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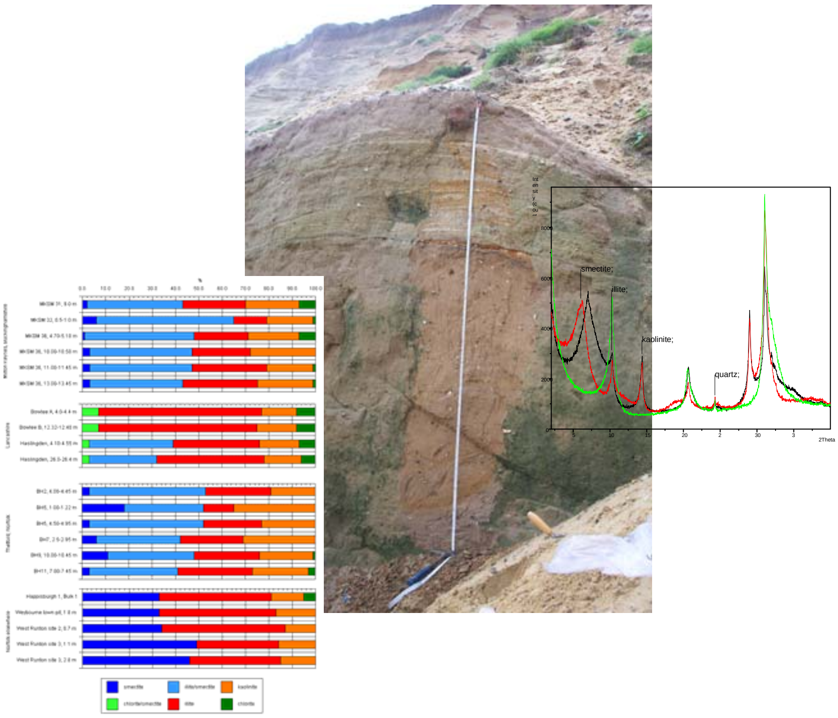
# The mineralogy and surface area of till samples from Buckinghamshire, Lancashire and Norfolk

Land Use and Development Programme

Internal Report IR/08/053



BRITISH GEOLOGICAL SURVEY

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INTERNAL REPORT IR/08/053

# The mineralogy and surface area of till samples from Buckinghamshire, Lancashire and Norfolk

S J Kemp, D Wagner & I Mounteney

*Keywords*

Tills, mineralogy, clay minerals, surface area, smectite.

*National Grid Reference*

*Map*

*Front cover*

Montage of West Runton site 3, Norfolk showing thinly bedded Bacton Green Member overlying the occasionally gravelly Runton Till Member, <2 µm XRD traces for sample from same locality and bar chart illustrating clay mineral assemblages for the suite of till samples.

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# Foreword

This report is the published product of a study by the British Geological Survey (BGS) and forms part of the ongoing BGS project, ‘Physical Properties and behaviour of UK rocks and soils’ under the Land Use and Development Science Theme. This report aims to provide mineralogical and surface area data to help explain the geotechnical behaviour of till deposits from various parts of England.

# Acknowledgements

The authors would like to thank Dave Boon and Dave Entwisle (BGS) for the field collection of the samples.

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# Summary

This report describes the results of mineralogical and surface area analysis completed on the ‘fine matrix’ (<425 µm material) of a suite of tills from England. The work was carried out as part of the ongoing BGS project, ‘Physical Properties and behaviour of UK rocks and soils’ under the Land Use and Development Science Theme.

The first part of the report gives a summary of previous BGS mineralogical studies of till deposits. A summary of analytical methods employed (X-ray diffraction analysis and surface area determinations) is then provided and the results discussed with reference to their likely effect on the engineering performance.

Analyses indicate that the till samples are ‘fine matrix’-rich and typically composed of location-dependant varying proportions of quartz, calcite and phyllosilicates/clay minerals together with a range of minor-trace constituents.

Given their typically ‘fine-matrix’-dominated nature, the geotechnical behaviour of the till samples examined is likely to be influenced by both the proportion of phyllosilicates/clay minerals present and their composition and can be indicated by the surface area measurements. This being the case, the tills from Thetford (BHs 2 and 5) and Milton Keynes would be expected to show the most problematic engineering behaviour.

Although the mineralogy of till deposits are typically thought to be derived from several sources, mineral and clay mineral assemblages suggest that the tills in this study are predominantly derived from underlying lithologies. Tills from various locations in Norfolk other than Thetford appear to be principally derived from the Norwich and Red Crag formations with some input from the Upper Chalk whilst the more carbonate-rich Thetford tills appear to have a greater Upper Chalk input.

The mineralogically distinct Lancashire tills suggest Permo-Triassic sources, probably the Mercia Mudstone Group while the Milton Keynes tills indicate that the underlying Jurassic limestones and mudstones probably produced their sediment supply.

# 1 Introduction

This report summarises the results of a mineralogical and surface area study of a suite of samples extracted from till deposits from various parts of England. This study forms part of the BGS project, ‘Physical Properties and behaviour of UK rocks and soils’ under the Land Use and Development Science Theme.

The main aims of the ‘Physical Properties and behaviour of UK rocks and soils’ project are to assess and report on the geotechnical properties and engineering behaviour of various UK bedrock and superficial formations, providing a comprehensive dataset to assist ground engineering users in the feasibility/desk study phases for engineering projects, hazard assessment and land use planning within these materials. As part of this wider project, the mineralogical and surface area analyses were requested in order to investigate their potential influence on engineering behaviour.

Due to their high surface area, residual charge and interaction with water, clay minerals (and smectite-group minerals in particular) are most frequently cited as the reason for the shrink-swell behaviour noted in sedimentary rocks. For this reason, particular attention was aimed at the evaluation of the nature of the clay minerals present to help explain the geotechnical behaviour of the till deposits.

# 2 Previous mineralogical studies of till deposits

During the 1990s, the BGS Mineralogy & Petrology Group carried out a series of investigations to characterise till deposits. Inglethorpe & Bloodworth (1994) researched and proposed a methodology to define a hydrogeological classification for lodgement till sequences and the degree to which theses tills control aquifer vulnerability. The methodology was then used to assess UK tills from East Anglia (Inglethorpe & Bloodworth, 1994), Wolverhampton (Kemp & Mitchell, 1994), Shropshire (Inglethorpe *et al.*, 1996), Humberside (Kemp *et al.*, 1998) and later, a Canadian till sheet (Pearce *et al.*, 2003).

Further, more analytically-limited characterisation studies were carried out as part of UK NIREX’s investigations in west Cumbria during the 1990s e.g. Bloodworth *et al.* (1994; 1995), Inglethorpe & Bloodworth (1995) and Inglethorpe *et al.* (1995).

# 3 Samples

For the present study, a suite of 21 till samples were submitted for mineralogical analysis using X-ray diffraction (XRD) and surface area analysis (Table 1).

# Table 1 List of sampling locations and samples studied.

| Location | Borehole/site | Grid ref | Depth (m)/ sample | MPL code | Field description |
|---|---|---|---|---|---|
| Milton Keynes, Buckinghamshire | MKSM 31 | 462338 244008 | 9.00 | MPLN300 | Very stiff grey gravelly clay (Oadby Till Member, Wolston Formation). |
| | MKSM 32 | 464479 238097 | 0.5-1.0 | MPLN301 | Stiff brown gravelly CLAY. Medium to coarse flint, quartz, limestone, strong crystalline limestone gravel and cobbles. (Oadby Till Member, Wolston Formation). |
| | MKSM 32A | 464493 238099 | 4.70-5.10 | MPLN302 | Very stiff dark blue grey slightly gravelly CLAY with cobbles. Gravel is generally fine to coarse. Rounded fine chalk gravel and coarse flint gravel. (Oadby Till Member, Wolston Formation). |
| | MKSM 36 | 466240 246311 | 10.00-10.50 | MPLN303 | Firm/stiff brown gravelly CLAY. (Oadby Till Member, Wolston Formation). |
| | | | 11.00-11.45 | MPLN304 | Stiff Lias CLAY with grey sand bands. |
| | | | 13.00-13.45 | MPLN305 | Very stiff grey Lias CLAY. |
| Lancashire | Bowlee A | SD 38535 40723 | 4.0-4.4 | MPLN306 | CLAY, firm, massive, dark yellowish brown 10YR 4/2, gravely with fine gravel of sandstone and Lake District igneous rocks; red sandstone cobble at 5.0m. (North Pennines Till). |
| | Bowlee B | SD 38476 40679 | 12.32-12.40 | MPLN307 | CLAY, soft to very soft, brownish grey 5YR 4/1, very silty and sandy; drop stone at base (North Pennines Till). |
| | Haslingden | SD 37938 42142 | 4.10-4.55 | MPLN308 | CLAY, soft, fissured, mottled brownish grey 5YR 4/1 and moderate yellowish brown 10YR 5/4; gravely, sandstone and Lake District igneous rocks (North Pennines Till). |
| | | | 26.0-26.4 | MPLN309 | CLAY, stiff, fissured, mottled brownish grey 5YR 4/1 and moderate yellowish brown 10YR 5/4; gravely, sandstone and Lake District igneous rocks (North Pennines Till). |
| Thetford, Norfolk | BH2 | TL 93257 76438 | 4.00-4.45 | MPLN310 | Stiff grey brown gravelly CLAY (Lowestoft Till Formation). |
| | BH5 | TL 93397 76606 | 1.00-1.22 | MPLN311 | Firm brown sandy gravelly CLAY (Lowestoft Till Formation). |
| | | | 4.50-4.95 | MPLN312 | Stiff grey brown gravelly CLAY (Lowestoft Till Formation). |
| | BH7 | TL 92140 79440 | 2.5-2.95 | MPLN313 | Stiff brown gravelly CLAY with chalk (Lowestoft Till Formation). |
| | BH9 | TL 98295 94002 | 10.00-10.45 | MPLN314 | Stiff grey gravelly CLAY, gravel mostly chalk gravel (Lowestoft Till Formation). |
| | BH11 | TL 97686 88513 | 7.00-7.45 | MPLN315 | Firm to stiff grey silty gravelly CLAY with chalk (Lowestoft Till Formation). |
| Norfolk, elsewhere | Happisburgh 1 | TG 3878 3069 | 0.00 – 0.30 | MPLN316 | Firm to stiff, medium to widely spaced joints, brownish grey slightly gravelly CLAY. Joints contain sand. (Happisburgh Till Member, Happisburgh Glacigenic Formation). |
| | Weybourne town pit | TG 11389 43072 | 1.8 | MPLN317 | Hard to very weak highly calcareous silt and chalk with clay beds. (Weybourne Town Till Member, Sheringham Cliffs Formation). |
| | West Runton site 2 | TG 19050 43050 | 0.7 | MPLN318 | Firm thinly laminated to thinly bedded, clay, silt, sand and gravel (Becton Green Till Member?, Sheringham Cliffs Formation). |
| | West Runton site 3 | TG 19120 43029 | 1.1 | MPLN319 | Stiff, distorted, thinly laminated to thinly bedded, orange brown to pale orange brown at base, occasionally to slightly gravelly, slightly sandy CLAY. Gravel is sub angular to rounded, fine to medium chalk and flint. With linear to curved, planar , smooth ‘shear’ plane cutting at 1.65 m at about 27°. (Runton Till Member, Sheringham Cliffs Formation). |
| | | | 2.8 | MPLN320 | Loose to moderately dense(?), thinly laminated to thinly bedded, yellow orange, light brown, pale grey to very dark grey, contorted, occasional mostly sub angular to rounded chalk and flint gravel, slightly silty or clayey fine SAND. Becomes less gravelly with depth. (Mundesley Sand Member, Sheringham Cliffs Formation). |

# 4 Laboratory methods

The particle-size distributions of till deposits can be conveniently divided into ‘clasts’ and ‘matrix’. Typically, the ‘clast’ component will be dominated by silica and relatively stable rock fragments when compared to the more ‘active’ phyllosilicates, clay minerals and fine-grained carbonates that often form the predominant components of the ‘matrix’.

However, the definition of till ‘matrix’ is not absolute. Many geological and Quaternary studies define the matrix as the <2 mm fraction whereas index classification tests for civil engineering site investigation (e.g. Atterberg limits and shrinkage) use the <425 µm fraction, referred to as ‘fine matrix’. As this study formed part of a wider project researching the engineering behaviour of tills, the analytical part of the study was therefore aimed at the more active ‘fine matrix’ so that results could be directly compared with generated geotechnical data.

The laboratory methodology employed was modified from that first presented by Inglethorpe & Bloodworth, (1994). For this study, initial particle-size separation was performed to isolate the ‘fine matrix’ (<425 µm) for XRD and surface area analyses only. No clast (>425 µm) analysis or cation exchange capacity determinations were carried out and full particle-size analyses are reported elsewhere (BGS Geotechnical reports LJ102, 110, 111 and 116).

## 4.1 GENERAL SAMPLE PREPARATION

Representative portions of each sample were dispersed in deionised water and passed through a 425 µm sieve. Both the >425 µm and <425 µm fractions were then dried at 55ºC and bagged.

Approximately one half of the <425 µm fractions were then passed to the BGS Sample Preparation Facility and tema-milled for surface area and matrix X-ray diffraction analyses. The remaining <425 µm was retained for clay mineral XRD analyses.

## 4.2 SURFACE AREA DETERMINATION

Surface area determinations were performed on all samples using the 2-ethoxyethanol (ethylene glycol monoethyl ether, EGME) technique (Carter *et al.*, 1965). The method is based on the formation of a monolayer of EGME molecules on the clay surface under vacuum. Aluminium dishes containing approximately 1.1 g tema-milled, <425 µm sample/clay standard (Patterson Court Blue bentonite) were placed in a desiccator containing anhydrous phosphorus pentoxide. The desiccator was evacuated and allowed to stand overnight before the dishes were reweighed. The samples were then saturated with 2-ethoxyethanol and placed in a second desiccator containing dry calcium chloride. After 1½ hours, the desiccator was evacuated and left overnight. The sample was then rapidly re-weighed and the weight of 2-ethoxyethanol absorbed determined and the surface area calculated. Finally, a correction based on the Patterson Court Blue standard was applied.

Smectite has a surface area of c.800 $m^2$/g while other clay minerals and quartz have surface areas typically less than 100 $m^2$/g and 1 $m^2$/g respectively. Such a difference in value means that the surface area of a sample can provide a useful estimate of its smectite content.

## 4.3 X-RAY DIFFRACTION ANALYSIS

### 4.3.1 Preparation

In order to achieve a finer and uniform particle-size for matrix XRD analysis, approximately 3 g portions of the tema-milled <425 µm material was micronised under acetone for 5 minutes and dried at 55°C. The dried material was then disaggregated in a pestle and mortar and back-loaded into a standard aluminium sample holder for analysis.

Approximately 10 g subsamples of the <425 µm material was dispersed in distilled water using a reciprocal shaker combined with treatment with ultrasound. The suspension was then sieved on 63 µm and the <63 µm material placed in a measuring cylinder and allowed to stand. In order to prevent flocculation of the clay crystals, 2 ml of 0.1M 'Calgon' (sodium hexametaphosphate) was added to each suspension. After a period dictated by Stokes' Law, a nominal <2 µm fraction was removed and dried at 55°C. 100 mg of the <2 µm material was then re-suspended in a minimum of distilled water and pipetted onto a ceramic tile in a vacuum apparatus to produce an oriented mount. The mounts were Ca-saturated using 2 ml 0.1M $CaCl_2.6H_2O$ solution and washed twice to remove excess reagent.

### 4.3.2 Analysis

XRD analysis was carried out using a PANalytical X'Pert Pro series diffractometer equipped with a cobalt-target tube, X'Celerator detector and operated at 45kV and 40mA. The matrix samples were scanned from 4.5-85°2θ at 2.76°2θ/minute. The diffraction data were then initially analysed using PANalytical X'Pert Pro software coupled to the latest version (2007) of the International Centre for Diffraction Data (ICDD) database.

The <2 µm oriented mounts were scanned from 2-40°2θ at 1.02°2θ/minute after air-drying, ethylene glycol solvation and heating at 550°C for 2 hours. Clay mineral species were then identified from their characteristic peak positions and their reaction to the diagnostic testing program.

### 4.3.3 Matrix quantification

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

### 4.3.4 XRD-profile modelling

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

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

# 5 Results

## 5.1 MILTON KEYNES, BUCKINGHAMSHIRE

Particle-size analysis indicates that the Milton Keynes till samples are consistently ‘fine matrix’-dominated (mean c.91%) with little >425 µm material present (Table 2, Figure 1).

The mineralogy of the ‘fine matrix’ of the Milton Keynes samples (Table 3, Figure 2) is composed of quartz (39.5-50.7, mean c.45%), calcite (20.9-28.4, mean c.24%) and phyllosilicates/clay minerals (17.7-25.6, mean c.21%) with subordinate feldspar (K-feldspar and albite, total mean c.7%), pyrite (mean c.1%), anatase (mean <0.5%). Occasional minor-trace quantities of dolomite, gypsum and goethite were also detected in the samples.

Surface areas appear similar (92-121, mean 109 $m^2/g$) and relatively high within the sample suite (Table 3 and Figure 3). The highest surface area was recorded for the deepest sample (13.00-13.45 m).

Clay mineral assemblages for the Milton Keynes samples (Table 4, Figure 4) are dominated by illite/smectite (40-59, mean 46%) with minor illite (14-32, mean 26%) and kaolinite (20-28, mean 23%) and traces of discrete smectite (1-5, mean 3%). Newmod-modelling suggests that the illite/smectite is an *R0*-ordered species with a composition of 75% illite, 25% smectite interlayers and a crystallite-size distribution of 1-30 layers and a mean defect-free distance of 7 layers. Calcite, quartz and occasionally goethite were also identified in the <2 µm fractions of samples from Milton Keynes.

## 5.2 LANCASHIRE

The Lancashire till samples are all dominated by ‘fine matrix’ material (mean c.89%) with little coarser material present (Table 2, Figure 1). The deepest sample (Haslingden 26.0-26.4 m), however, contains a relatively high proportion (12.1%) of >2 mm material.

The ‘fine matrix’ of the Lancashire till samples is predominantly composed of quartz (55.7-62.5, mean c.60%) with subordinate phyllosilicates/clay minerals (20.5-25.7, mean c.24%) and minor-trace amounts of feldspar (K-feldspar and albite, total mean c.12%), calcite (mean c.1%), dolomite (mean c.3%), hematite (mean c.<0.5%) and anatase (mean c.0.6%) (Table 3, Figure 2).

The Lancashire samples have relatively low surface areas (52-78, mean 68 $m^2/g$) in comparison to the other samples submitted. Slightly higher values were obtained for the two Haslingden samples (Table 3 and Figure 3).

Clay mineral assemblages are slightly different for the two Lancashire sites (Table 4, Figure 4). At Bowlee, assemblages are predominantly composed of illite (c.69%) with minor kaolinite (c.16%) and traces of chlorite (c.8%) and chlorite/smectite (c.7%). However at Haslingden, clay assemblages are composed of major amounts of illite (c.42%) and illite/smectite (c.32%) with minor kaolinite (c.17%) and traces of chlorite (c.6%) and chlorite/smectite (c.3%). Quartz, feldspars, calcite and occasional lepidocrocite were also identified in these <2 µm fractions.

## 5.3 THETFORD, NORFOLK

The Thetford till samples are also consistently ‘fine matrix’-rich (mean c.92%) with comparatively little coarser material (Table 2, Figure 1).

The mineralogy of the ‘fine matrix’ of the Thetford samples (Table 3, Figure 2) is predominantly composed of quartz (20.4-75.1, mean c.36%), calcite (1.3-66, mean c.42%) and phyllosilicates/clay minerals (3.2-29.5, mean c.17%). The quartz concentration of the shallow sample from BH5 (75.1%) is anomalously high. Calcite concentrations are much higher in BHs 7, 9 and 11 (mean c.65%) than BHs 2 and 5 (mean c.19%) and are very low in the shallow sample from BH5. Phyllosilicate/clay mineral contents are lower in the BH 7, 9 and 11 samples (mean c.8%) compared to the samples from BHs 2 and 5 (mean c.25%). Other phases detected include feldspar (K-feldspar and albite, total mean c.4%) and occasional minor-trace amounts of gypsum, pyrite, goethite, hematite and anatase.

Two noticeable groups are apparent from surface area analyses (Table 3 and Figure 3). The samples from BHs 2 and 5 have relatively high surface areas for the sample suite (128-149, mean 138 $m^2/g$), particularly when compared to the lower values obtained for the samples from BHs 7, 9 and 11 (30-65, mean 49 $m^2/g$).

The clay mineral assemblages of the Thetford samples (Table 4, Figure 4) are predominantly composed of illite/smectite (34-50, mean 41%) with minor illite (13-32, mean 25%) and kaolinite (19-35, mean 26%) together with traces of chlorite in the BH9 and BH11 samples. Newmod-modelling suggests that the illite/smectite is similar to that detected in the Milton Keynes samples Calcite, and quartz were also identified in all the <2 µm fractions of samples from Thetford. Calcite was very abundant in the samples from BHs 7, 9 and 11. Various iron oxides (hematite, goethite and lepidocrocite) were also identified in the samples from BHs 2 and 5.

## 5.4 NORFOLK (LOCATIONS OTHER THAN THETFORD)

As was found in other cases detailed above, till samples from various locations in Norfolk other than Thetford are predominantly composed ‘fine matrix’ (generally >95%). However, the West Runton site 2 0.7 m sample is much coarser-grained with only 60% <425 µm material (Table 2, Figure 1). .

The ‘fine matrix’ of the Norfolk elsewhere till samples are quartz-rich (63.1-81.4, mean 69%) with variable proportions of calcite (<0.5-28.3, mean c.14%) and relatively low proportions of phyllosilicates/clay minerals (1.8-12.2, mean c.8%) compared to the other samples in this study (Table 3, Figure 2). Minor amounts of feldspar (K-feldspar and albite, total mean c.11%) together with traces of pyrite (mean <0.5%) and occasional dolomite were also detected.

The Norfolk elsewhere samples are characterised by low surface areas (26-84, mean 46 $m^2/g$, Table 3 and Figure 3).

Clay mineral assemblages (Table 4, Figure 4) are generally similarly composed of major amounts of illite (35-50, mean 45%) and smectite (33-49, mean 39%) with minor amounts of kaolinite (13-17, mean 15%). Traces of chlorite were also identified in the Happisburgh sample. Calcite was identified in all the <2 µm fractions with the exception of the Happisburgh sample and is particularly abundant in the Weybourne town pit and West Runton site 2 samples. Quartz was also identified in all the <2 µm fractions.

# 6 Discussion

All the till samples examined in this study are ‘fine matrix’-rich and typically composed of more than 90% <425 µm material. This ‘fine matrix’ is in all cases predominantly composed of quartz, calcite and phyllosilicates/clay minerals. However, the proportions and nature of each of these mineral components varies from location to location. Such variations are important as these are likely to determine the geotechnical properties of the tills.

In general terms, the greater the proportion of clay minerals and particularly smectite present in the till, the greater the degree of shrink-swell behaviour that should be expected. Surface area values may therefore provide a broad indication of potential geotechnical behaviour. In addition, although till mineralogies are typically thought to be the result of input from several sources, these may be used to propose possible sediment sources.

The ‘fine matrix’ of the Thetford BH5 1.00-1.22 m tills and those from Norfolk locations other than Thetford are silicate-rich (quartz and feldspar) and contain only small proportions of phyllosilicates/clay minerals. This lack of phyllosilicates/clay minerals and high proportions of fine-grained calcite explains their low surface area values despite showing relatively smectite-rich clay mineral assemblages. The quartz/silicate-rich nature of these tills suggests derivation from the underlying Plio-Pleistocene Norwich and Red Crag formations with a minor input from the Upper Chalk suggested by the minor carbonate component. A single previous clay mineral analysis from the Norwich Crag suggested an illite-dominated clay mineralogy with a trace of kaolin (Perrin, 1971). The minor smectite-component of the till clay mineral assemblages would therefore lend further evidence for additional sediment input from the Upper Chalk.

The Lancashire tills are also silicate-rich but unlike the non-Thetford, Norfolk tills these contain greater proportions of phyllosilicates/clay minerals. Low surface areas for the Lancashire tills therefore result from a lack of discrete smectite in these deposits, chlorite/smectite forming only a trace component of the clay assemblage. The identification of illite/smectite in the Haslingden tills may account for their slightly greater surface area than the Bowlee tills. Although the mineralogy of tills may be the result of derivation from one or more sources, and the field description of ‘Lake District igneous’-derived clasts, the ‘fine matrix’ mineralogy shows a strong resemblance to that recorded for the underlying Mercia Mudstone Group (e.g. Jeans, 2006a; Kemp, 1999; Bloodworth & Prior, 1993). The identification of the relatively rare ‘chlorite/smectite’ clay mineral in the tills is particularly diagnostic of derivation from Permo-Triassic rocks.

The ‘fine matrix’ of the Milton Keynes tills is composed of more equal proportions of silicates (c.50%), carbonates (c.25%) and phyllosilicates/clay minerals (c.20%). Relatively high surface areas for these samples are the result of their relatively high phyllosilicate/clay mineral contents and their illite/smectite-dominated clay mineral assemblages. Such mineralogies would appear to be sourced from the underlying Jurassic limestones and mudstones of the Great Oolite Group, the Whitby Mudstone and Rutland formations. Similar clay mineral assemblages have also been described from these stratigraphic units by Jeans (2006b).

