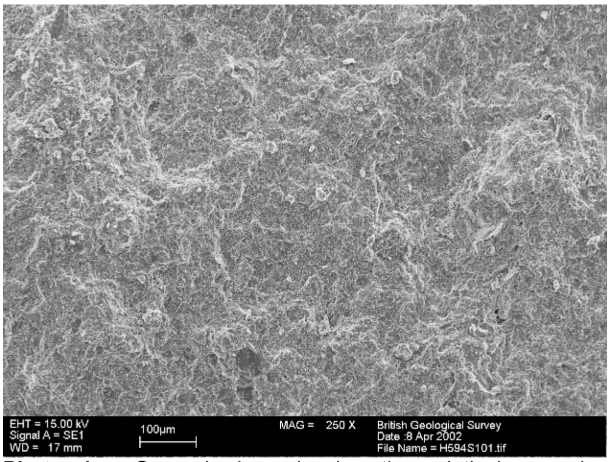


**Photo 1:** General view showing the relatively massive character of this sample.

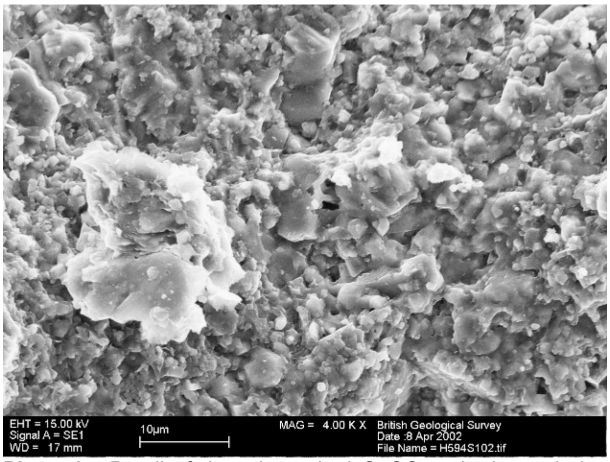


**Photo 2:** Detail of densely packed $CaCO_3$ euhedra and clay platelets.

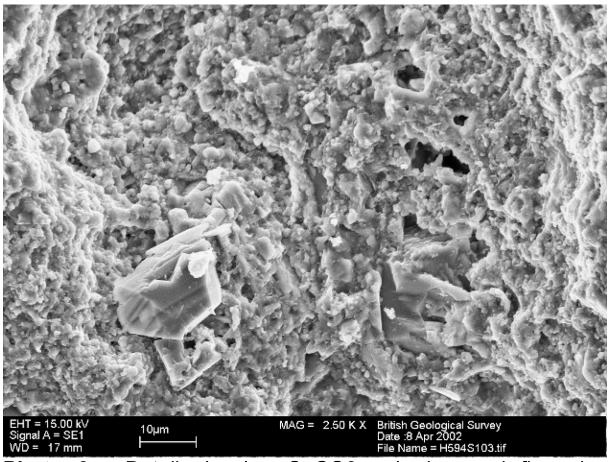


**Photo 3:** Detail showing CaCO3 euhedra, and fine clay particles, adjacent to unusually porous patch within sample.

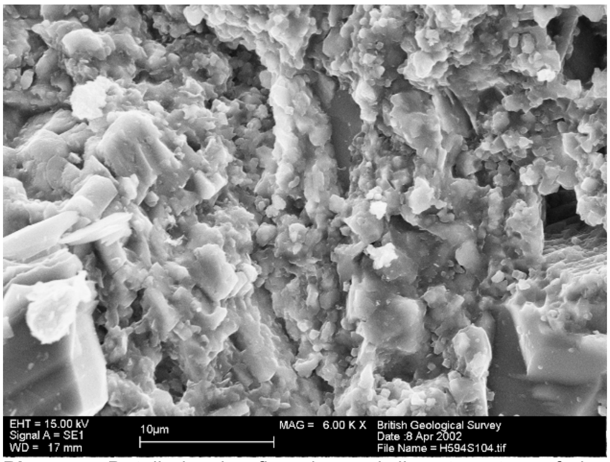


**Photo 4:** Detail showing fine size and discrete nature of clay particles. Also note finely crystalline rhombic $CaCO_3$.