Lastly the Thetford tills, with the exception of BH5 1.00-1.22 m, are relatively carbonate-rich and particularly those from BHs 7, 9 and 11. As all the Thetford samples have illite/smectite-dominated clay mineral assemblages and also contain minor amounts of discrete smectite, the difference in carbonate-content accounts for the high surface areas recorded for the samples from BHs 2 and 5 compared to the lower values measured for the BH 7, 9 and 11 samples. The carbonate-rich nature of the tills also suggests derivation from the underlying Upper Chalk. Clay mineral assemblages for the Upper Cretaceous Chalk facies from southern England are dominated by a heterogeneous mixture of different collapsible clay minerals (smectite, illite/smectite etc) with minor mica but kaolin is notably absent (Jeans, 2006c). The presence of abundant kaolinite in the till clay mineral assemblages would therefore appear to suggest that other sources have also contributed sediment to these deposits.

# 7 Conclusion

Mineralogical and surface area analyses have been completed on the ‘fine matrix’ (<425 µm material) of a suite of till samples from various locations across England in order to help understand their geotechnical behaviour.

Analyses indicate that the till samples are ‘fine matrix’-rich and typically composed of location-dependant varying proportions of quartz, calcite and phyllosilicates/clay minerals together with a range of minor-trace constituents.

Given their typically ‘fine-matrix’ nature, the geotechnical behaviour of the till samples examined is likely to be influenced by both the proportion of phyllosilicates/clay minerals present and their composition and can be indicated by the surface area measurements. This being the case, the tills from Thetford (BHs 2 and 5) and Milton Keynes would be expected to show the most problematic engineering behaviour.

Although the mineralogy of till deposits are typically thought to be derived from several sources, mineral and clay mineral assemblages suggest that the tills in this study are predominantly derived from underlying lithologies. The tills from Norfolk locations other than Thetford appear to be principally derived from the Norwich and Red Crag formations with some input from the Upper Chalk whilst the more carbonate-rich Thetford tills appear to have a greater Upper Chalk input.

The mineralogically distinct Lancashire tills suggest Permo-Triassic sources, probably the Mercia Mudstone Group while the Milton Keynes tills indicate that the underlying Jurassic limestones and mudstones probably produced their sediment supply.

**Table 2. Summary of particle-size distributions obtained during sample preparation**

| Location | Borehole/site | Depth (m)/ sample | MPL code | Particle-size (mm, %) | | | |
|---|---|---|---|---|---|---|---|
| | | | | >2 | 2 - 0.6 | 0.6 - 0.425 | <0.425 |
| | | | | gravel | coarse sand | coarse medium sand | ‘fine matrix’ |
| Milton Keynes, Buckinghamshire | MKSM 31 | 9.00 | MPLN300 | 3.8 | 2.2 | 1.0 | 93.0 |
| | MKSM 32 | 0.5-1.0 | MPLN301 | 6.9 | 2.6 | 1.2 | 89.3 |
| | MKSM 36 | 4.70-5.10 | MPLN302 | 4.6 | 2.9 | 1.4 | 91.0 |
| | MKSM 36 | 10.00-10.50 | MPLN303 | 6.9 | 3.7 | 1.9 | 87.5 |
| | MKSM 36 | 11.00-11.45 | MPLN304 | 6.9 | 3.6 | 2.2 | 87.3 |
| | MKSM 36 | 13.00-13.45 | MPLN305 | 1.3 | 2.2 | 1.0 | 95.5 |
| Lancashire | Bowlee A | 4.0-4.4 | MPLN306 | 2.4 | 1.7 | 1.4 | 94.6 |
| | Bowlee B | 12.32-12.40 | MPLN307 | 8.8 | 0.3 | 0.4 | 90.4 |
| | Haslingden | 4.10-4.55 | MPLN308 | 8.5 | 2.8 | 1.6 | 87.1 |
| | Haslingden | 26.0-26.4 | MPLN309 | 12.1 | 2.5 | 1.5 | 83.8 |
| Thetford, Norfolk | BH2 | 4.00-4.45 | MPLN310 | 2.3 | 1.5 | 0.7 | 95.4 |
| | BH5 | 1.00-1.22 | MPLN311 | 2.2 | 4.0 | 5.1 | 88.8 |
| | BH5 | 4.50-4.95 | MPLN312 | 1.4 | 5.1 | 1.9 | 91.7 |
| | BH7 | 2.5-2.95 | MPLN313 | 3.2 | 2.6 | 1.0 | 93.2 |
| | BH9 | 10.00-10.45 | MPLN314 | 4.0 | 3.8 | 1.8 | 90.5 |
| | BH11 | 7.00-7.45 | MPLN315 | 7.1 | 1.1 | 0.7 | 91.0 |
| Norfolk, elsewhere | Happisburgh 1 | Bulk 1 | MPLN316 | 0.4 | 1.4 | 1.5 | 96.6 |
| | Weybourne town pit | 1.8 | MPLN317 | 0.0 | 0.2 | 0.2 | 99.7 |
| | West Runton site 2 | 0.7 | MPLN318 | 16.1 | 15.2 | 8.6 | 60.1 |
| | West Runton site 3 | 1.1 | MPLN319 | 1.2 | 1.2 | 1.4 | 96.1 |
| | West Runton site 3 | 2.8 | MPLN320 | 1.4 | 1.2 | 1.7 | 95.7 |

**Table 3. Summary of matrix X-ray diffraction and surface area analyses**

| Location | Borehole/site | Depth (m)/ sample | MPL code | Silicates (%) | | | Carbonates, sulphates, sulphides (%) | | | | Oxyhydroxides, oxides (%) | | | Phyllosilicates, clay minerals (%) | | | | Surface area ($m^2/g$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | quartz | albite | K-feldspar | calcite | dolomite | gypsum | pyrite | goethite | hematite | anatase | 'mica' | kaolinite | smectite | chlorite | |
| Milton Keynes, Buckinghamshire | MKSM 31 | 9.00 | MPLN300 | 39.5 | 2.0 | 3.6 | 25.0 | 3.3 | 2.5 | 0.9 | nd | nd | <0.5 | 9.7 | 5.6 | 4.1 | 3.4 | 111 |
| | MKSM 32 | 0.5-1.0 | MPLN301 | 43.1 | 2.6 | 4.1 | 28.4 | nd | nd | <0.5 | 1.1 | nd | <0.5 | 8.0 | 4.4 | 5.3 | 2.6 | 118 |
| | MKSM 36 | 4.70-5.10 | MPLN302 | 43.1 | 2.0 | 4.7 | 26.0 | 2.2 | 3.2 | 0.8 | nd | nd | <0.5 | 9.2 | 4.1 | 2.2 | 2.2 | 97 |
| | MKSM 36 | 10.00-10.50 | MPLN303 | 50.2 | 2.4 | 4.8 | 20.9 | nd | nd | <0.5 | 1.3 | nd | <0.5 | 10.5 | 5.1 | 4.3 | nd | 113 |
| | MKSM 36 | 11.00-11.45 | MPLN304 | 50.7 | 2.8 | 4.6 | 21.4 | nd | 1.2 | <0.5 | 0.9 | nd | <0.5 | 8.3 | 3.2 | 4.0 | 2.4 | 92 |
| | MKSM 36 | 13.00-13.45 | MPLN305 | 41.8 | 2.1 | 4.3 | 22.4 | nd | 2.0 | 1.3 | nd | nd | 0.5 | 10.8 | 6.3 | 4.5 | 4.0 | 121 |
| Lancashire | Bowlee A | 4.0-4.4 | MPLN306 | 55.7 | 5.5 | 6.4 | 1.6 | 4.5 | nd | nd | nd | <0.5 | <0.5 | 15.5 | 5.5 | nd | 4.5 | 68 |
| | Bowlee B | 12.32-12.40 | MPLN307 | 62.5 | 5.9 | 5.7 | 1.2 | 3.5 | nd | nd | nd | <0.5 | 0.5 | 12.5 | 4.4 | nd | 3.6 | 52 |
| | Haslingden | 4.10-4.55 | MPLN308 | 61.6 | 6.1 | 5.2 | 1.5 | 1.6 | nd | nd | nd | <0.5 | 0.6 | 13.4 | 5.7 | nd | 4.0 | 76 |
| | Haslingden | 26.0-26.4 | MPLN309 | 59.7 | 7.0 | 4.5 | 0.8 | 1.4 | nd | nd | nd | <0.5 | 0.6 | 15.4 | 6.0 | nd | 4.3 | 78 |
| Thetford, Norfolk | BH2 | 4.00-4.45 | MPLN310 | 36.0 | 2.3 | 3.7 | 28.6 | nd | nd | nd | 0.8 | <0.5 | 0.5 | 12.6 | 9.3 | 6.0 | nd | 149 |
| | BH5 | 1.00-1.22 | MPLN311 | 75.1 | 2.3 | 4.4 | 1.3 | nd | nd | nd | 0.8 | <0.5 | nd | 7.4 | 3.6 | 4.9 | nd | 128 |
| | BH5 | 4.50-4.95 | MPLN312 | 32.9 | 2.0 | 3.5 | 27.2 | nd | 3.9 | nd | 0.5 | nd | 0.5 | 13.7 | 9.8 | 6.0 | nd | 138 |
| | BH7 | 2.5-2.95 | MPLN313 | 20.7 | 1.1 | 1.4 | 66.0 | nd | nd | nd | nd | nd | nd | 3.6 | 4.5 | 2.7 | nd | 65 |
| | BH9 | 10.00-10.45 | MPLN314 | 29.6 | 1.1 | 1.5 | 64.3 | nd | nd | <0.5 | nd | nd | nd | 1.9 | 0.7 | 0.6 | nd | 30 |
| | BH11 | 7.00-7.45 | MPLN315 | 20.4 | 0.9 | 1.5 | 65.8 | nd | 2.4 | <0.5 | nd | nd | nd | 3.6 | 2.7 | 1.1 | 1.2 | 54 |
| Norfolk, elsewhere | Happisburgh 1 | Bulk 1 | MPLN316 | 65.8 | 5.6 | 5.7 | 10.0 | <0.5 | nd | <0.5 | nd | nd | nd | 7.6 | 1.4 | 1.8 | 1.4 | 84 |
| | Weybourne town pit | 1.8 | MPLN317 | 63.1 | 6.3 | 5.4 | 22.0 | nd | nd | <0.5 | nd | nd | nd | 2.2 | <0.5 | 0.8 | nd | 28 |
| | West Runton site 2 | 0.7 | MPLN318 | 63.1 | 3.0 | 3.5 | 28.3 | nd | nd | <0.5 | nd | nd | nd | 1.3 | <0.5 | 0.5 | nd | 26 |
| | West Runton site 3 | 1.1 | MPLN319 | 72.1 | 6.5 | 6.3 | 7.8 | nd | nd | <0.5 | nd | nd | nd | 5.0 | 0.7 | 1.4 | nd | 60 |
| | West Runton site 3 | 2.8 | MPLN320 | 81.4 | 6.9 | 6.4 | <0.5 | nd | nd | <0.5 | nd | nd | nd | 3.6 | <0.5 | 1.2 | nd | 32 |

**Table 4. Summary of <2 µm clay mineral XRD analyses**

| Location | Borehole/site | Depth (m)/ sample | MPL code | %clay mineral in <2 µm fraction | | | | | | Non clay minerals (! indicates major amounts) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | smectite | chlorite/ smectite | illite/ smectite | illite | kaolinite | chlorite | |
| Milton Keynes, Buckinghamshire | MKSM 31 | 9.00 | MPLN300 | 2 | nd | 41 | 27 | 23 | 7 | calcite, quartz |
| | MKSM 32 | 0.5-1.0 | MPLN301 | 6 | nd | 59 | 14 | 20 | 1 | calcite, quartz, goethite |
| | MKSM 36 | 4.70-5.10 | MPLN302 | 1 | nd | 47 | 23 | 22 | 7 | calcite, quartz |
| | MKSM 36 | 10.00-10.50 | MPLN303 | 3 | nd | 44 | 25 | 28 | nd | calcite, quartz, goethite |
| | MKSM 36 | 11.00-11.45 | MPLN304 | 3 | nd | 44 | 32 | 20 | 1 | calcite, quartz, goethite |
| | MKSM 36 | 13.00-13.45 | MPLN305 | 3 | nd | 40 | 32 | 24 | 1 | calcite, quartz |
| Lancashire | Bowlee A | 4.0-4.4 | MPLN306 | nd | 7 | nd | 70 | 15 | 9 | quartz, K-feldspar, albite, calcite |
| | Bowlee B | 12.32-12.40 | MPLN307 | nd | 7 | nd | 68 | 17 | 8 | quartz, K-feldspar, albite, calcite |
| | Haslingden | 4.10-4.55 | MPLN308 | nd | 3 | 36 | 37 | 17 | 7 | quartz, albite, calcite, lepidocrocite |
| | Haslingden | 26.0-26.4 | MPLN309 | nd | 3 | 29 | 46 | 16 | 6 | quartz, albite, calcite, lepidocrocite |
| Thetford, Norfolk | BH2 | 4.00-4.45 | MPLN310 | 3 | nd | 50 | 28 | 19 | nd | calcite, quartz, hematite, goethite |
| | BH5 | 1.00-1.22 | MPLN311 | 18 | nd | 34 | 13 | 35 | nd | calcite, quartz, hematite, lepidocrocite, goethite |
| | BH5 | 4.50-4.95 | MPLN312 | 3 | nd | 49 | 25 | 23 | nd | calcite, quartz, hematite, goethite |
| | BH7 | 2.5-2.95 | MPLN313 | 6 | nd | 36 | 27 | 31 | nd | calcite !, quartz |
| | BH9 | 10.00-10.45 | MPLN314 | 11 | nd | 37 | 28 | 23 | 1 | calcite !, quartz |
| | BH11 | 7.00-7.45 | MPLN315 | 3 | nd | 38 | 32 | 24 | 4 | calcite !, quartz |
| Norfolk, elsewhere | Happisburgh 1 | Bulk 1 | MPLN316 | 33 | nd | nd | 48 | 14 | 5 | calcite, quartz |
| | Weybourne town pit | 1.8 | MPLN317 | 33 | nd | nd | 50 | 17 | nd | calcite !, quartz |
| | West Runton site 2 | 0.7 | MPLN318 | 34 | nd | nd | 53 | 13 | nd | calcite !, quartz |
| | West Runton site 3 | 1.1 | MPLN319 | 49 | nd | nd | 35 | 16 | nd | calcite, quartz |
| | West Runton site 3 | 2.8 | MPLN320 | 46 | nd | nd | 39 | 16 | nd | quartz |

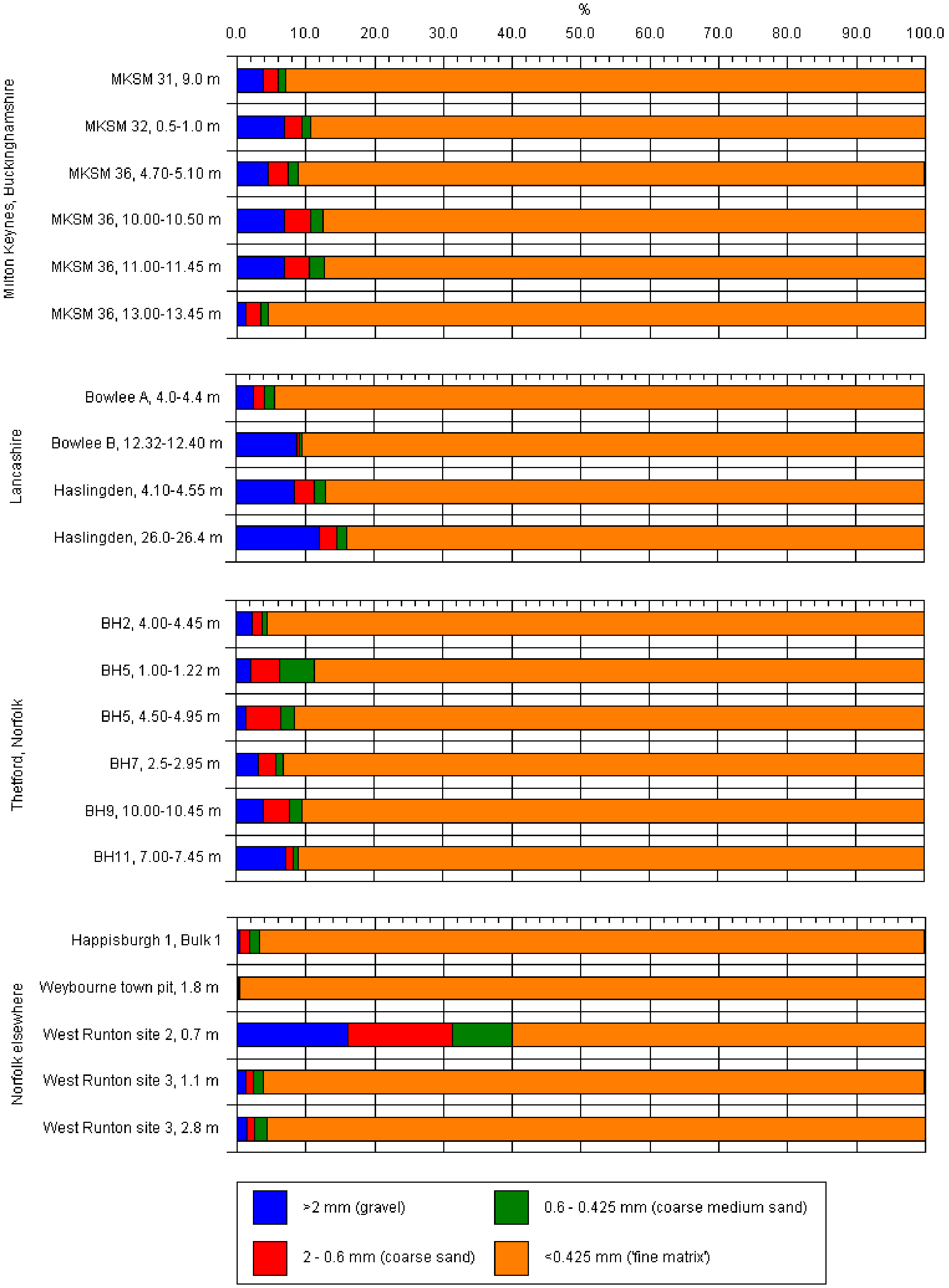

**Figure 1. Particle-size distributions for the till samples**

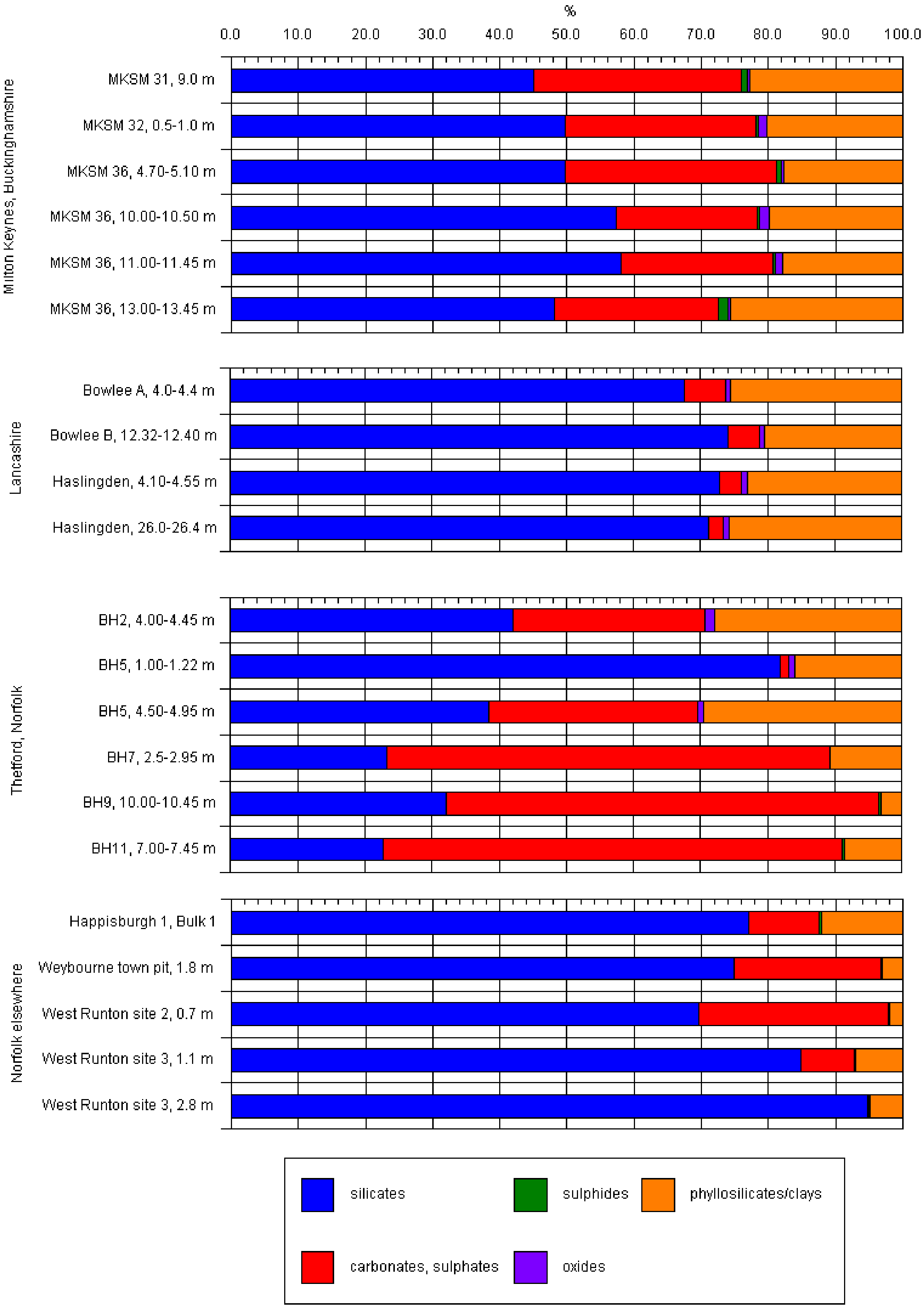

**Figure 2. Distribution of mineral species in the till <425 μm fractions ('fine matrix')**

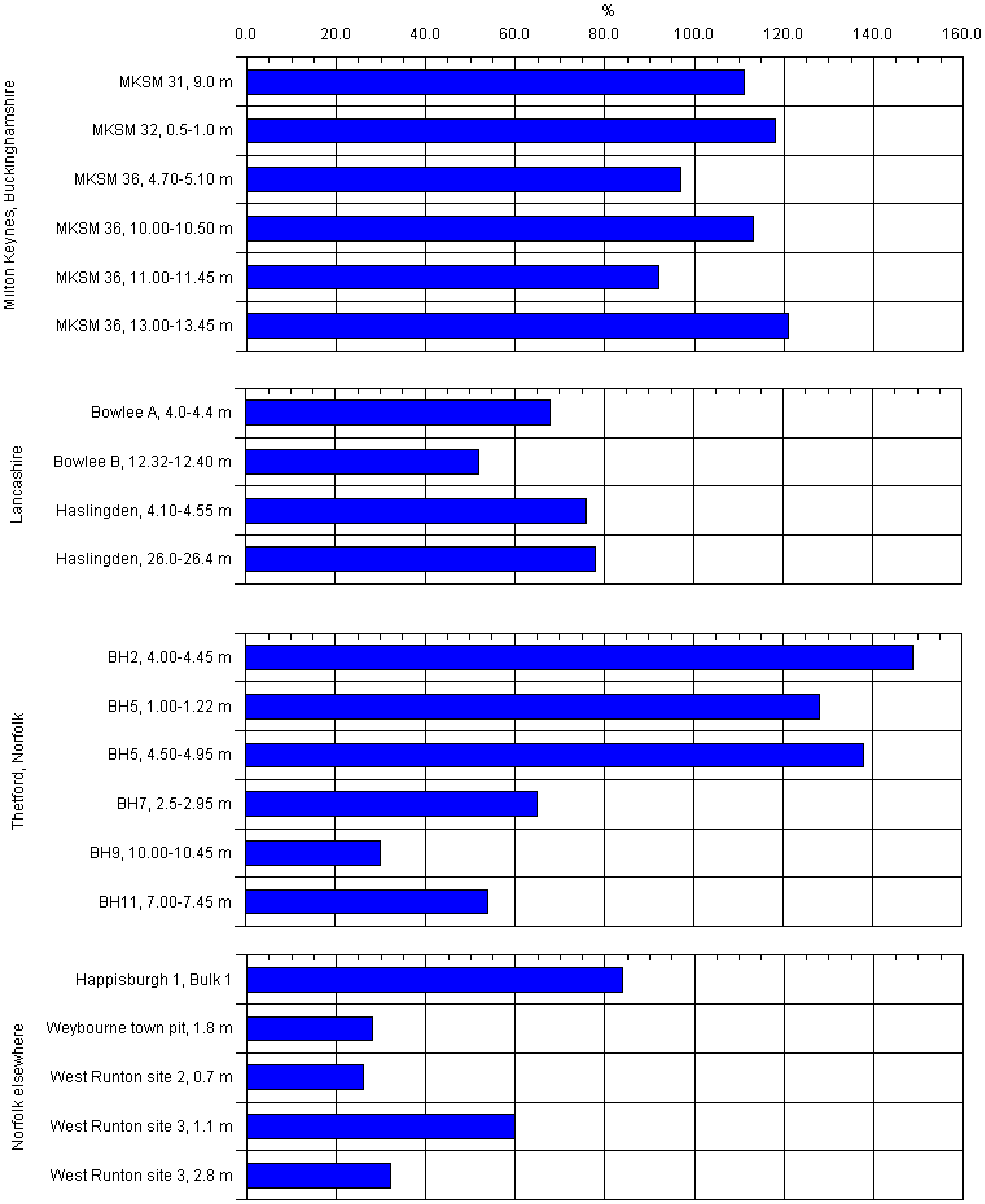

**Figure 3. Surface area of the 'fine matrix' of the till samples**

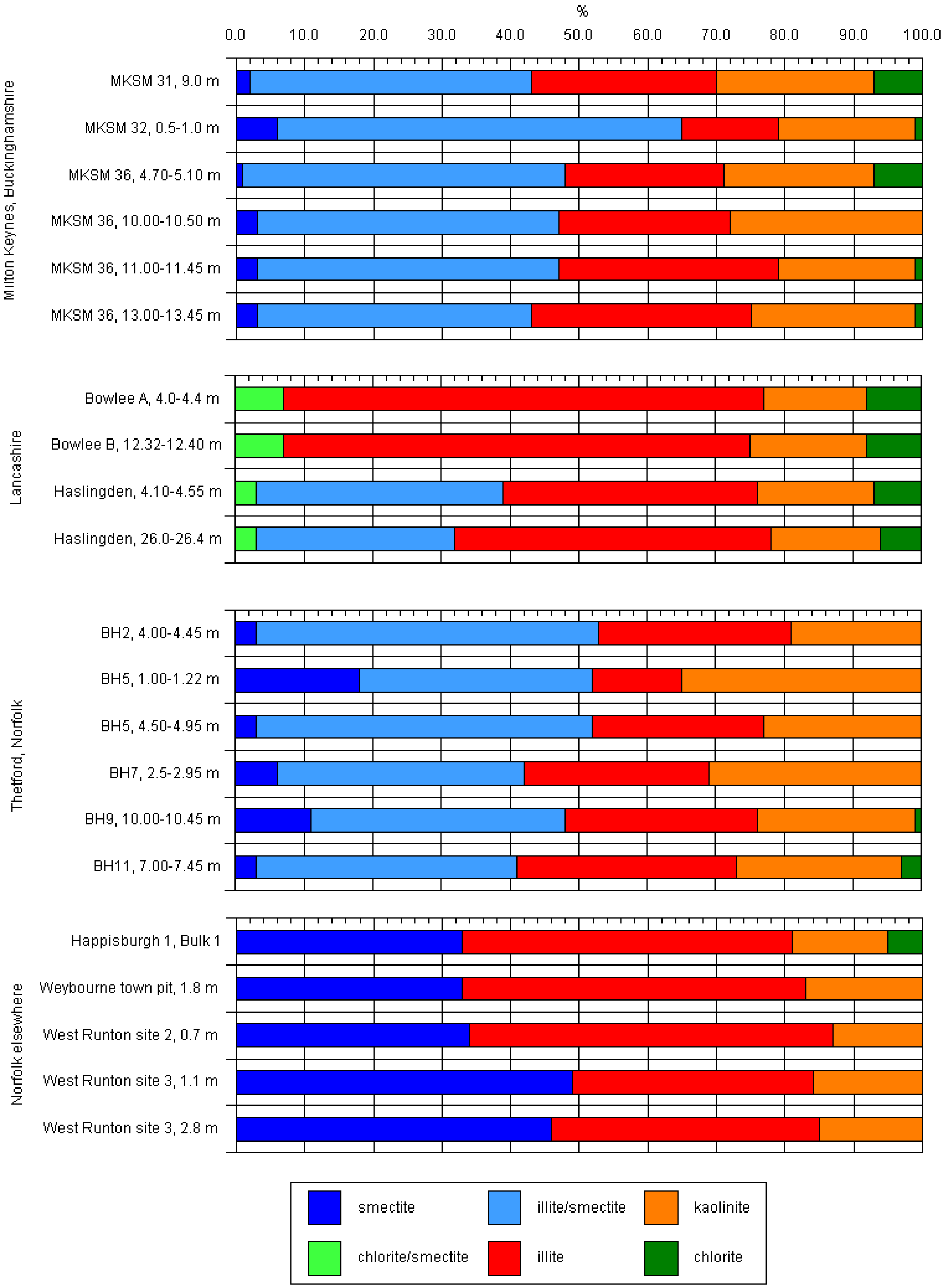

**Figure 4. Distribution of %clay mineral species in the till <2 µm fractions**

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# Appendix 1 X-RAY DIFFRACTION TRACES:

## KEY

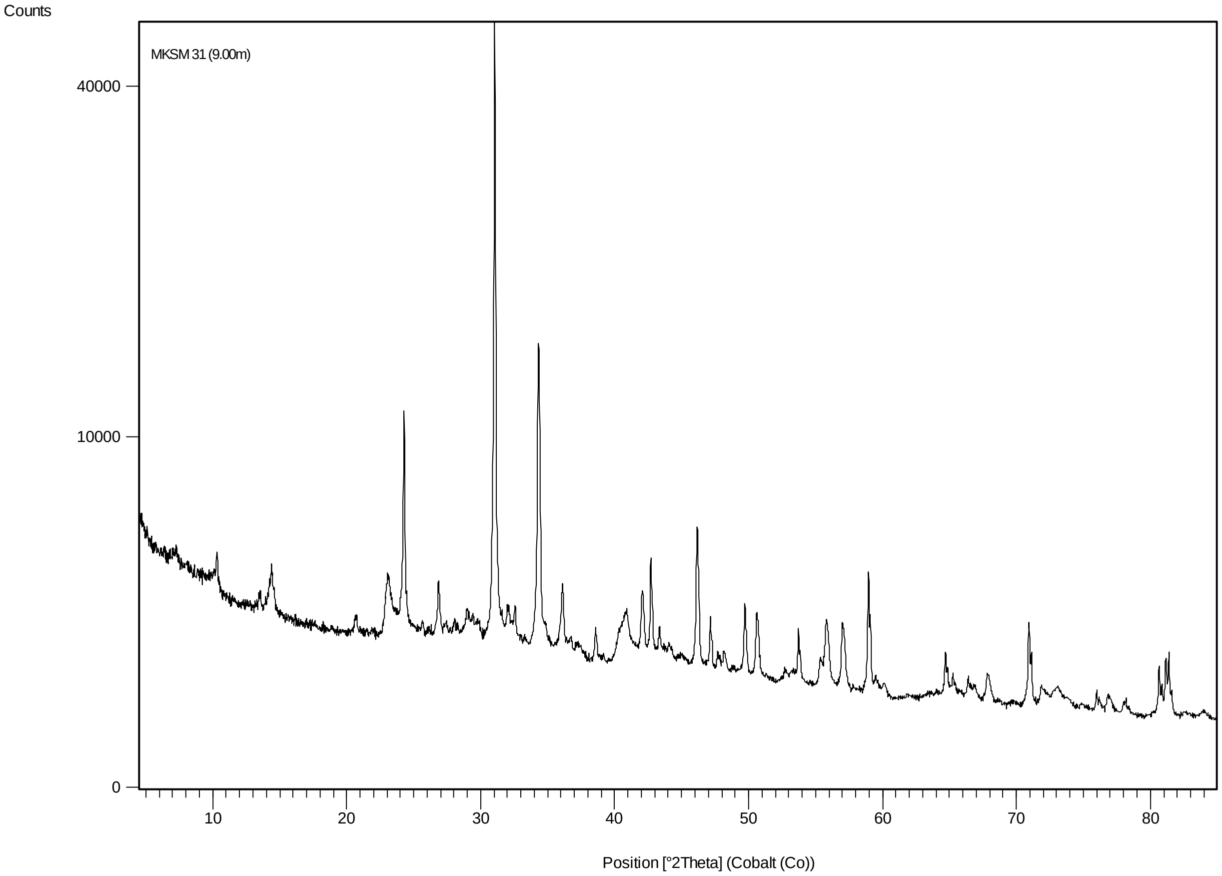
Vertical axis – Intensity (counts per second)

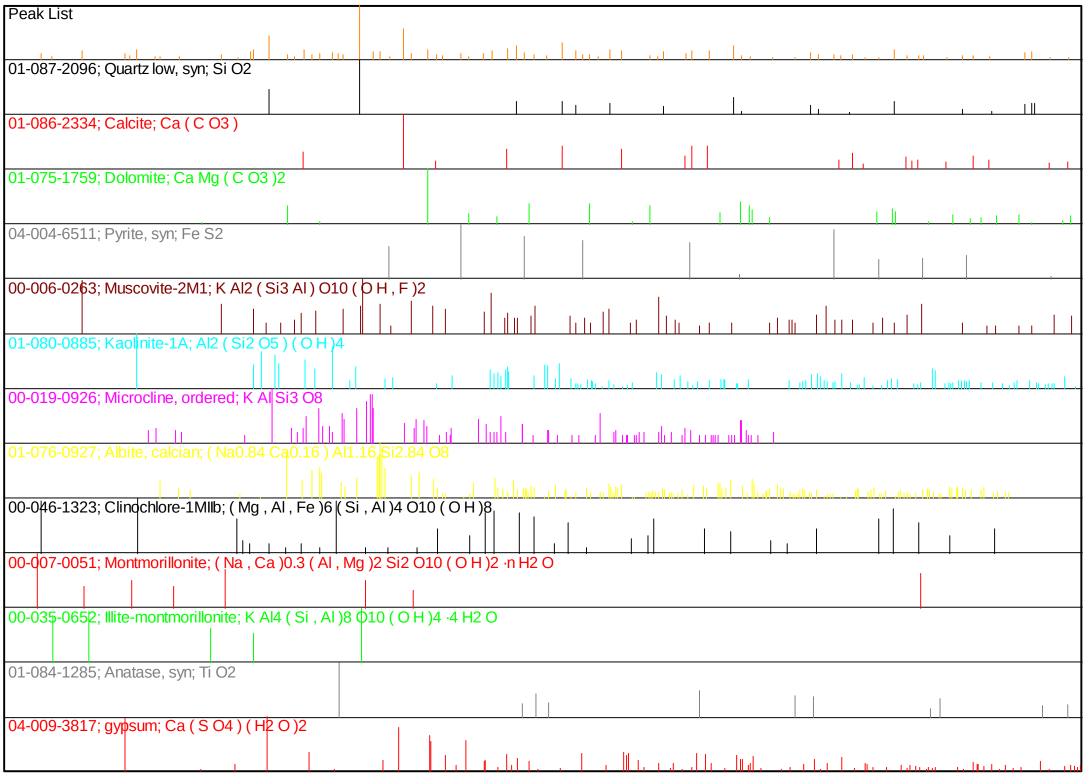
Horizontal axis - °2θ Co-Kα

For the matrix traces, only the most intense/diagnostic peak of each identified mineral is labelled.

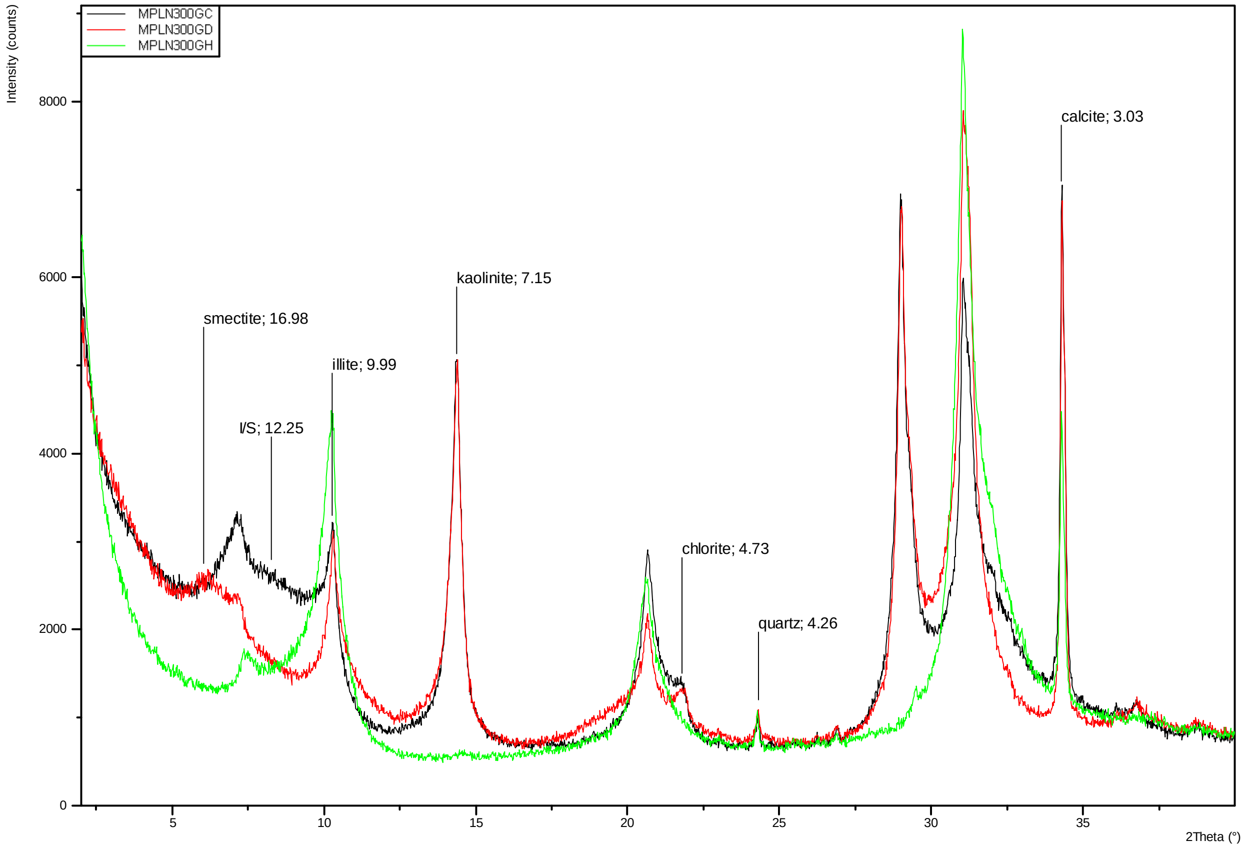
For the <2 µm traces. Black trace (air-dry), red trace (glycol-solvated) and green trace (heated 550°C/2 hours). Only the $d_{001}$ of each identified clay mineral is labelled on the glycol-solvated trace.