| | | | |
|---|---|---|---|
| Site: | **Aberthaw**, Barry | SampleID: | **Aberthaw** |
| Basin: | **Wessex** | Formation: | **Blue Lias** |
| MPL Sample Code: | **H596S1** | Preparation: | **Air dried, fresh fracture surface** |

This sample has a massive fabric and is $CaCO_3$-rich, with very abundant finely crystalline (< 10 micron) to coarse (100's microns) rhombic crystals throughout. The $CaCO_3$ engulfs webby to amorphous clay. In more clay-rich patches, a mixture of webby/amorphous clay and clusters of finely crystalline plates (individual plates 1-10 microns diameter) are observed. EDXA indicates a mixture of K- and Ca- bearing compositions for the clay, although the high $CaCO_3$ content of this sample makes it difficult to obtain reliable EDXA spectra for the clay. These mineralogical interpretations are supported by the XRD data which records major amounts of illite, and minor amounts of illite-smectite in the sample. Minor rhombic dolomite and pyrite framboids occur throughout.

Photomicrographs:

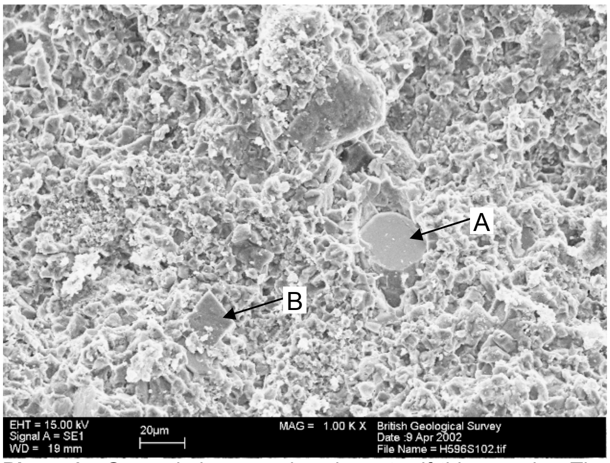