# Milton Keynes, MKSM 31, 9.00 m, whole-rock

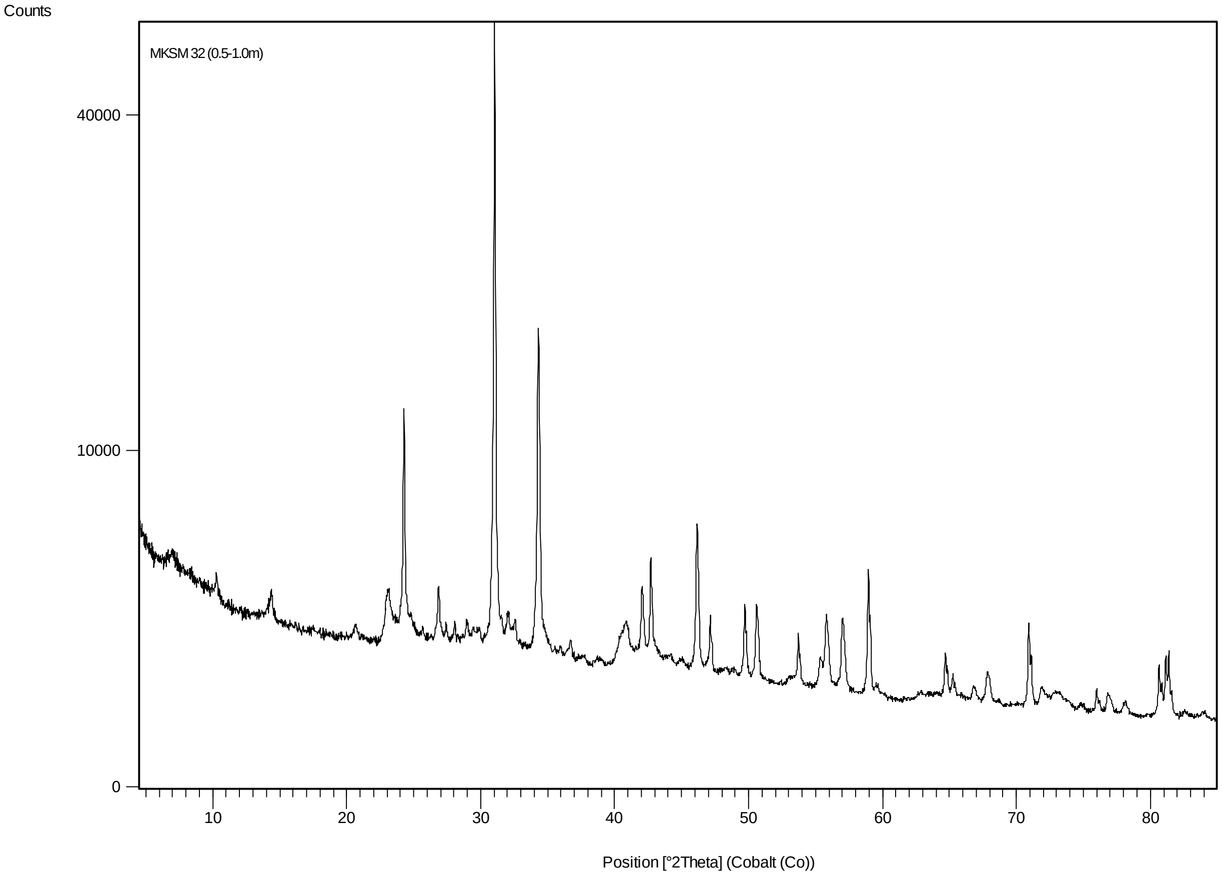


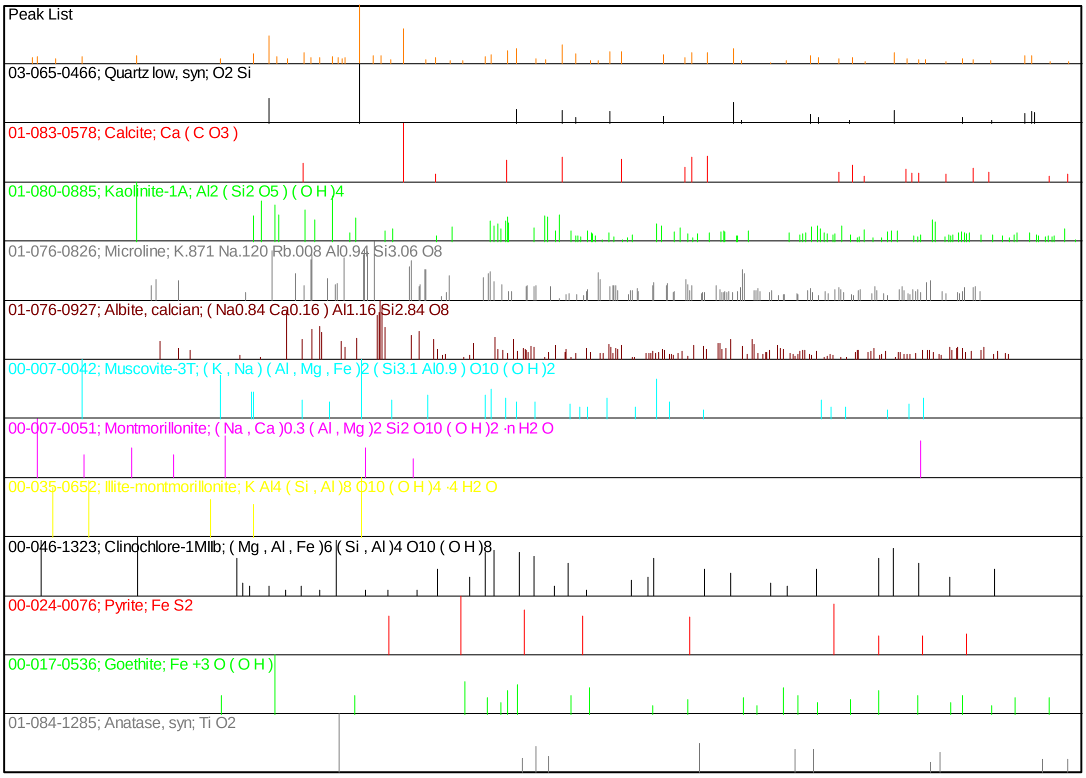


## Milton Keynes, MKSM 31, 9.00 m, <2 µm fraction

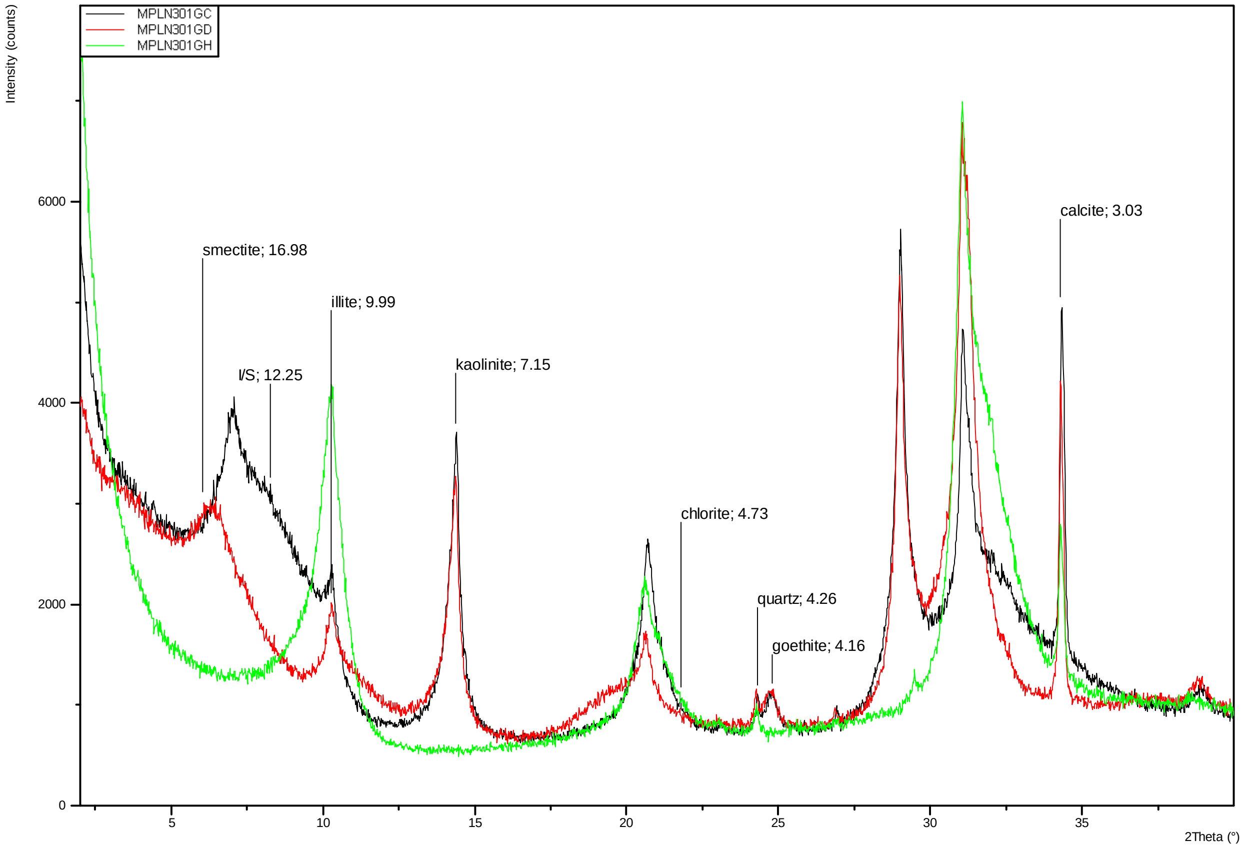


# Milton Keynes, MKSM 32, 0.5-1.0 m, whole-rock

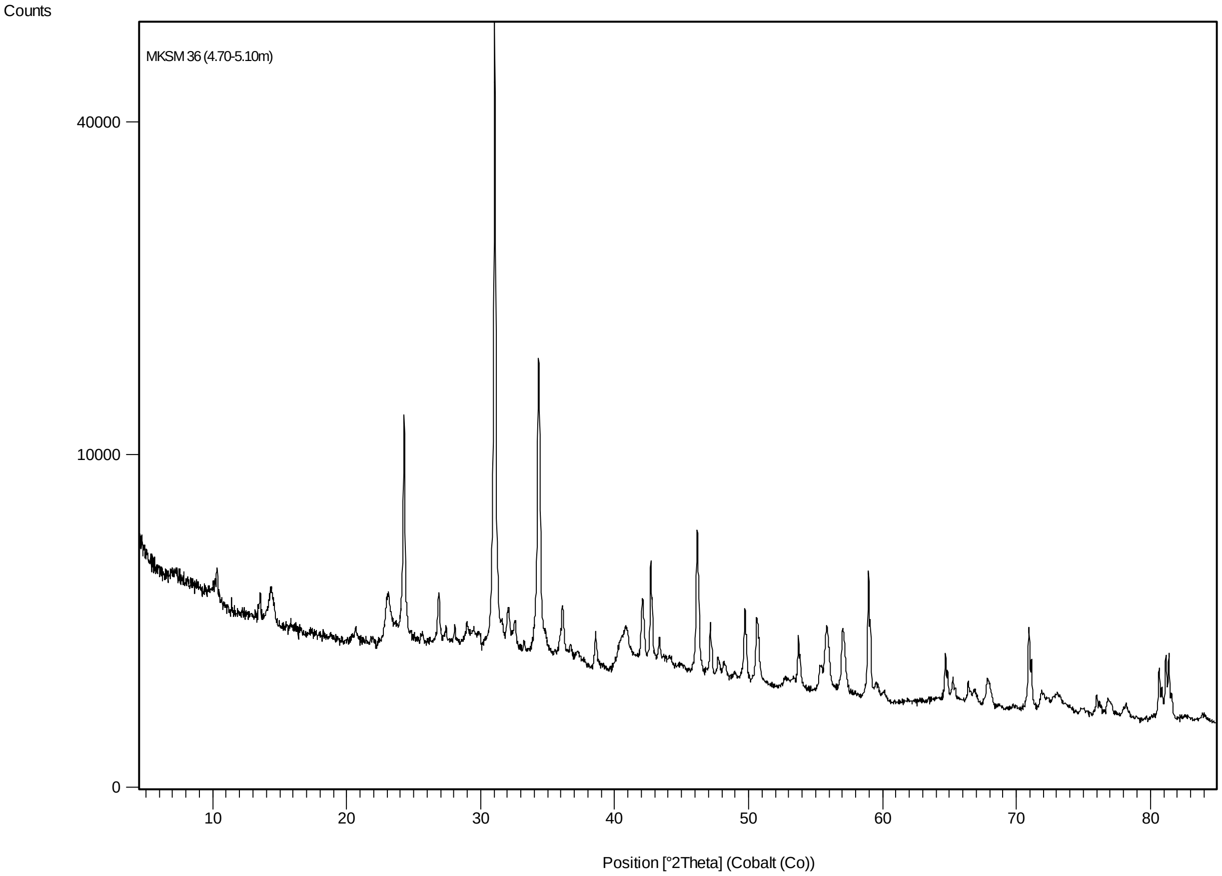


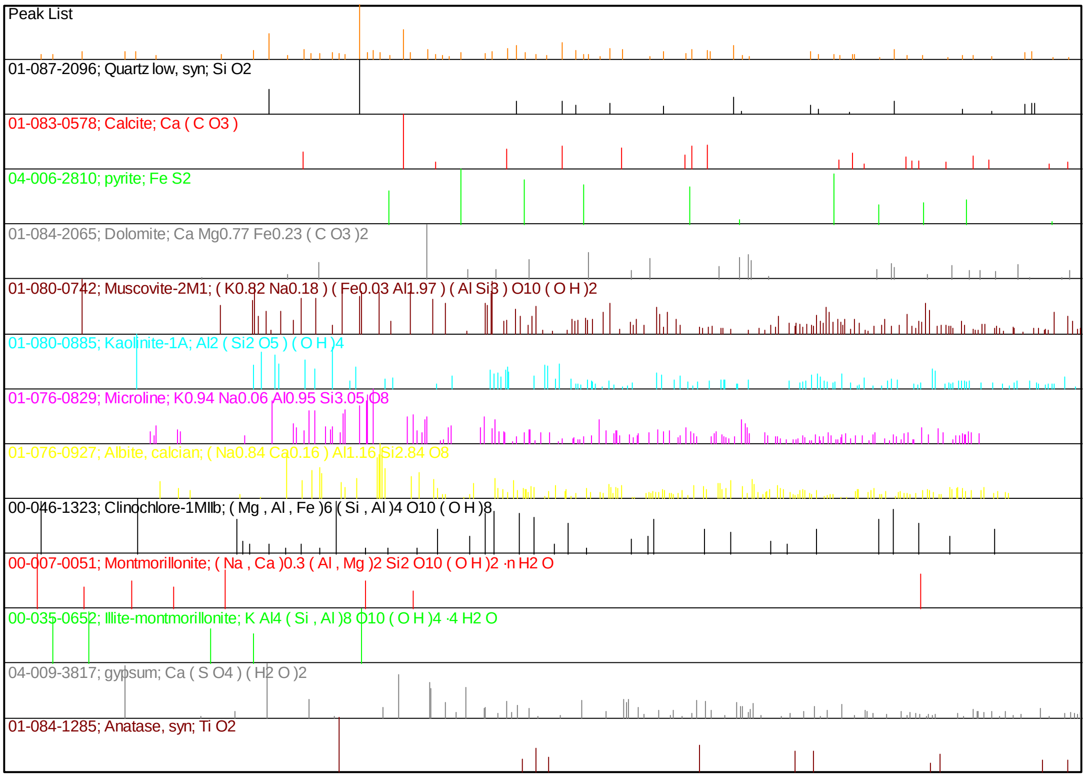


## Milton Keynes, MKSM 32, 0.5-1.0 m, <2 µm fraction

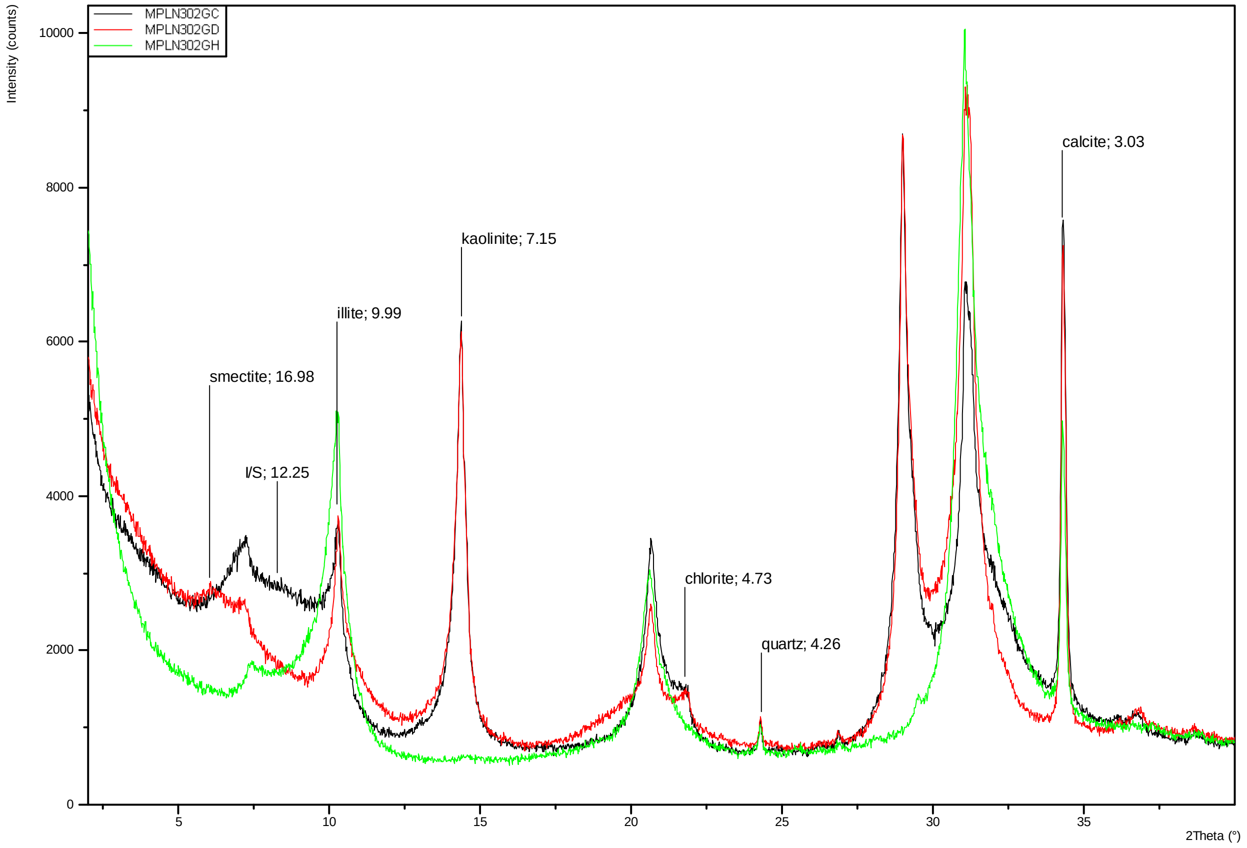


# Milton Keynes, MKSM 36, 4.70-5.10 m, whole-rock

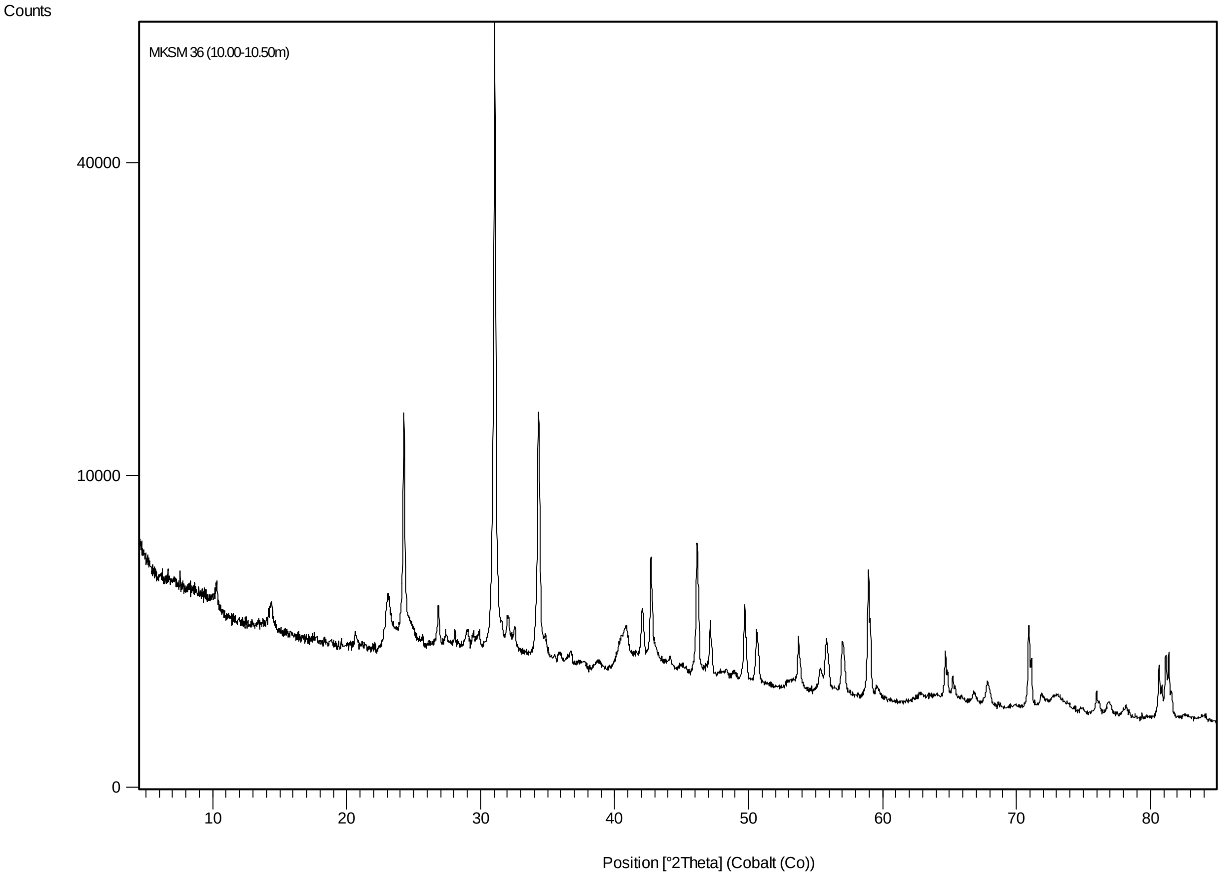


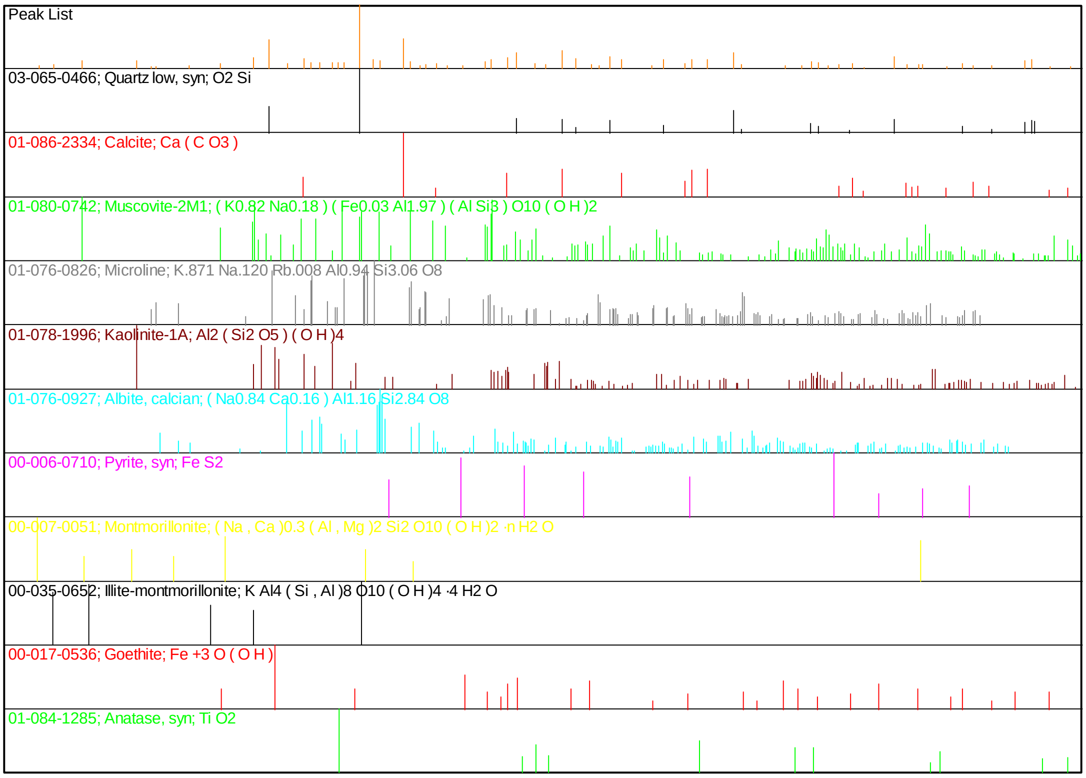


## Milton Keynes, MKSM 36, 4.70-5.10 m, <2 µm fraction

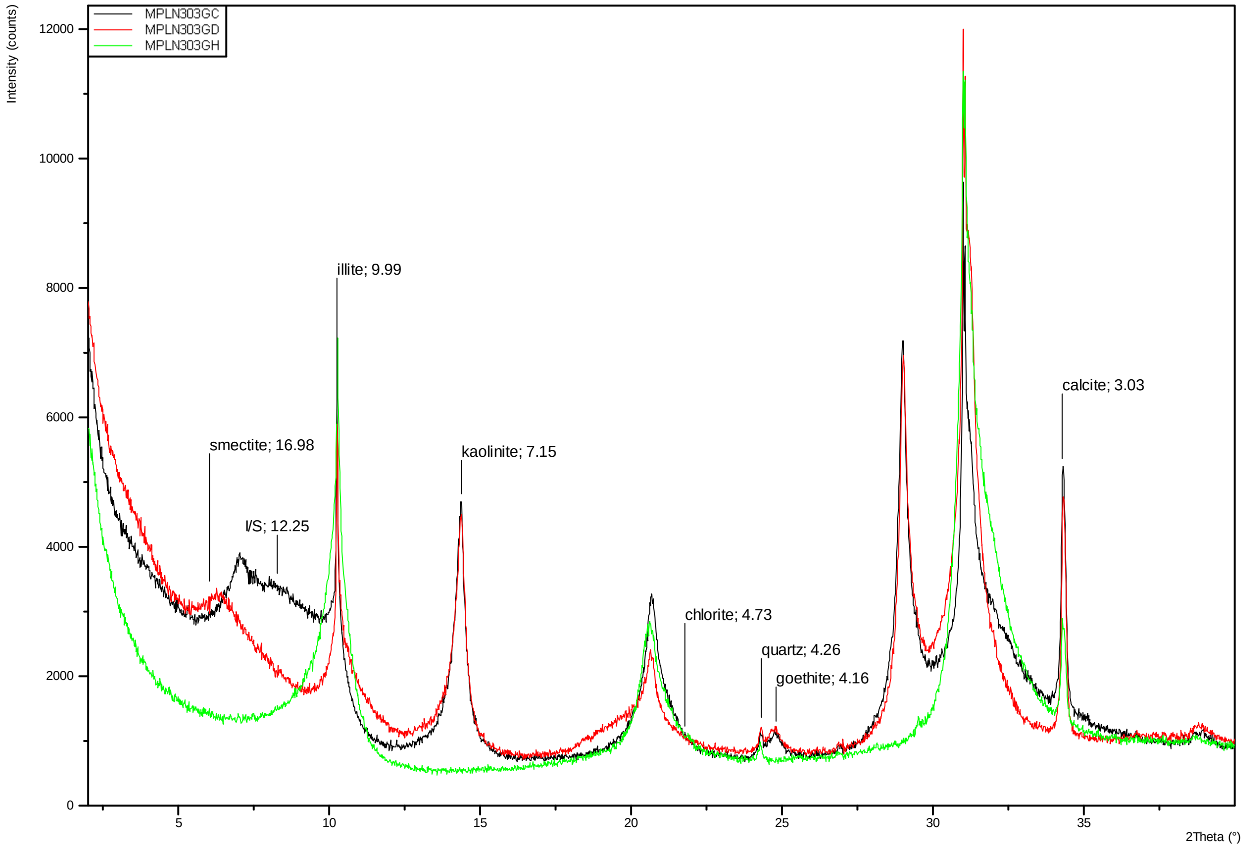


# Milton Keynes, MKSM 36, 10.00-10.50 m, whole-rock

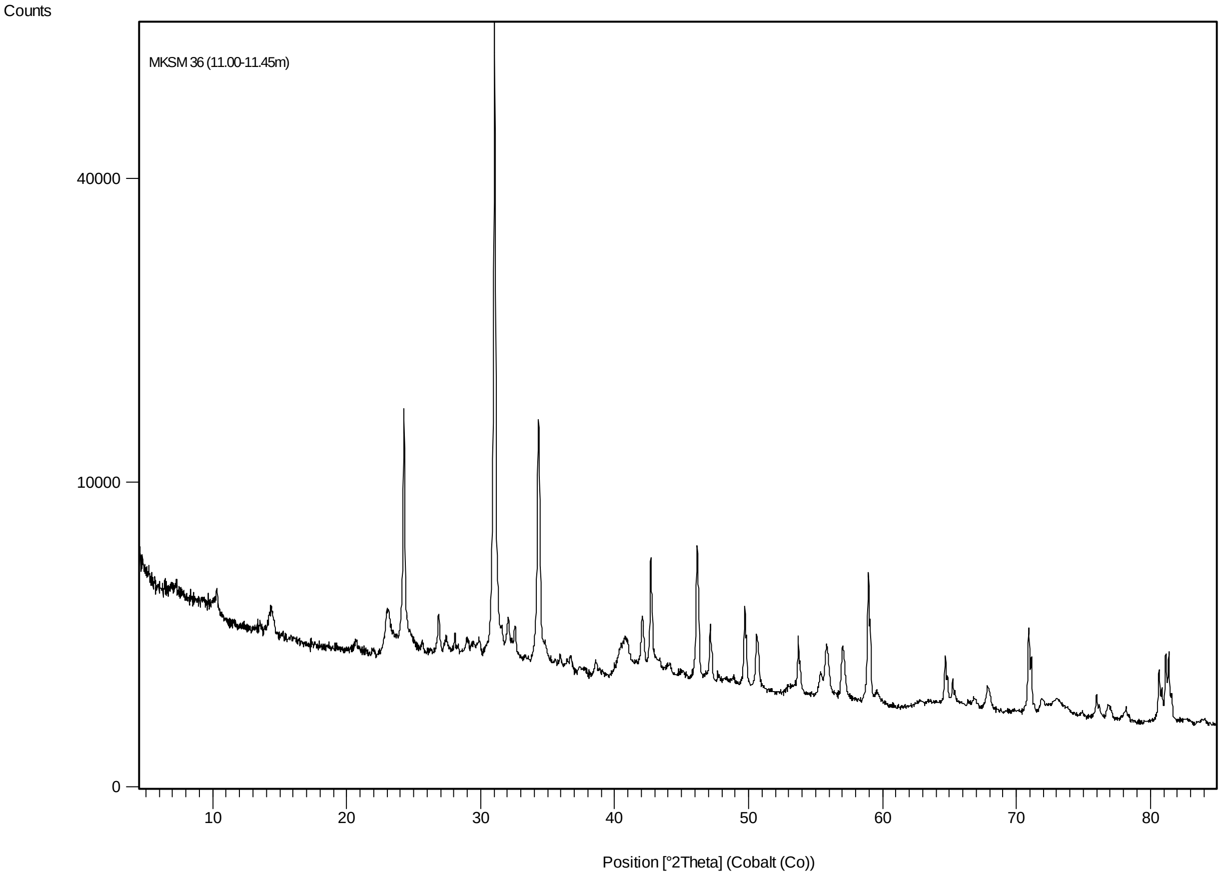


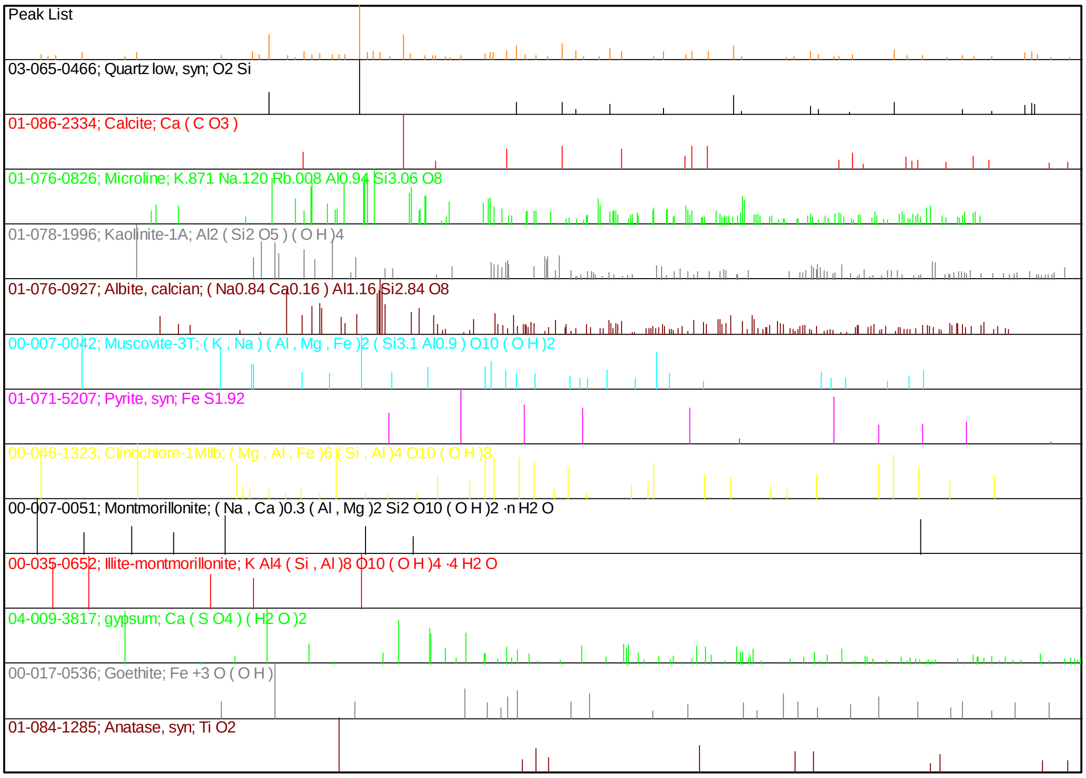


## Milton Keynes, MKSM 36, 10.00-10.50 m, <2 µm fraction



# Milton Keynes, MKSM 36, 11.00-11.45 m, whole-rock





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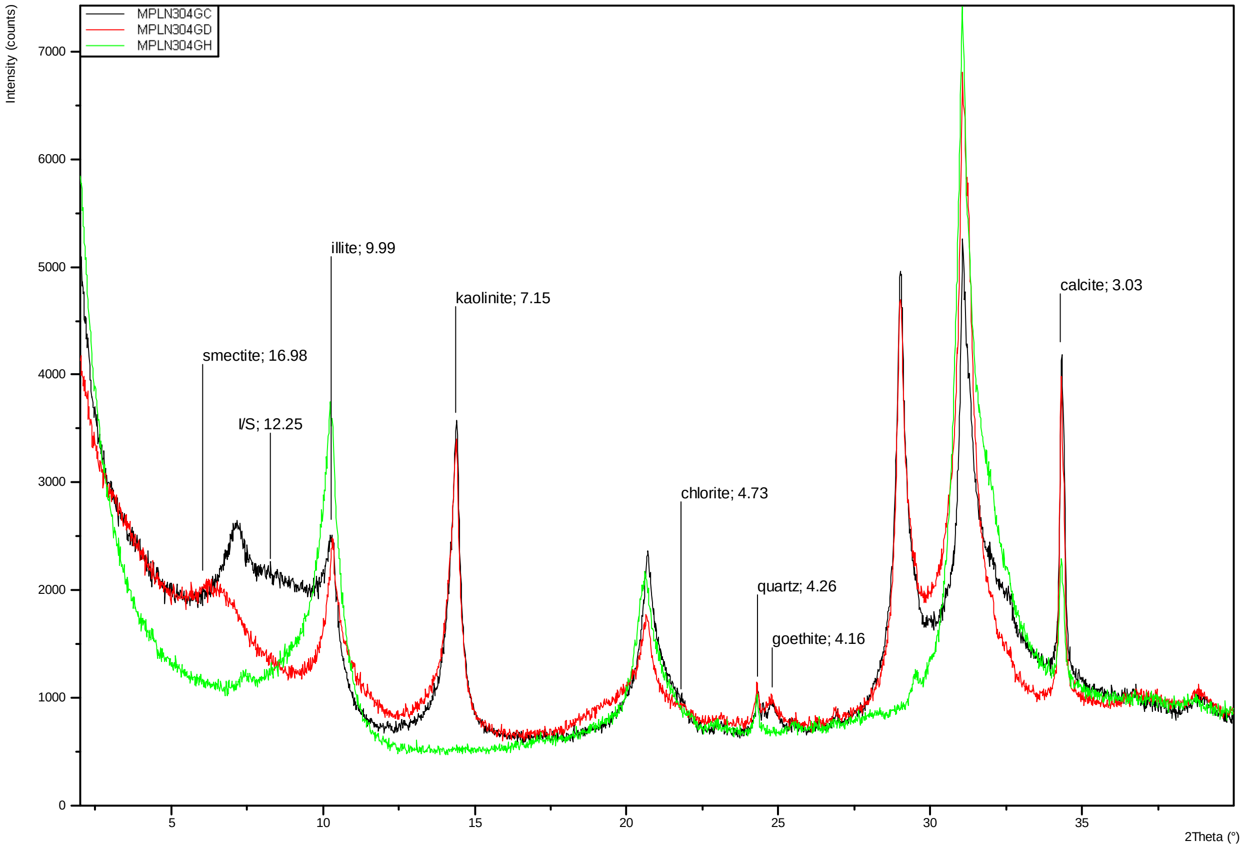

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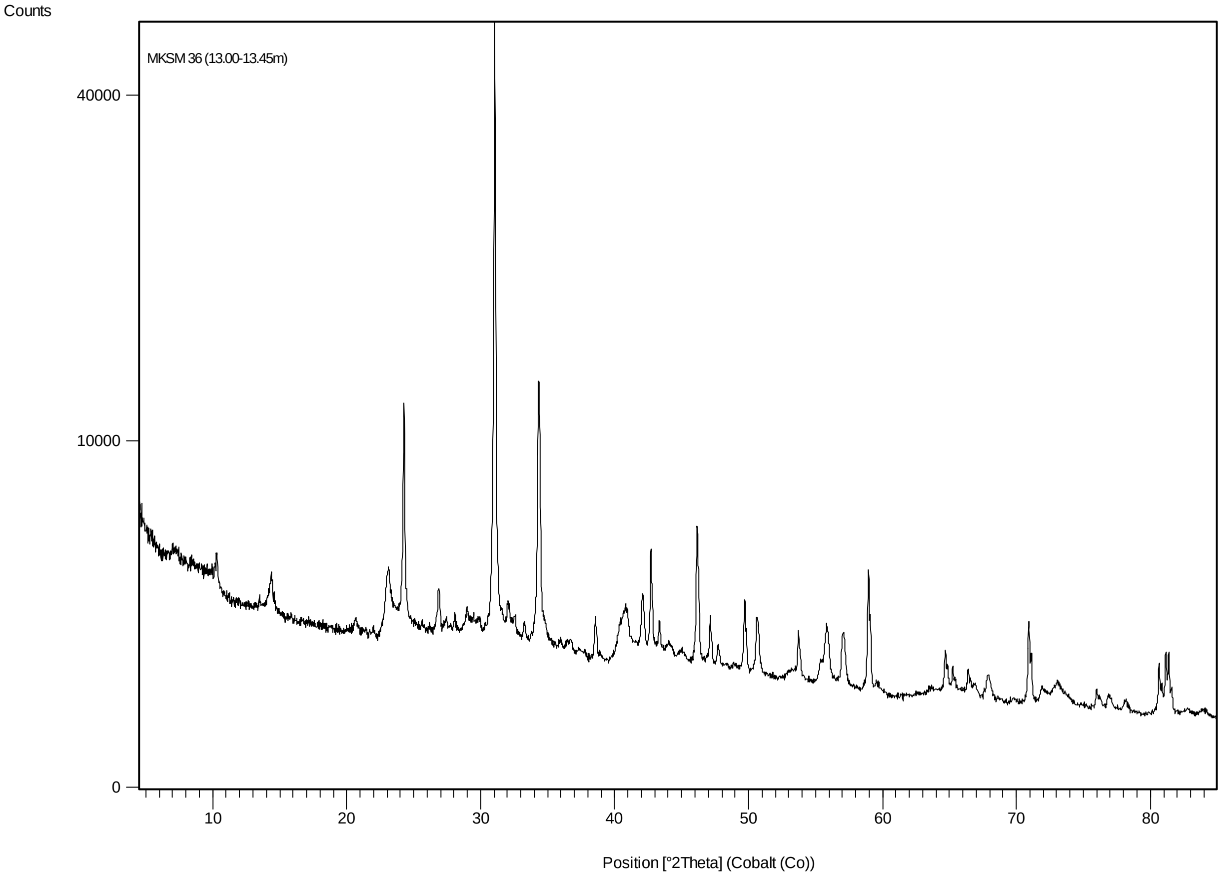

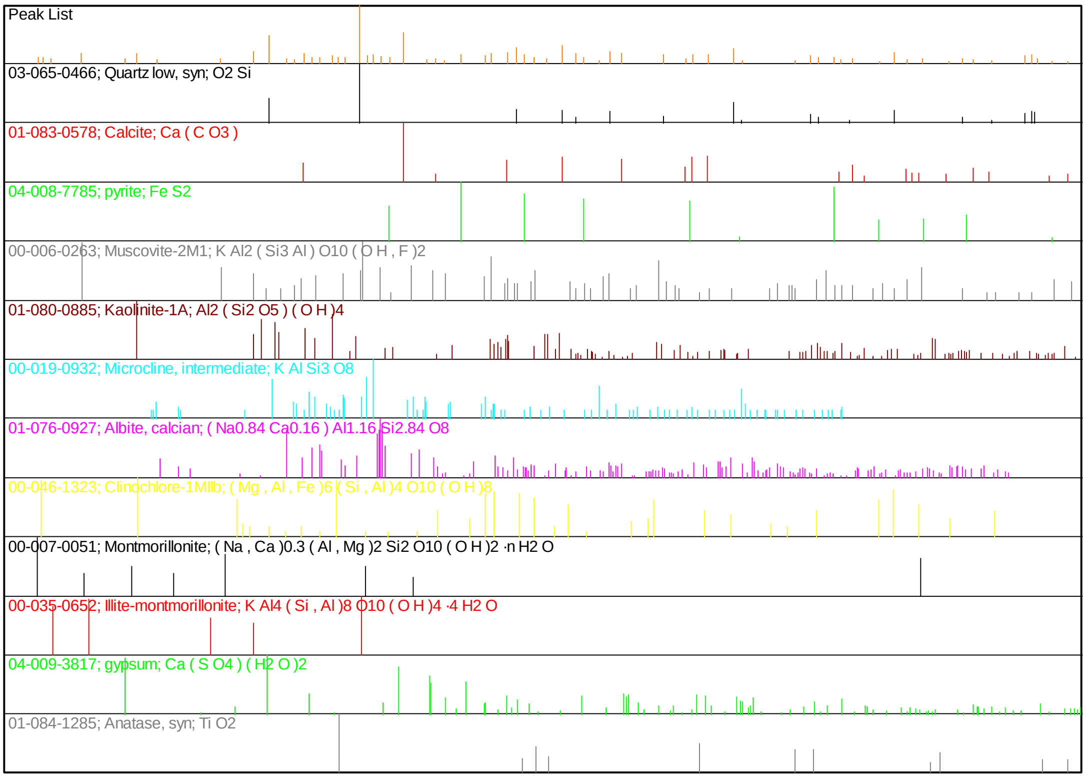

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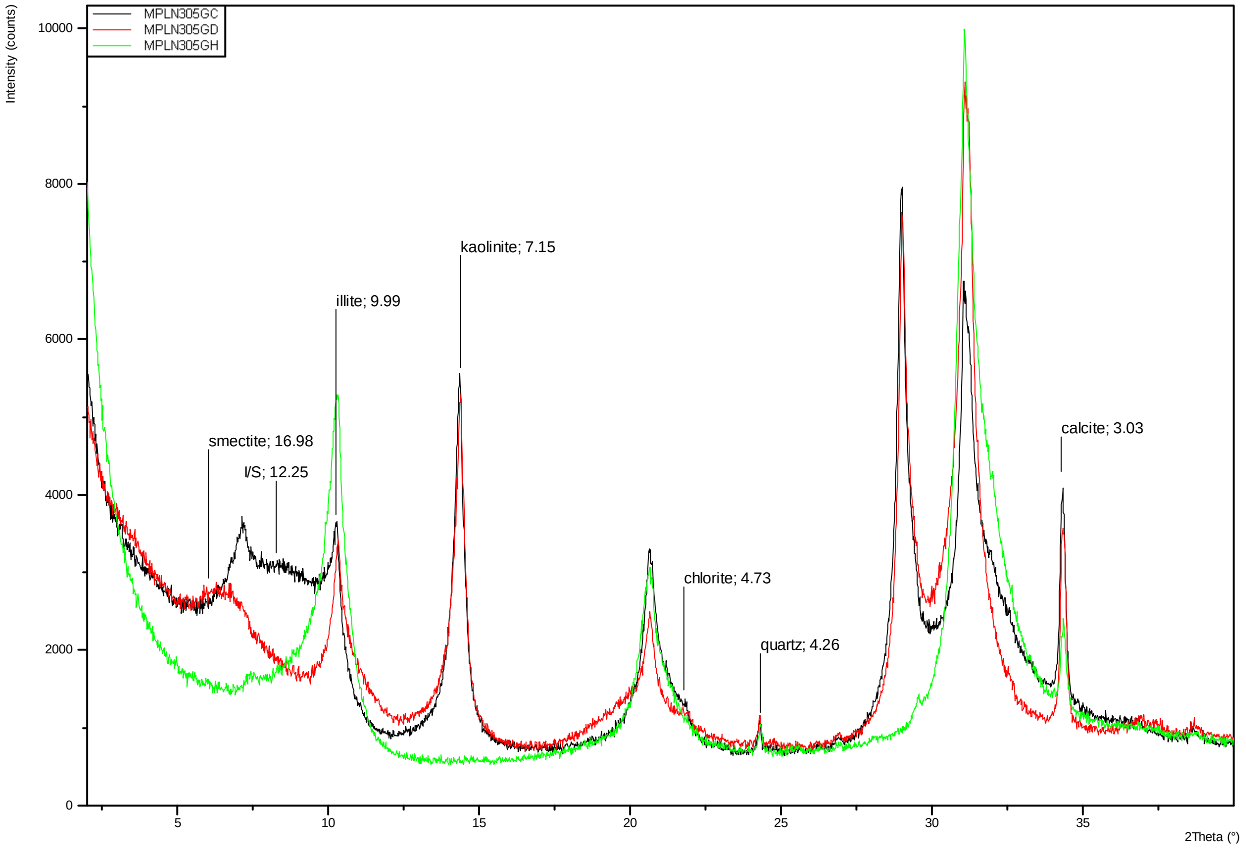
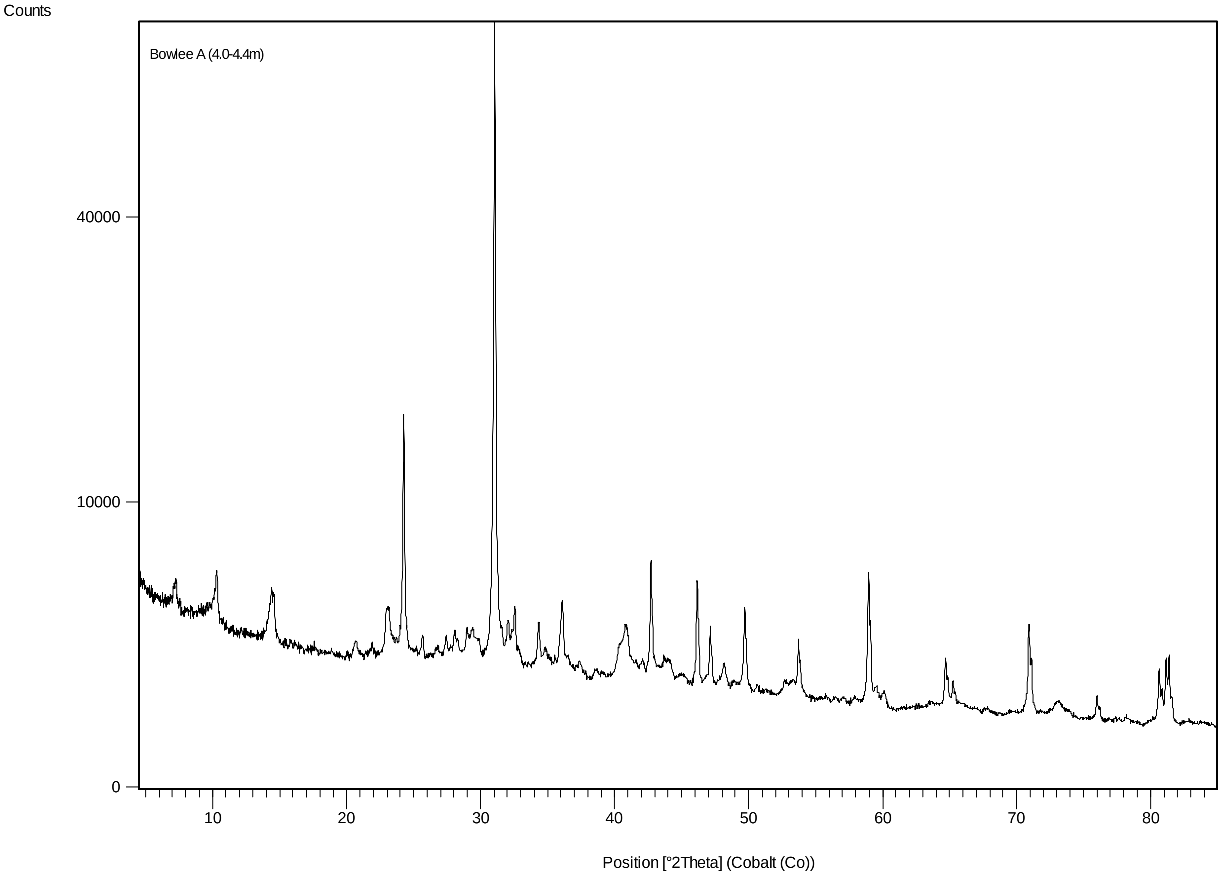
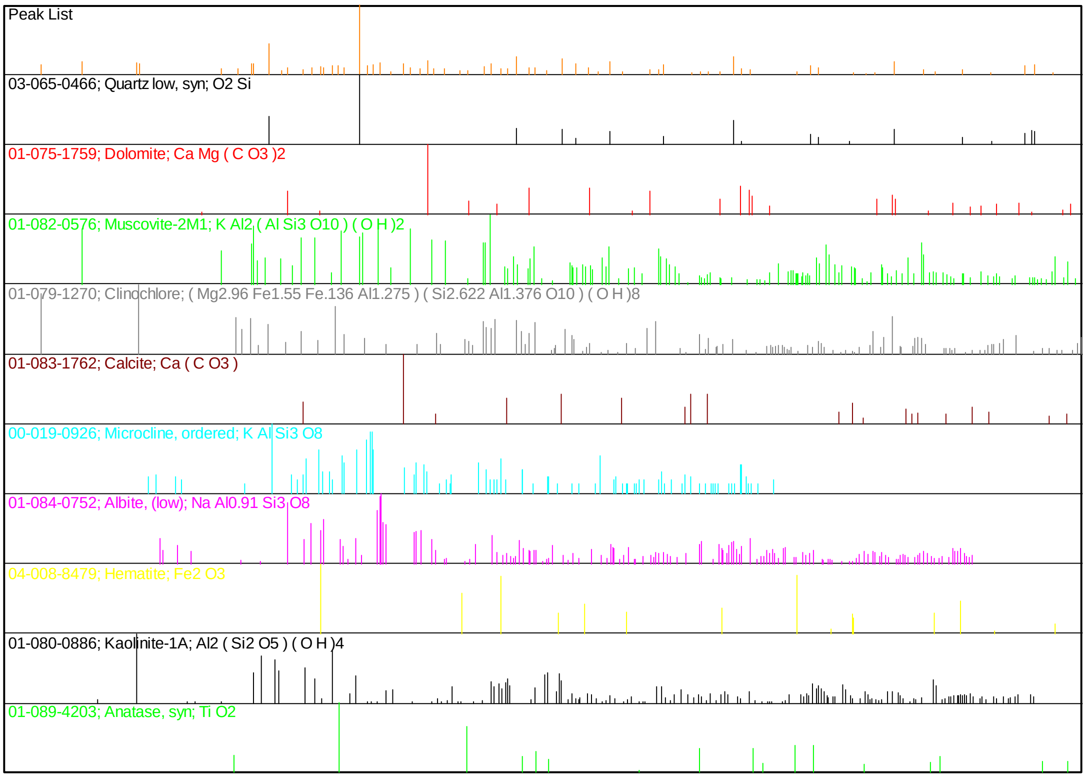
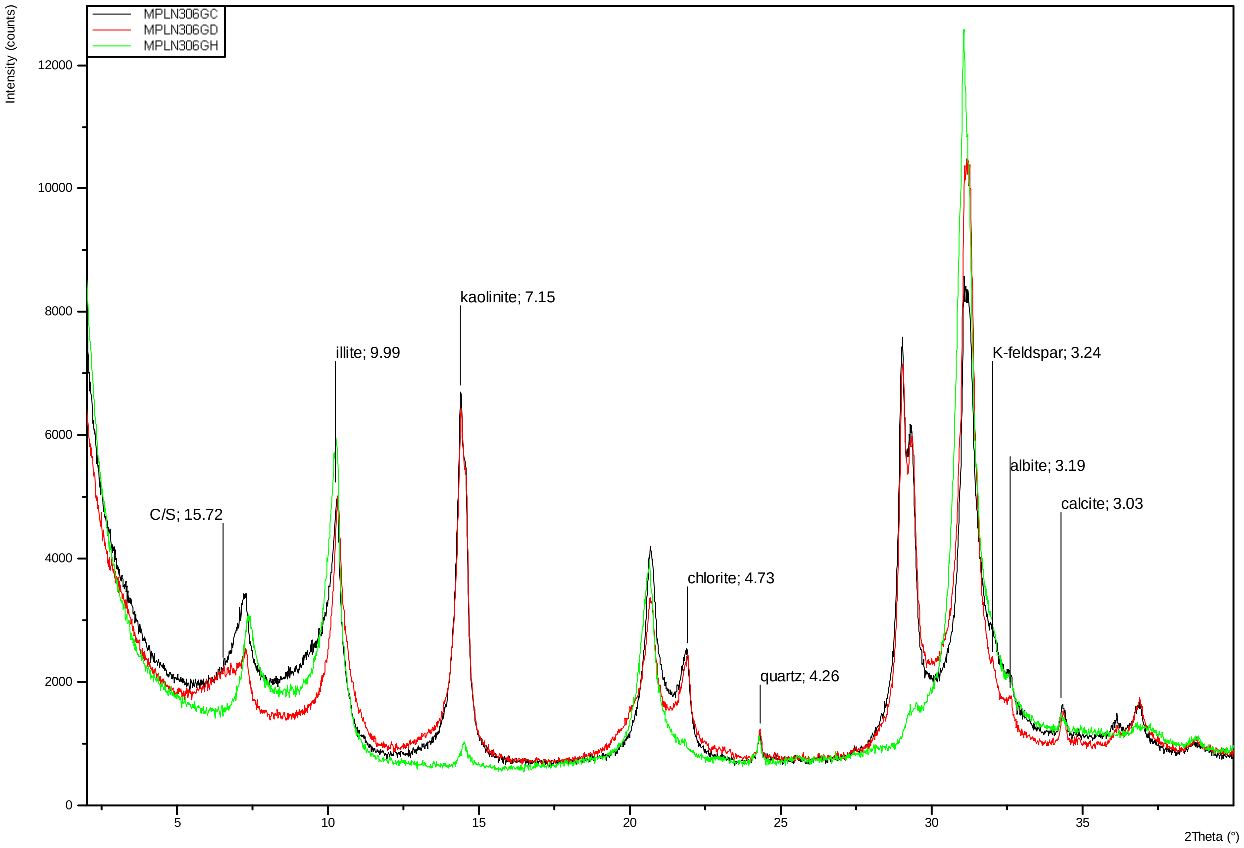