**Photo 1:** General view massive character if this sample. The crystal at (A) is $CaCO_3$, and that at (B) is dolomite.

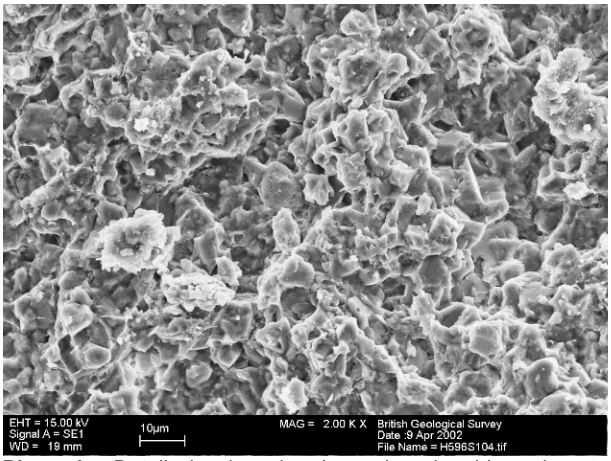


**Photo 2:** Detail showing abundant micro-rhombic carbonate engulfing small aggregates of clay platelets.

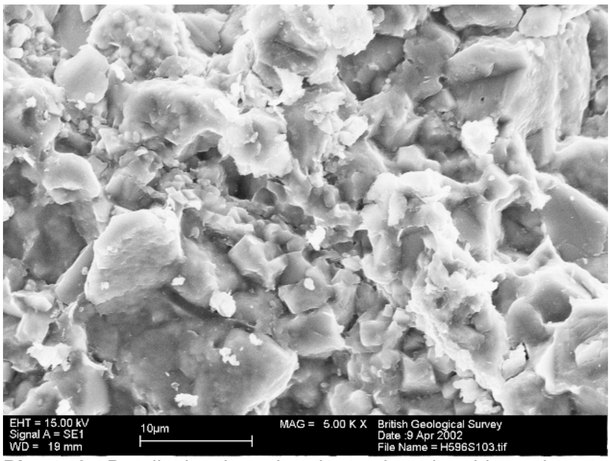


**Photo 3:** Detail showing abundant micro-rhombic carbonate engulfing small aggregates of clay platelets.

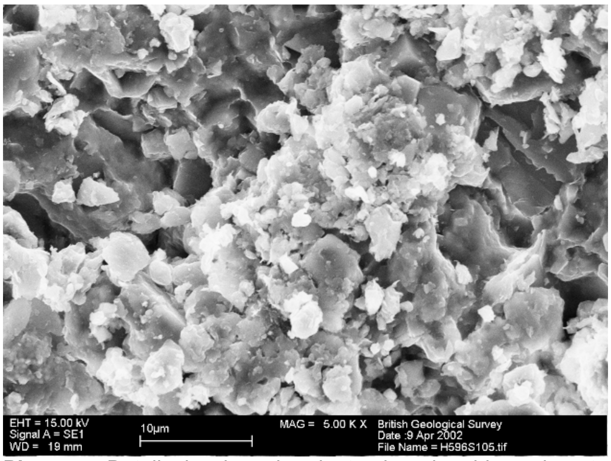


**Photo 4:** Detail showing abundant micro-rhombic carbonate engulfing small aggregates of clay platelets.

| | | | |
|---|---|---|---|
| Site: | **Station**, Somerton | SampleID: | **Station** |
| Basin: | **Wessex** | Formation: | **Blue Lias** |
| MPL Sample Code: | **H599S1** | Preparation**:** | **Air dried, fresh fracture surface** |

A massive, homogenous calcareous mudstone, of similar character to that from Aberthaw (H596S1), although it possibly has a higher clay content. EDXA indicates that the bulk of this sample is made up of $CaCO_3$ (i.e. micrite). These high $CaCO_3$ levels prevent acquisition of EDXA spectra for any other clay minerals present.

Photomicrographs:

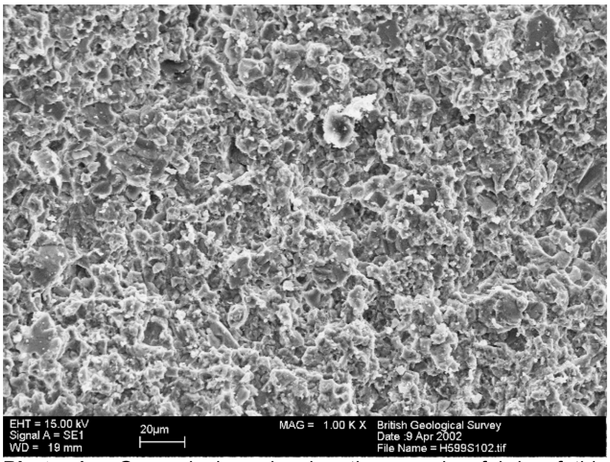


**Photo 1:** General view showing the massive fabric of this sample.

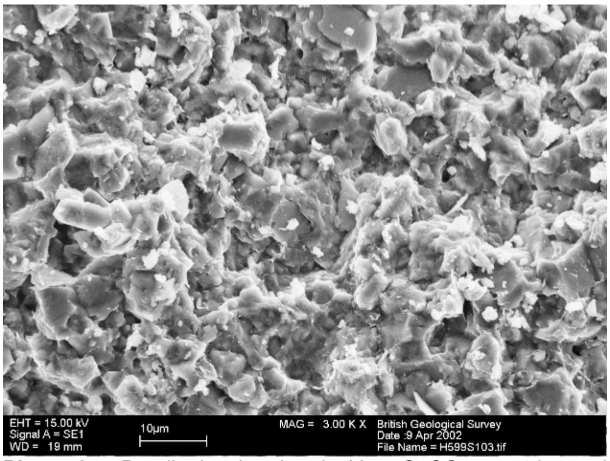


**Photo 2:** Detail showing interlocking $CaCO_3$ crystals, and relatively abundant clays.

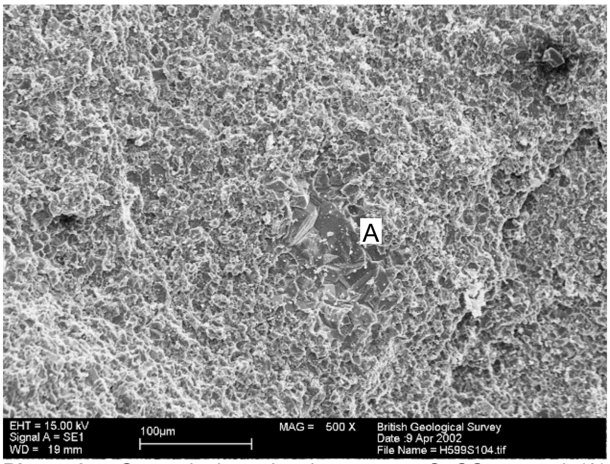


**Photo 3:** General view showing coarse $CaCO_3$ crystal (A) within matrix of microcrystalline $CaCO_3$ and clays.

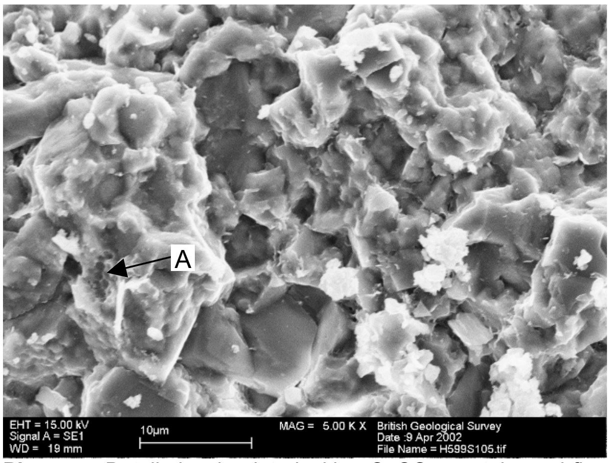


**Photo 4:** Detail showing interlocking $CaCO_3$ crystals, and fine clay platelets. Also note small patch of webby clay (?smectite) at (A).

| | | | |
|---|---|---|---|
| Site: | **Lake View**, Street | SampleID: | **Lake View** |
| Basin: | **Wessex** | Formation: | **Blue Lias** |
| MPL Sample Code: | **H598S1** | Preparation**:** | **Air dried, fresh fracture surface** |

A massive, homogeneous calcareous mudstone of similar character to the sample from Aberthaw (H596S1). In detail this sample comprise fine interlocking rhombs, and other fragments (typically 2-5 microns diameter) of $CaCO_3$, with minor platey K-Ca-Al-silicates (illite and/or smectite; supported by XRD analysis which indicates major illite, and minor kaolinite, chlorite and illite/smectite in the clay fraction). This sample has a well-connected micropore system, with pores of 3-5 microns, connected through pore throats of <1 micron. Minor pyrite framboids are present.