# Lancashire, Bowlee A, 4.00-4.45 m, whole-rock

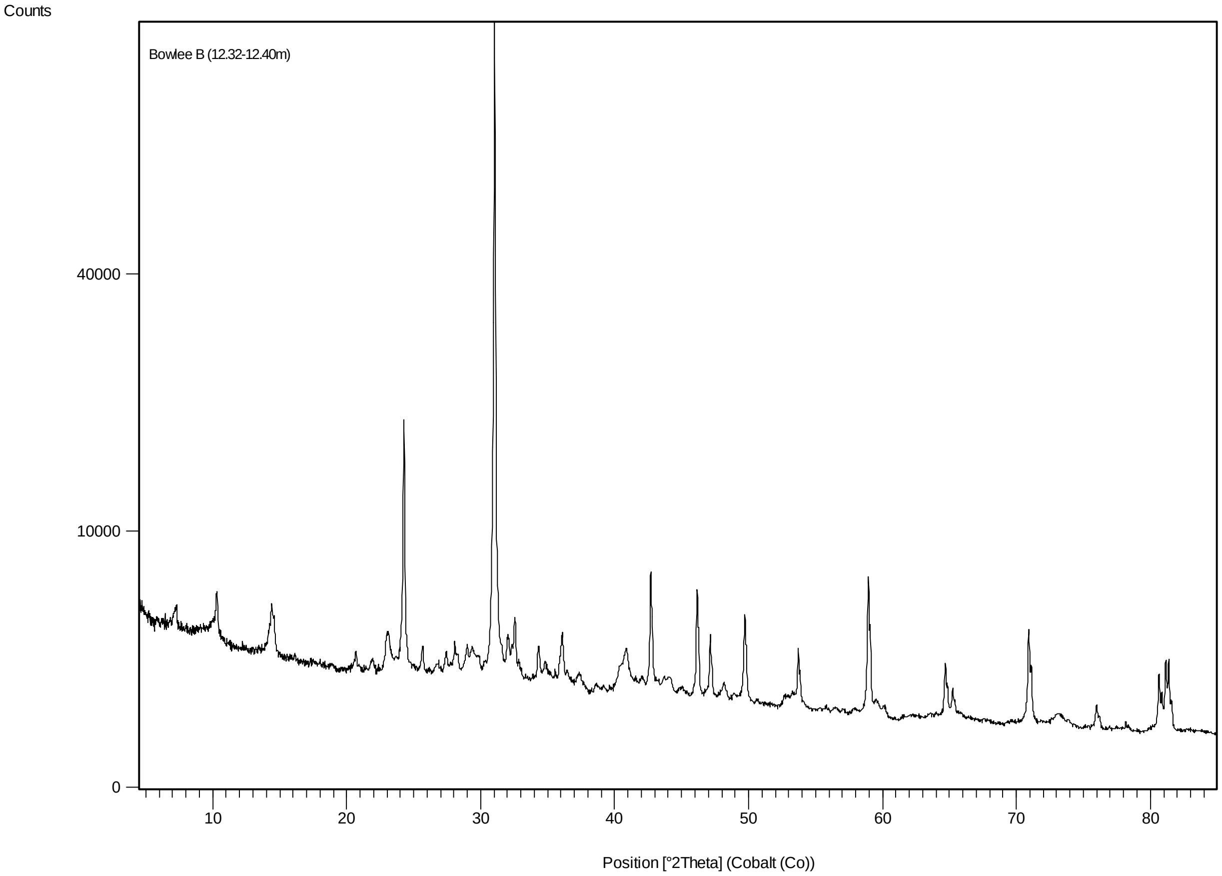


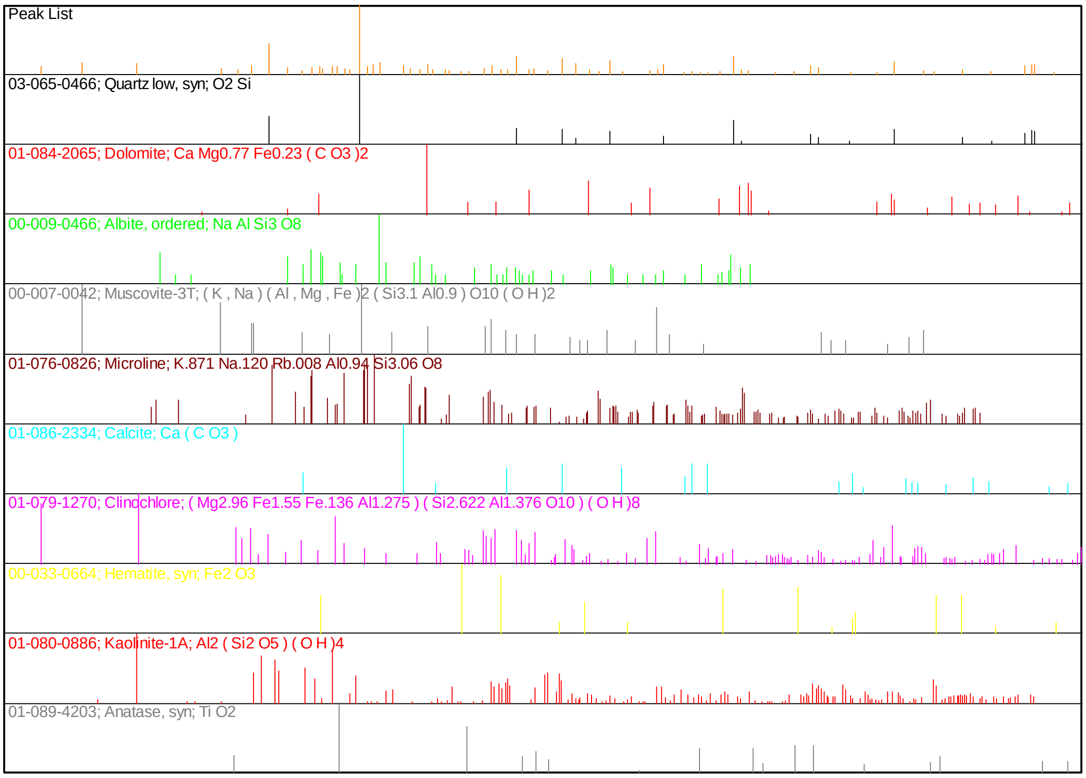


## Lancashire, Bowlee A, 4.00-4.45 m, <2 µm fraction

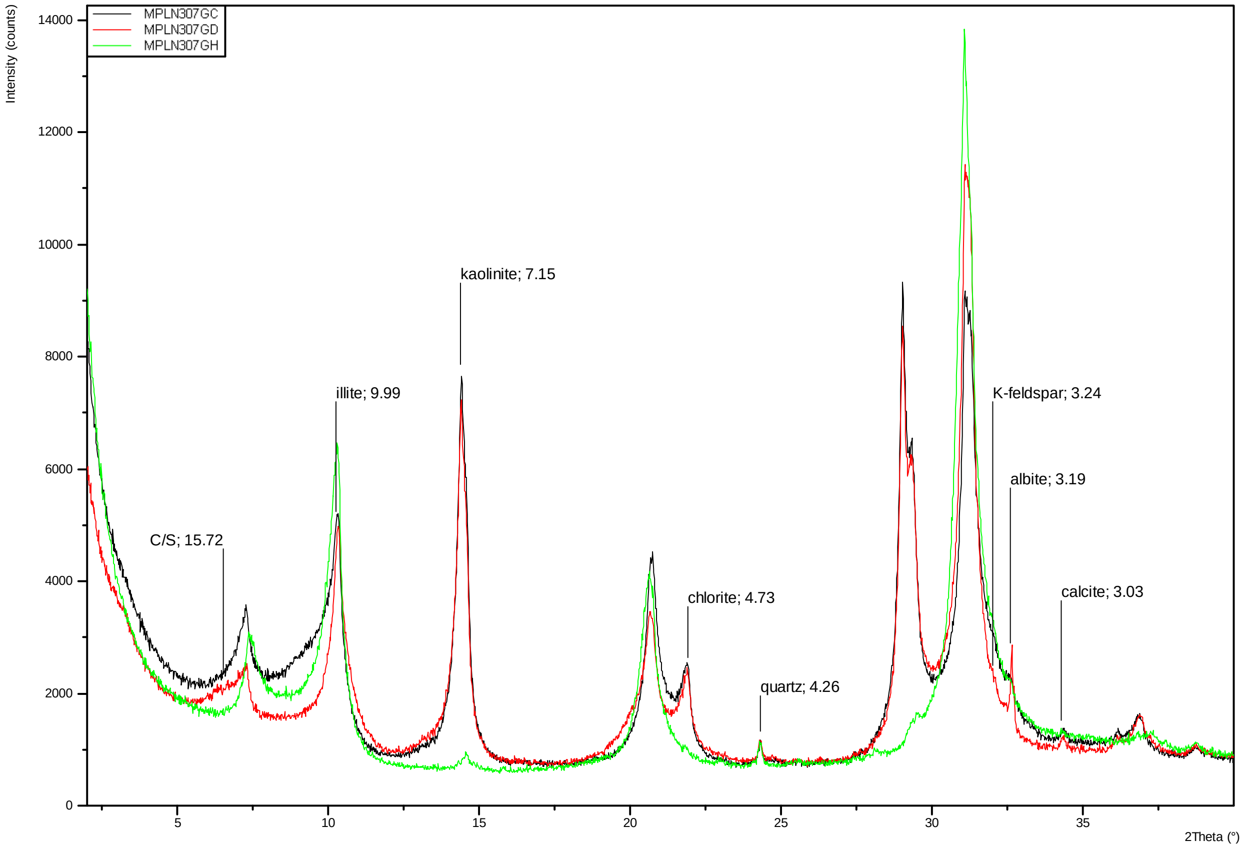


# Lancashire, Bowlee B, 12.32-12.40 m, whole-rock

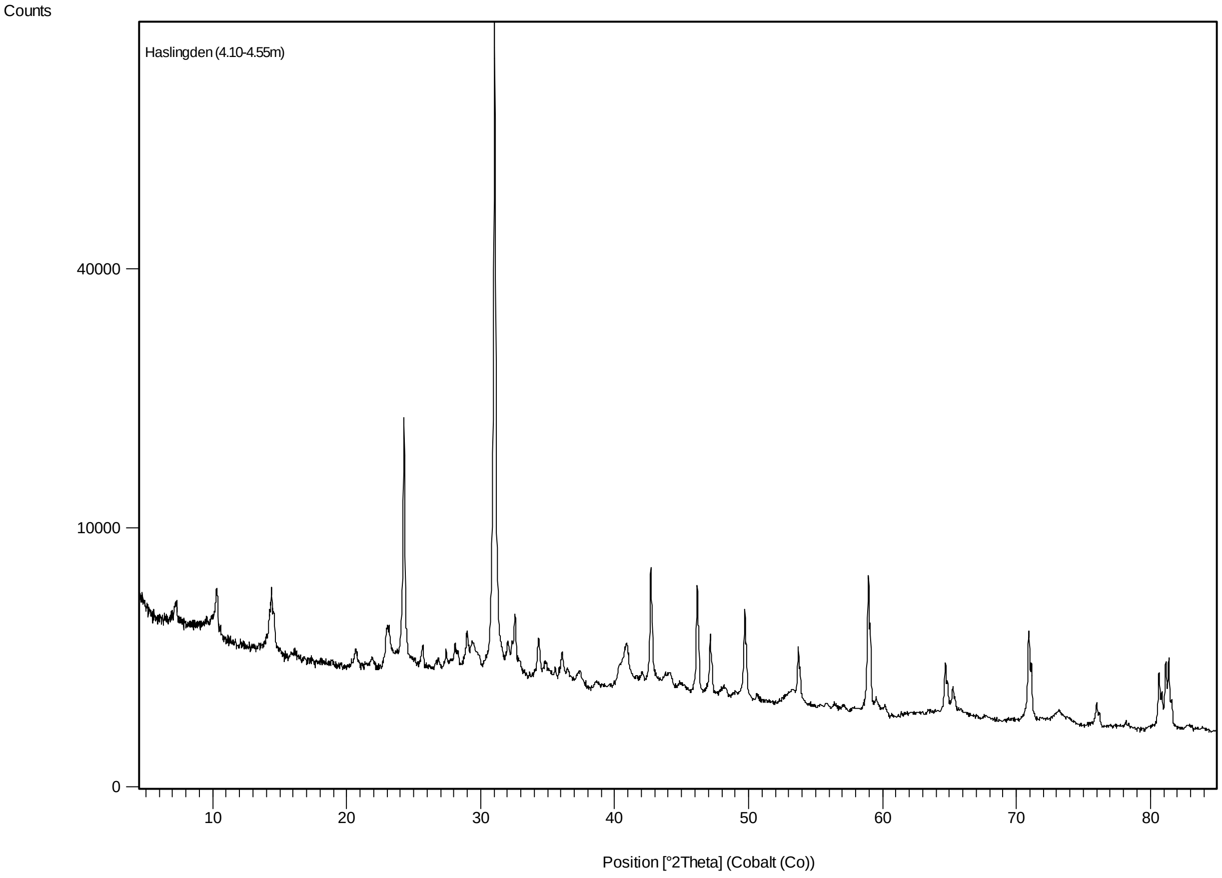


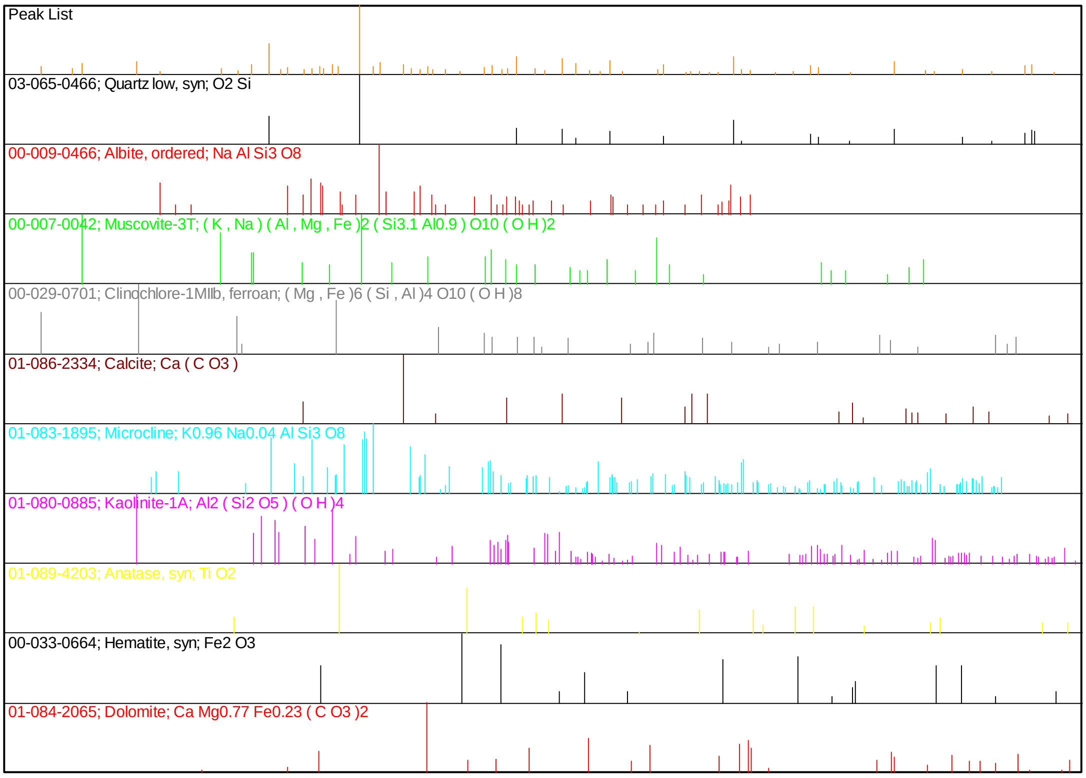


## Lancashire, Bowlee B, 12.32-12.40 m, <2 µm fraction

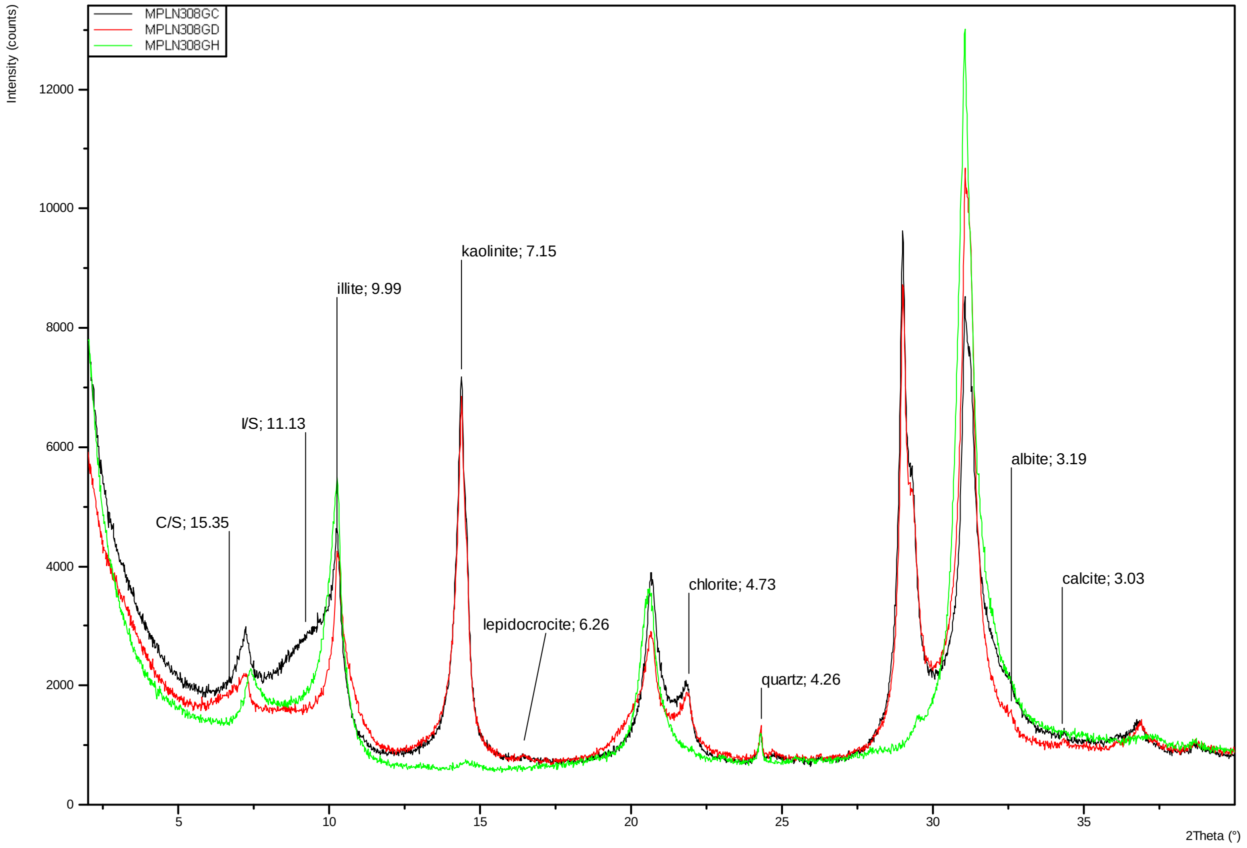


# Lancashire, Haslingden, 4.10-4.55 m, whole-rock

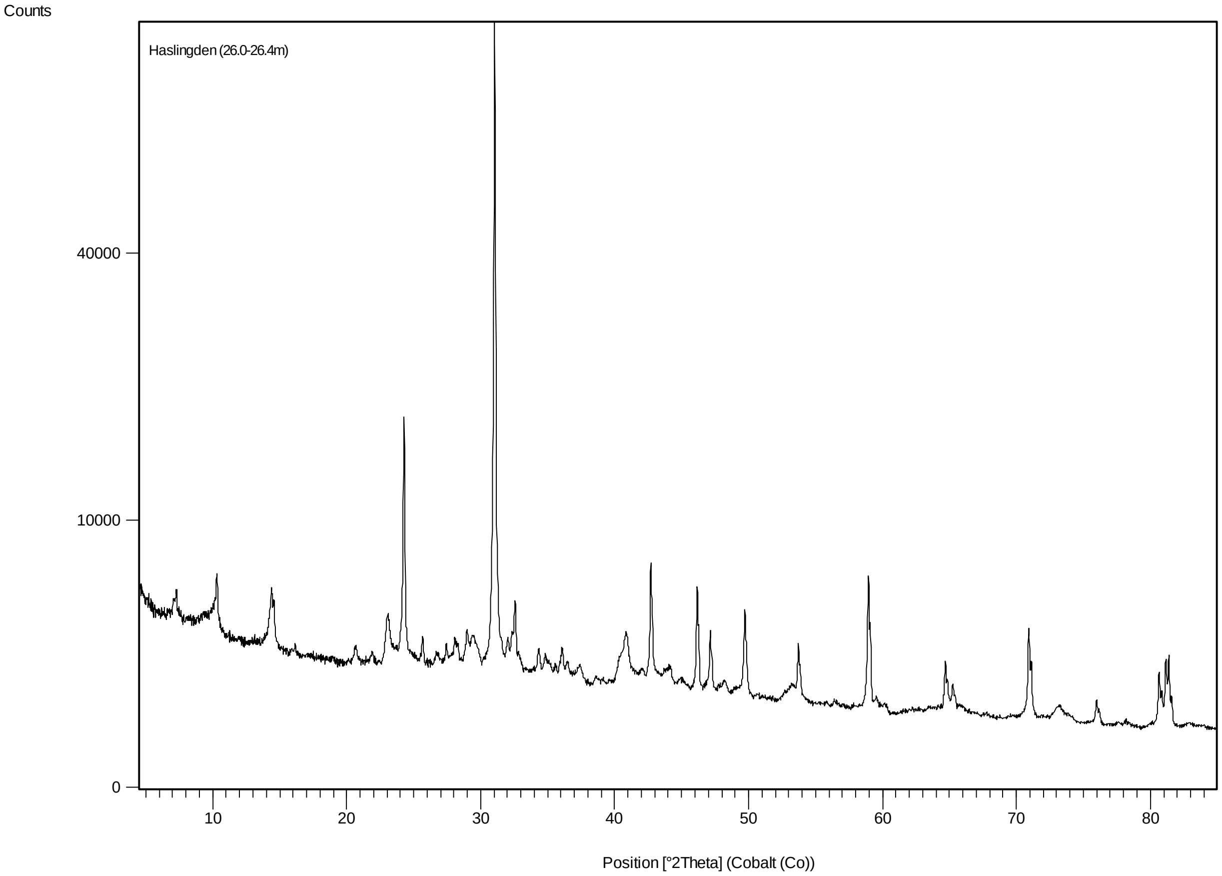


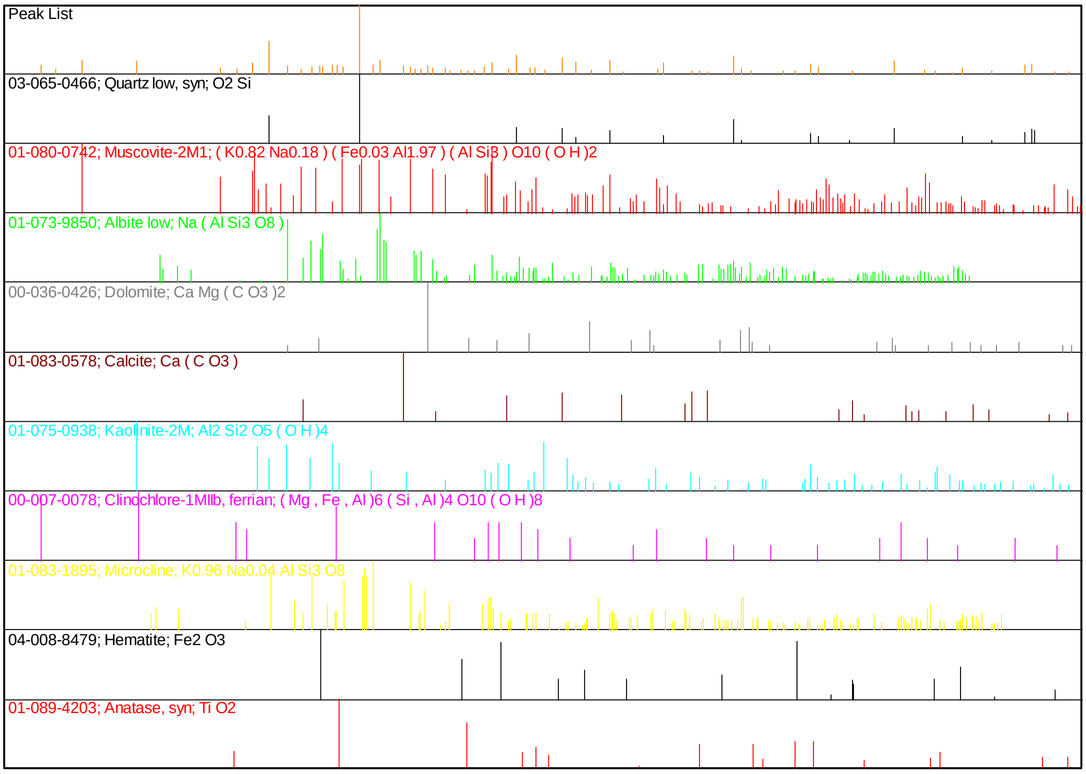


## Lancashire, Haslingden, 4.10-4.55 m, <2 µm fraction

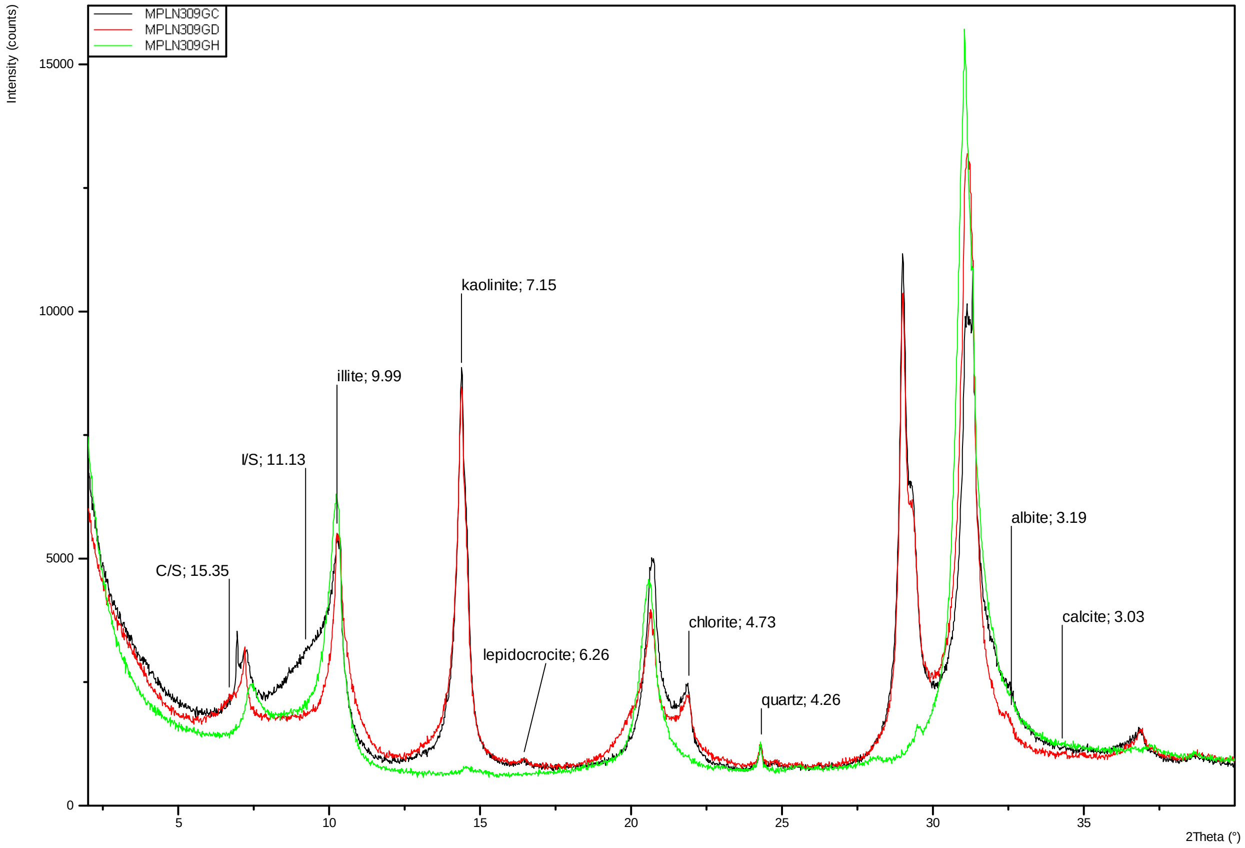


# Lancashire, Haslingden, 26.0-26.4 m, whole-rock

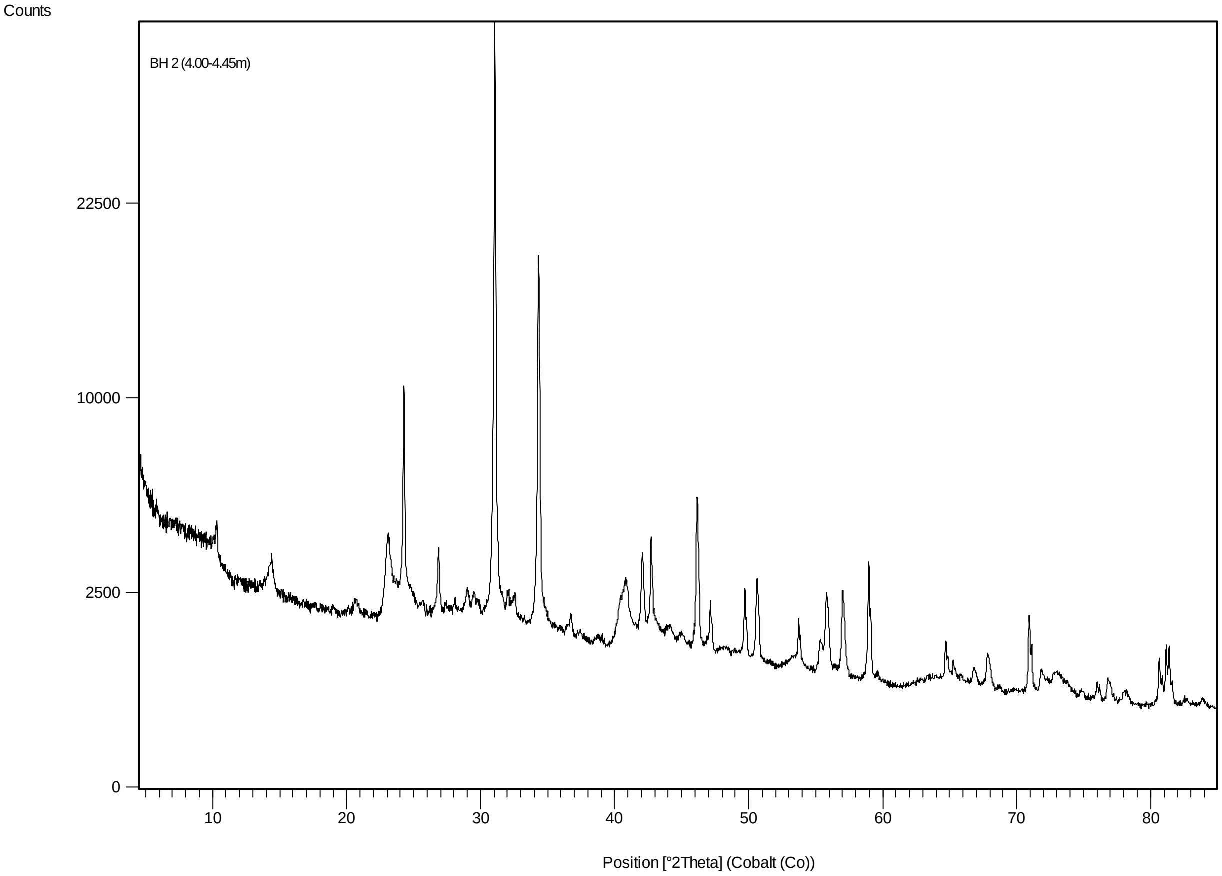


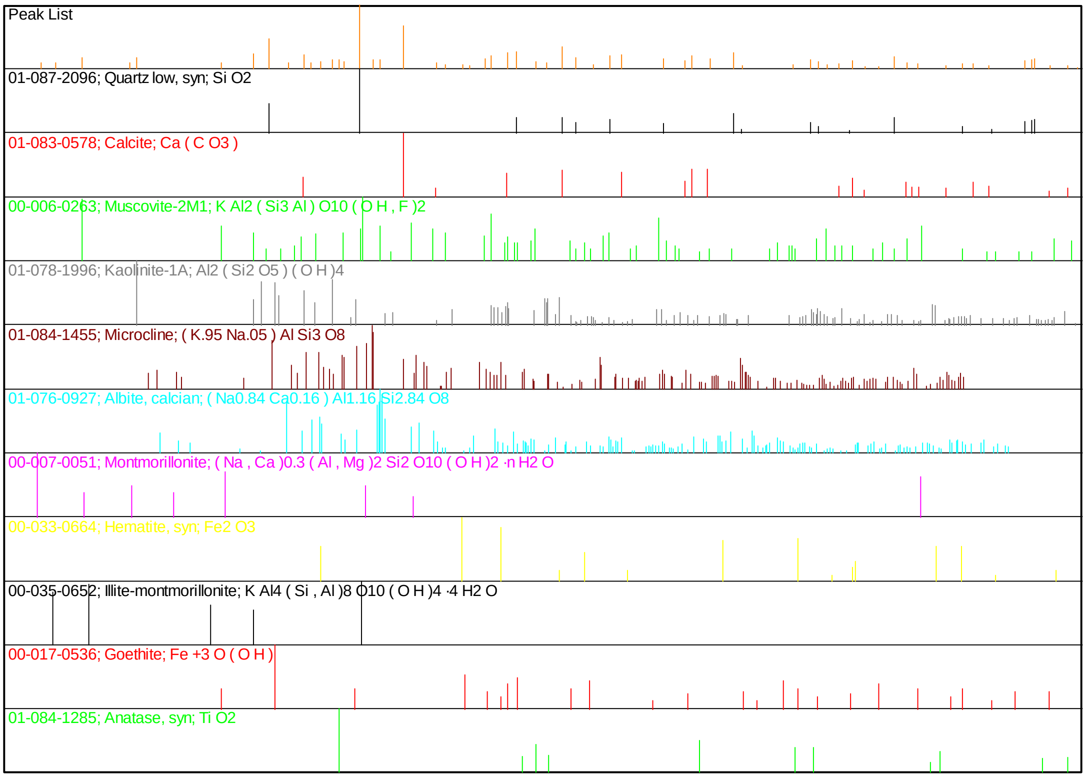


## Lancashire, Haslingden, 26.0-26.4 m, <2 µm fraction

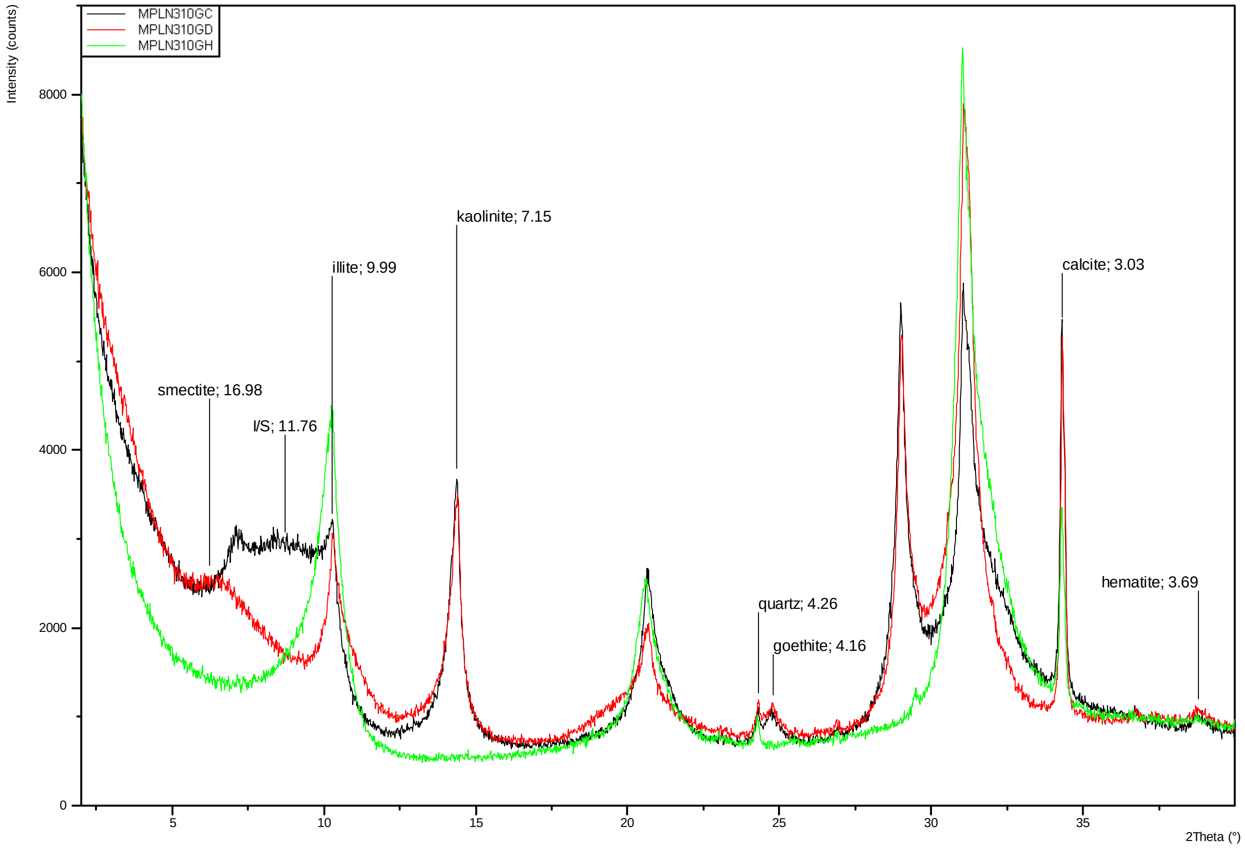


# Thetford, BH2, 4.00-4.55 m, whole-rock

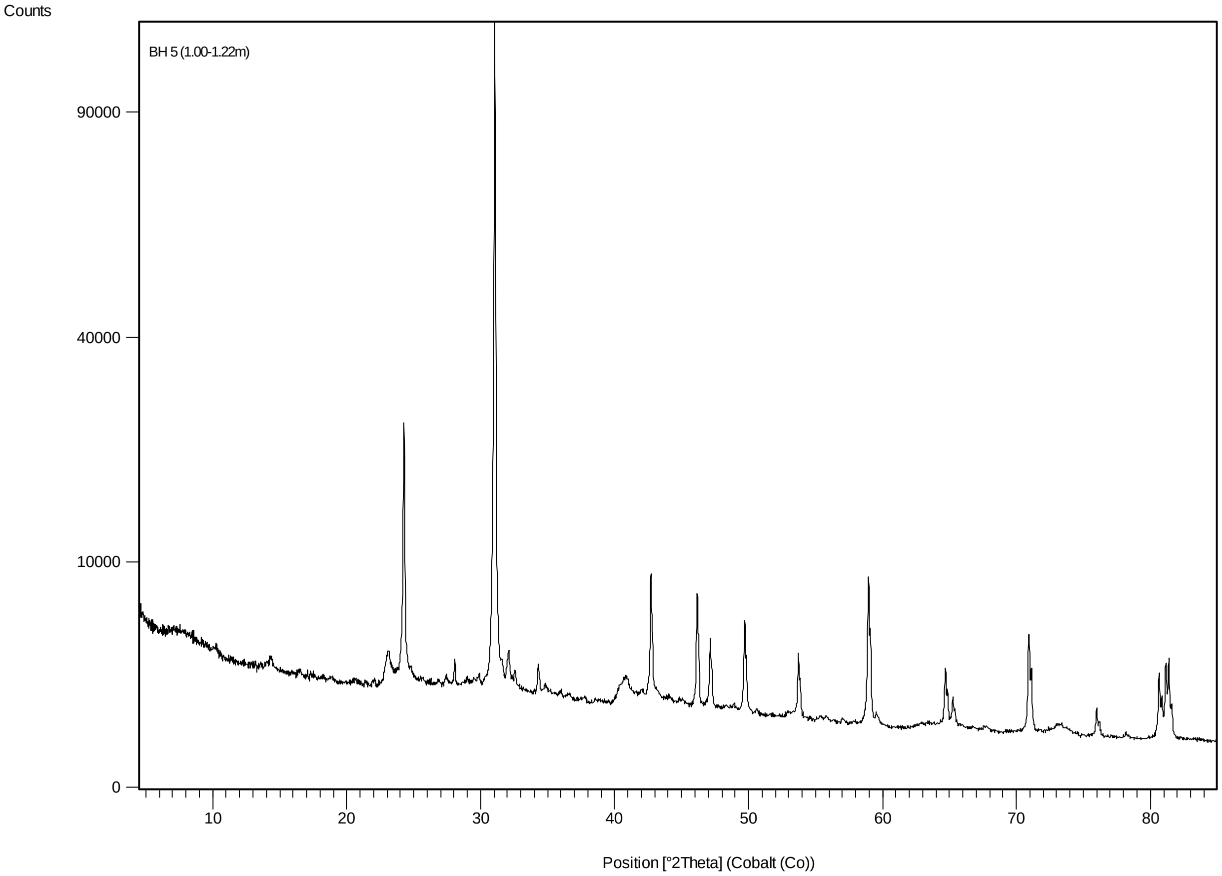


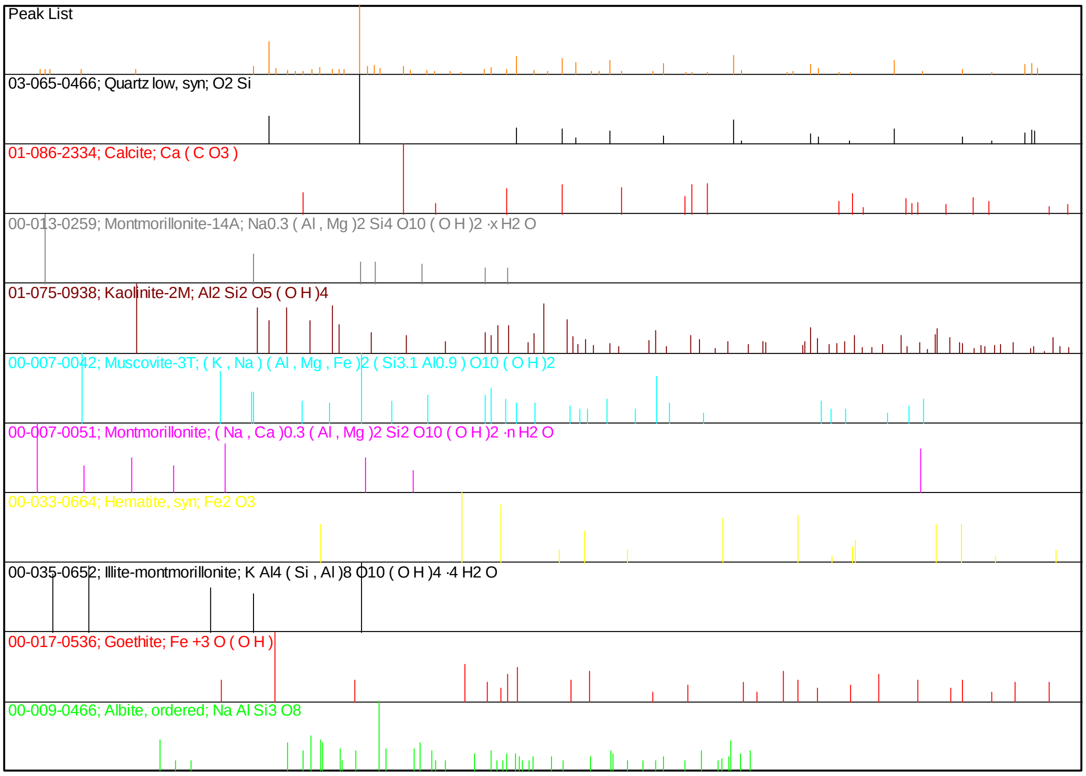


## Thetford, BH2, 4.00-4.55 m, <2 µm fraction

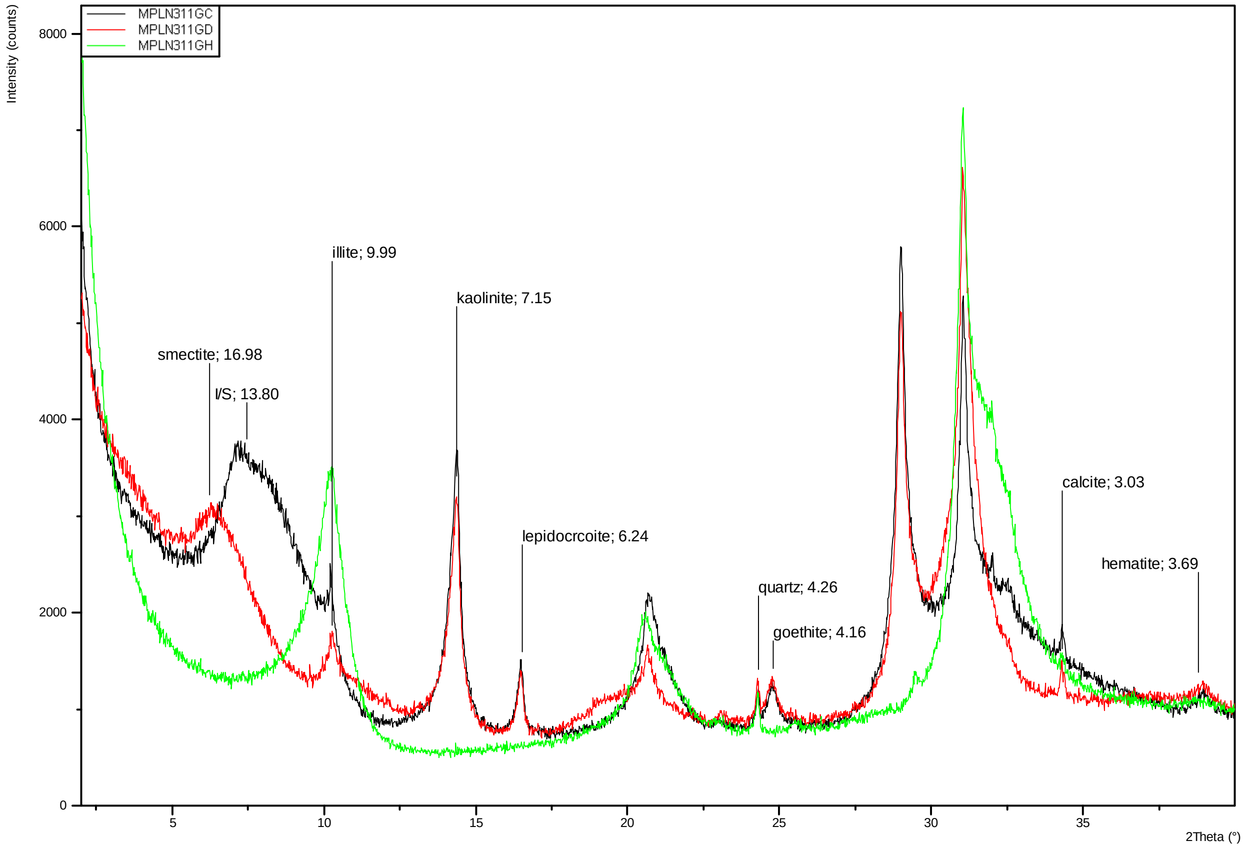


# Thetford, BH5, 1.00-1.22 m, whole-rock

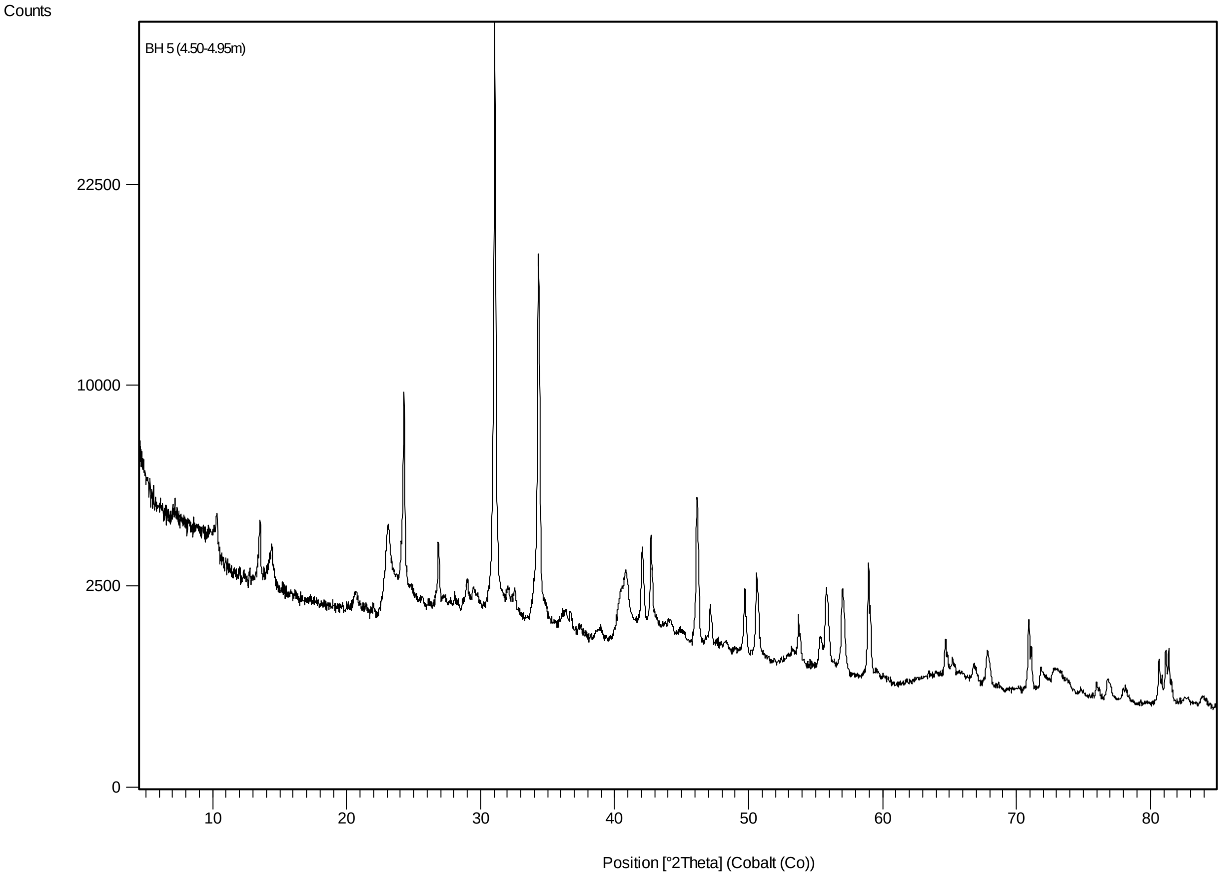


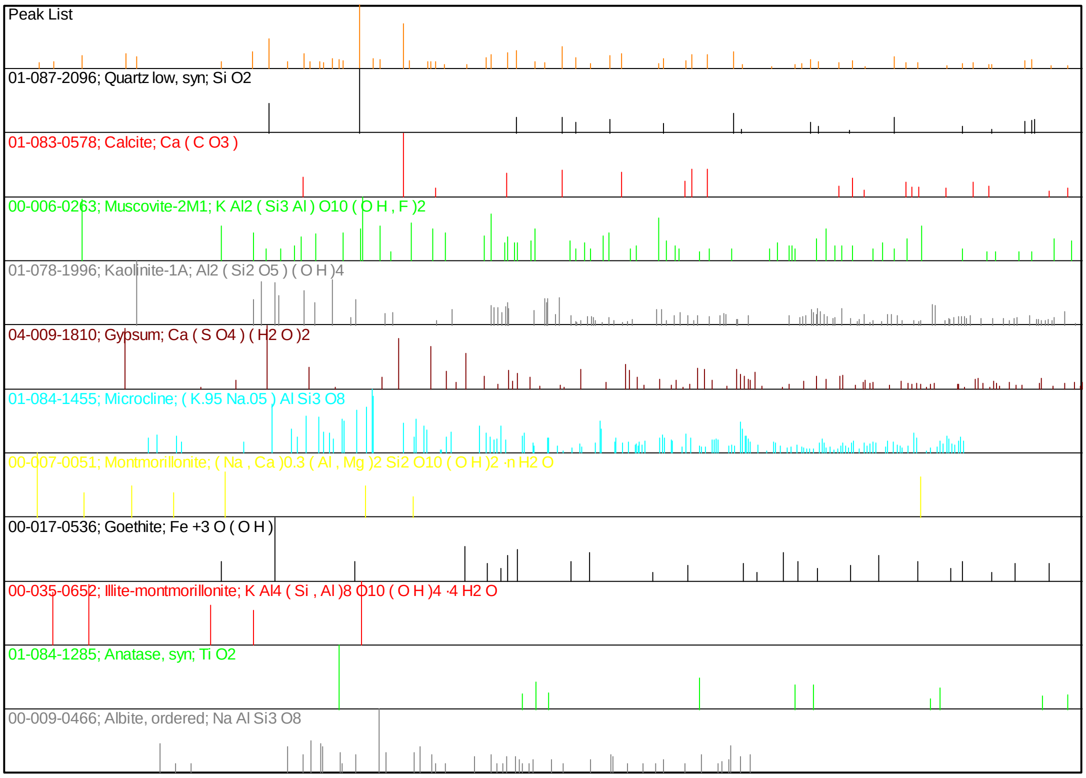