Photomicrographs:

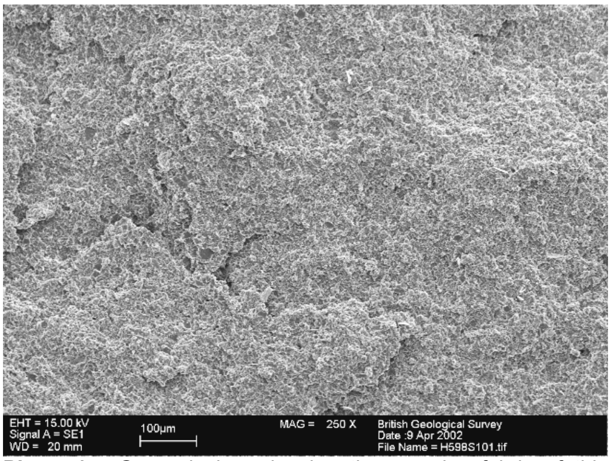


**Photo 1:** General view showing the massive fabric of this sample.

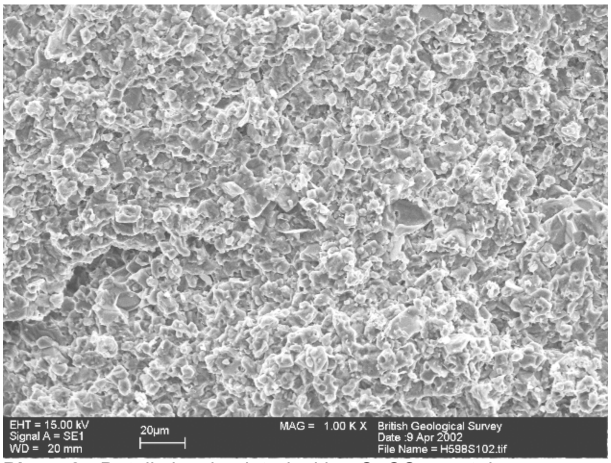


**Photo 2:** Detail showing interlocking $CaCO_3$ crystals.

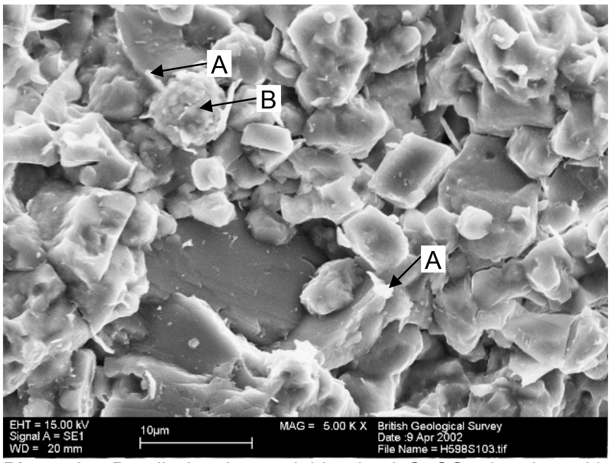


**Photo 3:** Detail showing variably sized $CaCO_3$ rhombs, with very minor clay (A) and an example of a pyrite framboid (B).

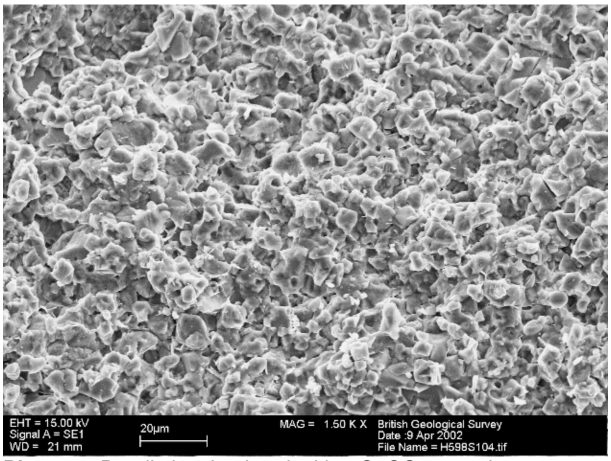


**Photo 4:** Detail showing interlocking $CaCO_3$ crystals.