## Thetford, BH5, 1.00-1.22 m, <2 µm fraction

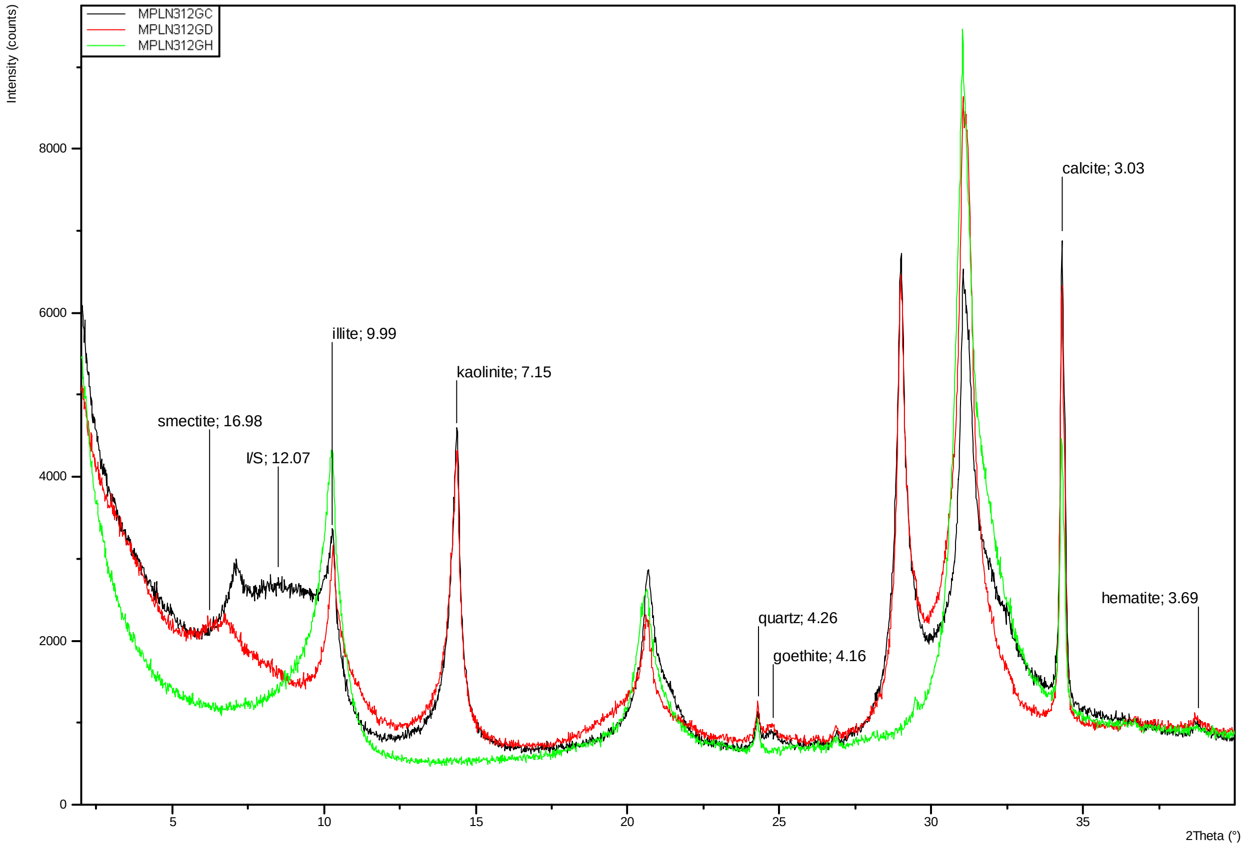


# Thetford, BH5, 4.50-4.95 m, whole-rock

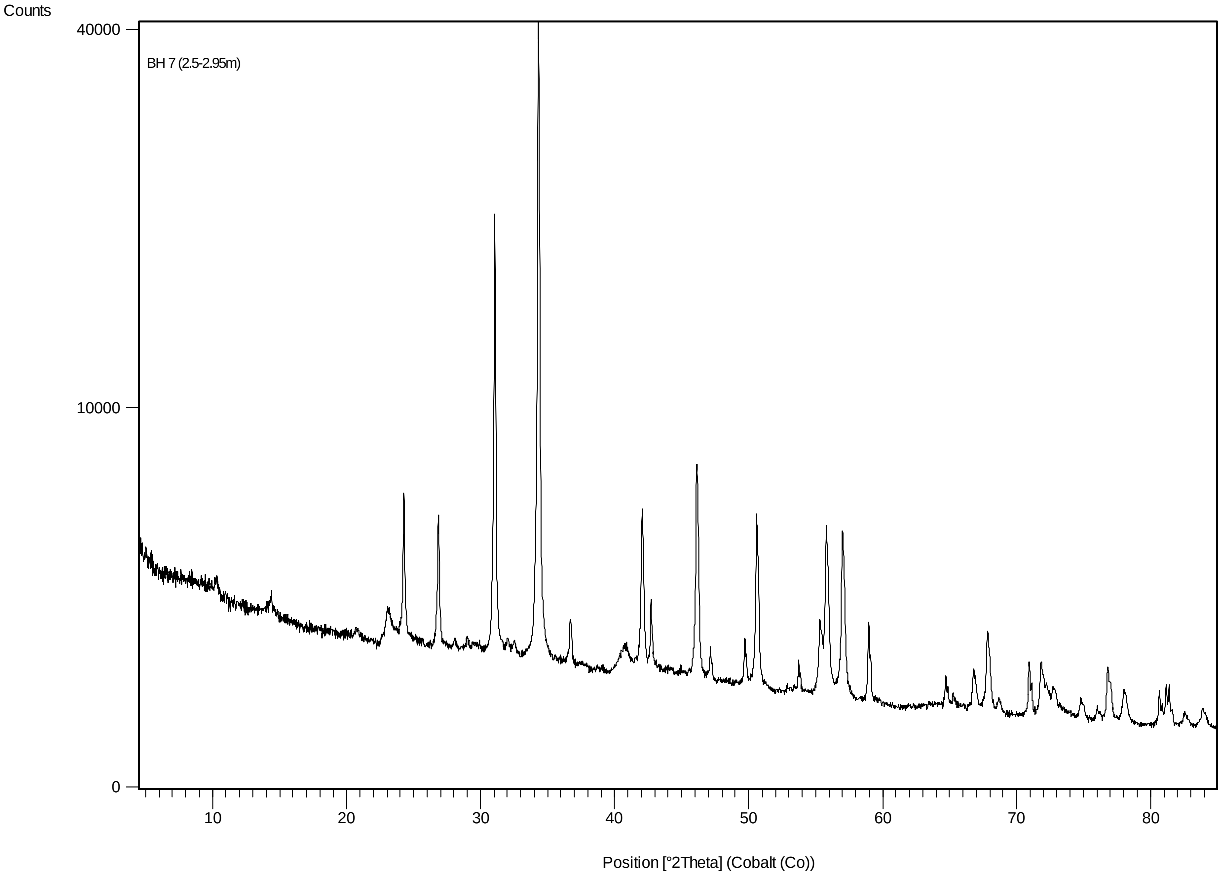


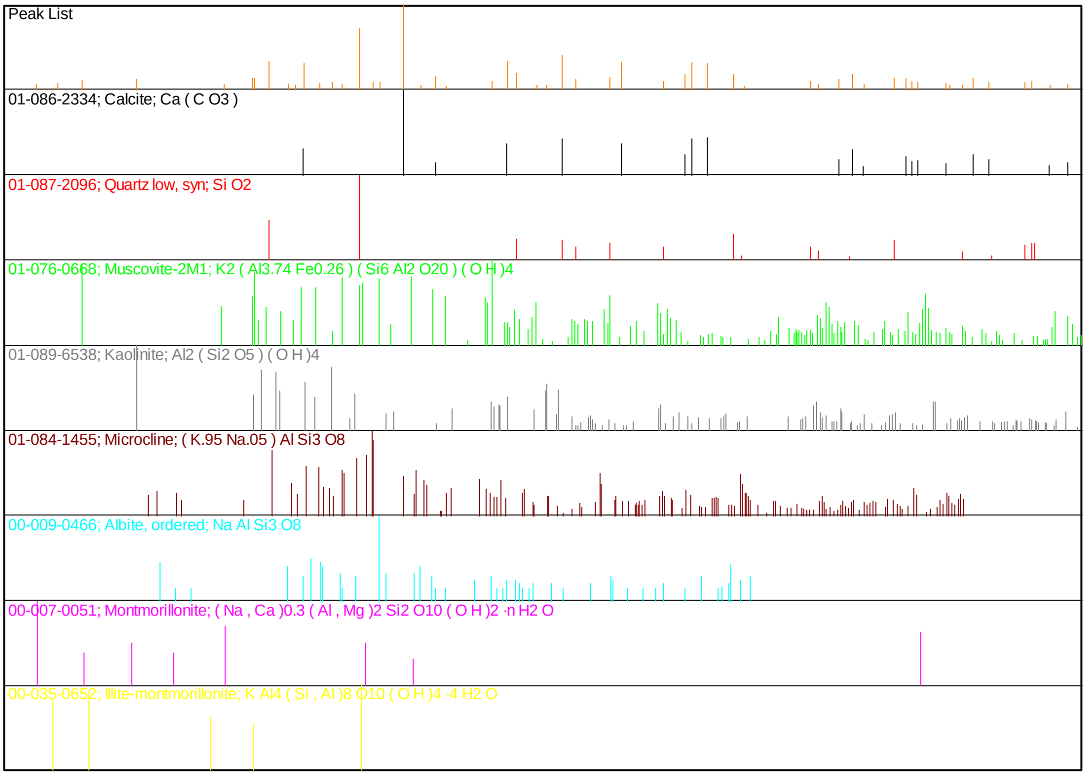


## Thetford, BH5, 4.50-4.95 m, <2 µm fraction

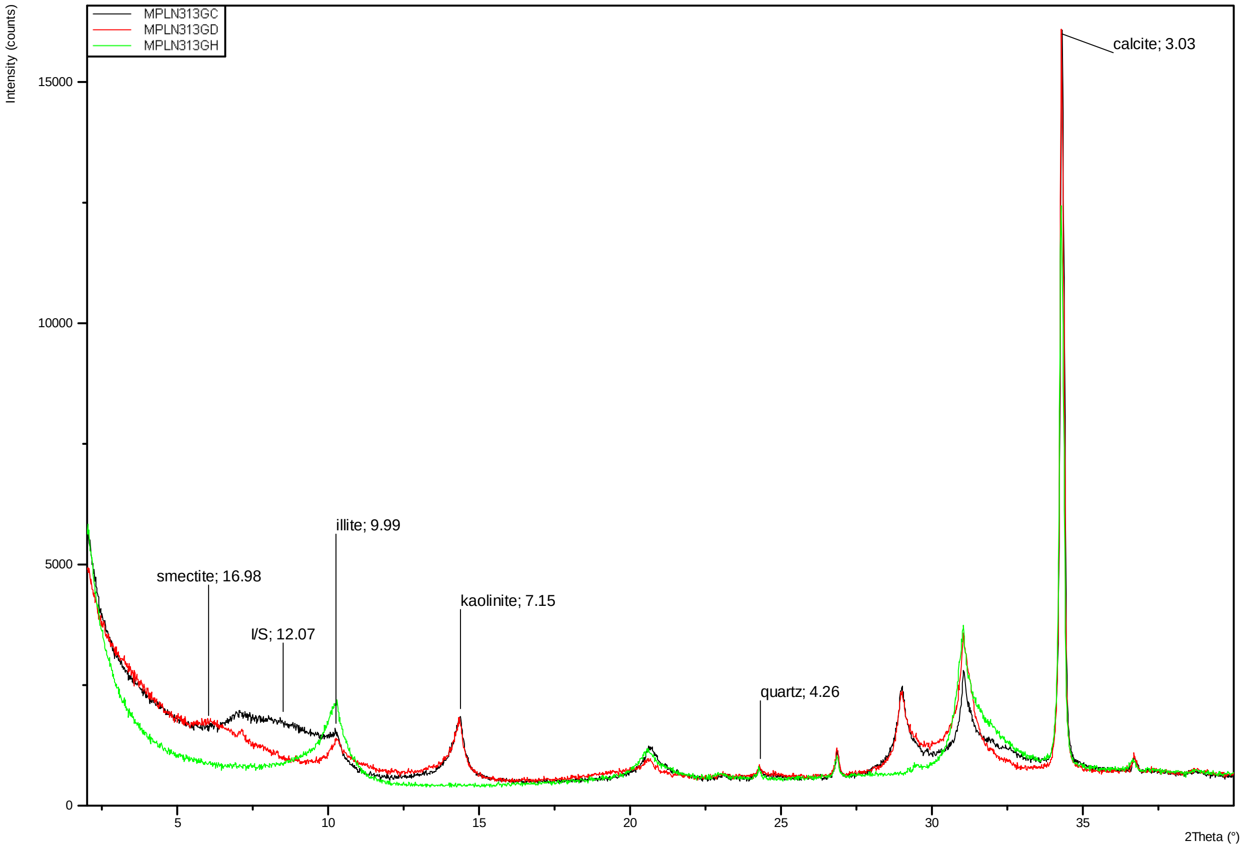


# Thetford, BH7, 2.5-2.95 m, whole-rock

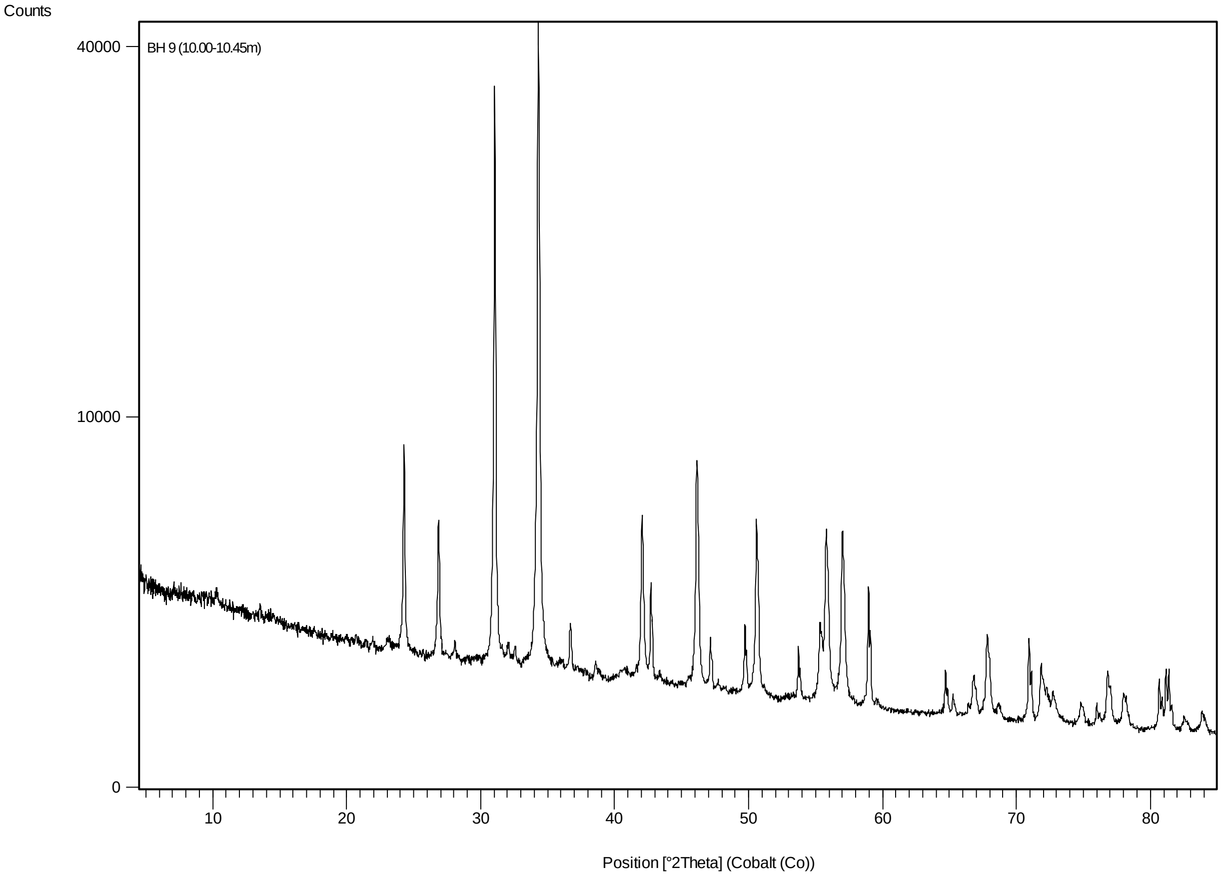


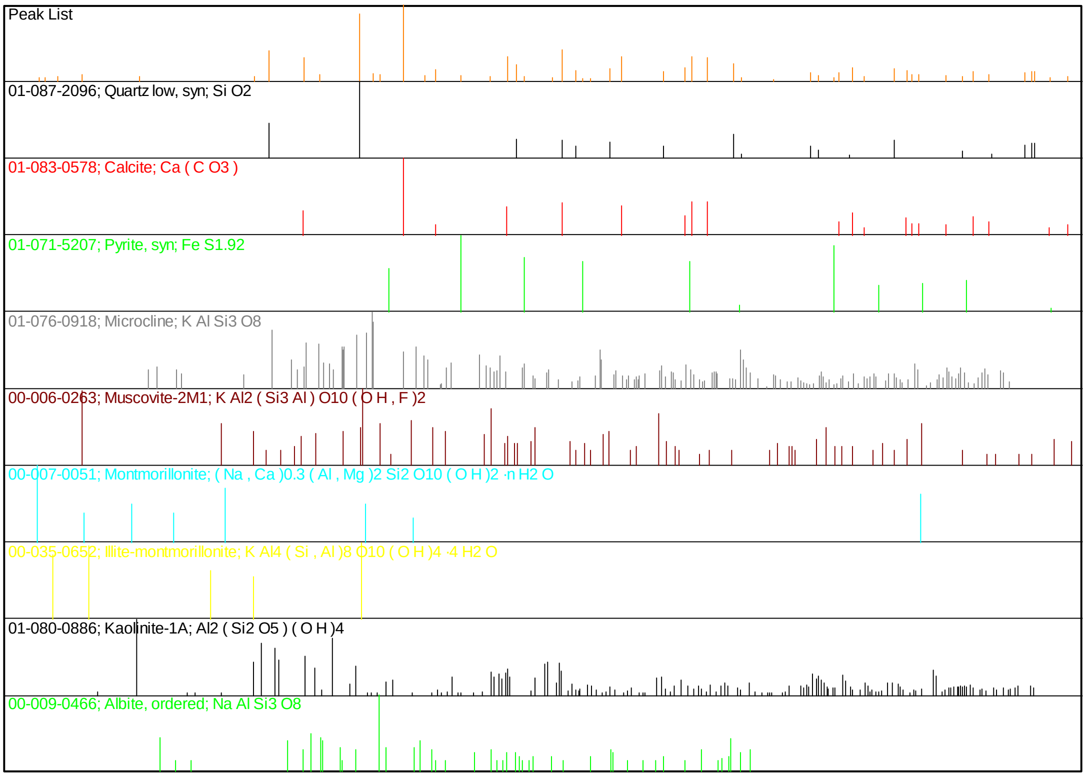


## Thetford, BH7, 2.5-2.95 m, <2 µm fraction

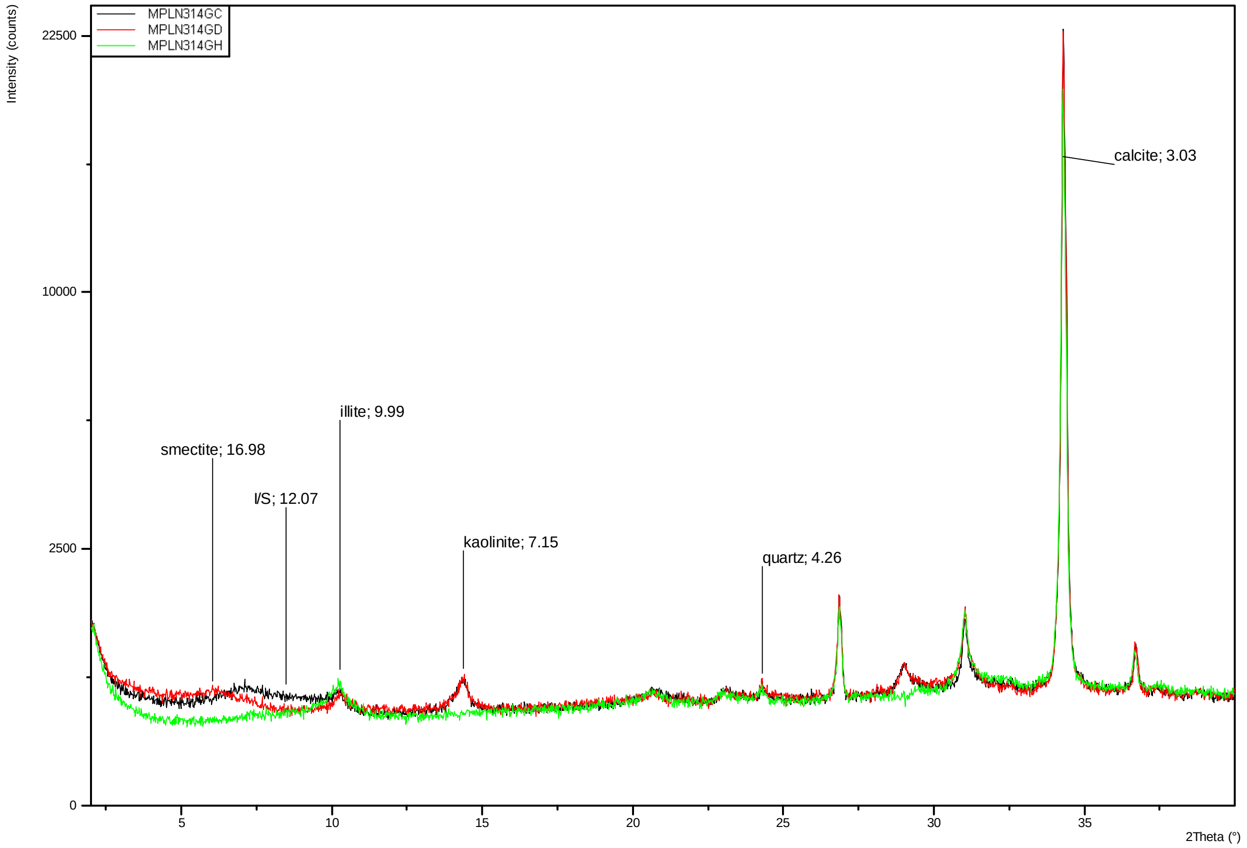


# Thetford, BH9, 10.00-10.45 m, whole-rock

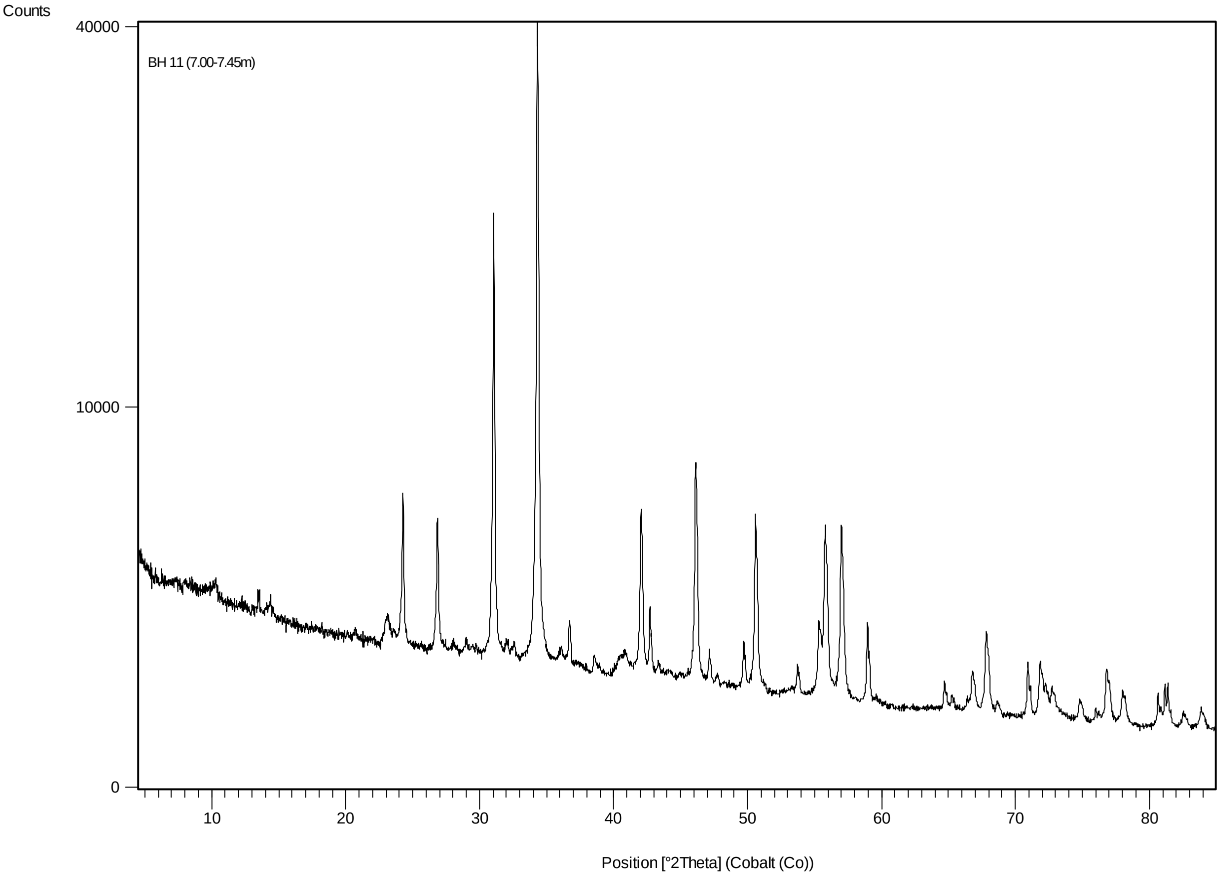


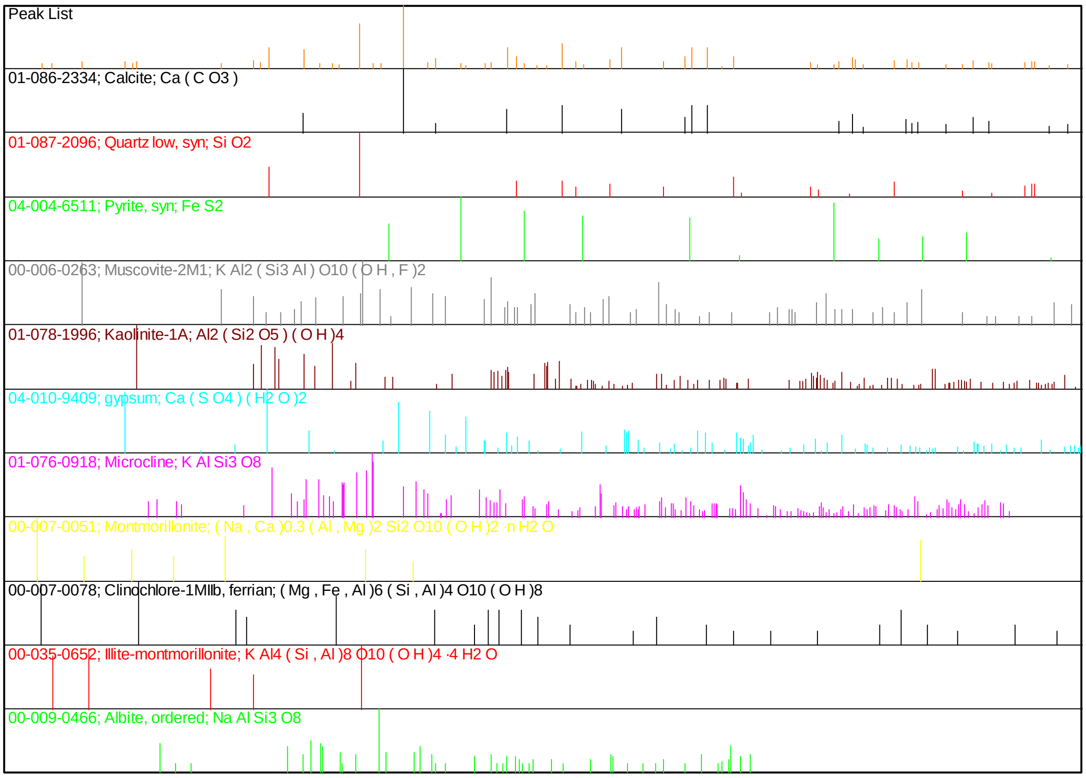


## Thetford, BH9, 10.00-10.45 m, <2 μm fraction

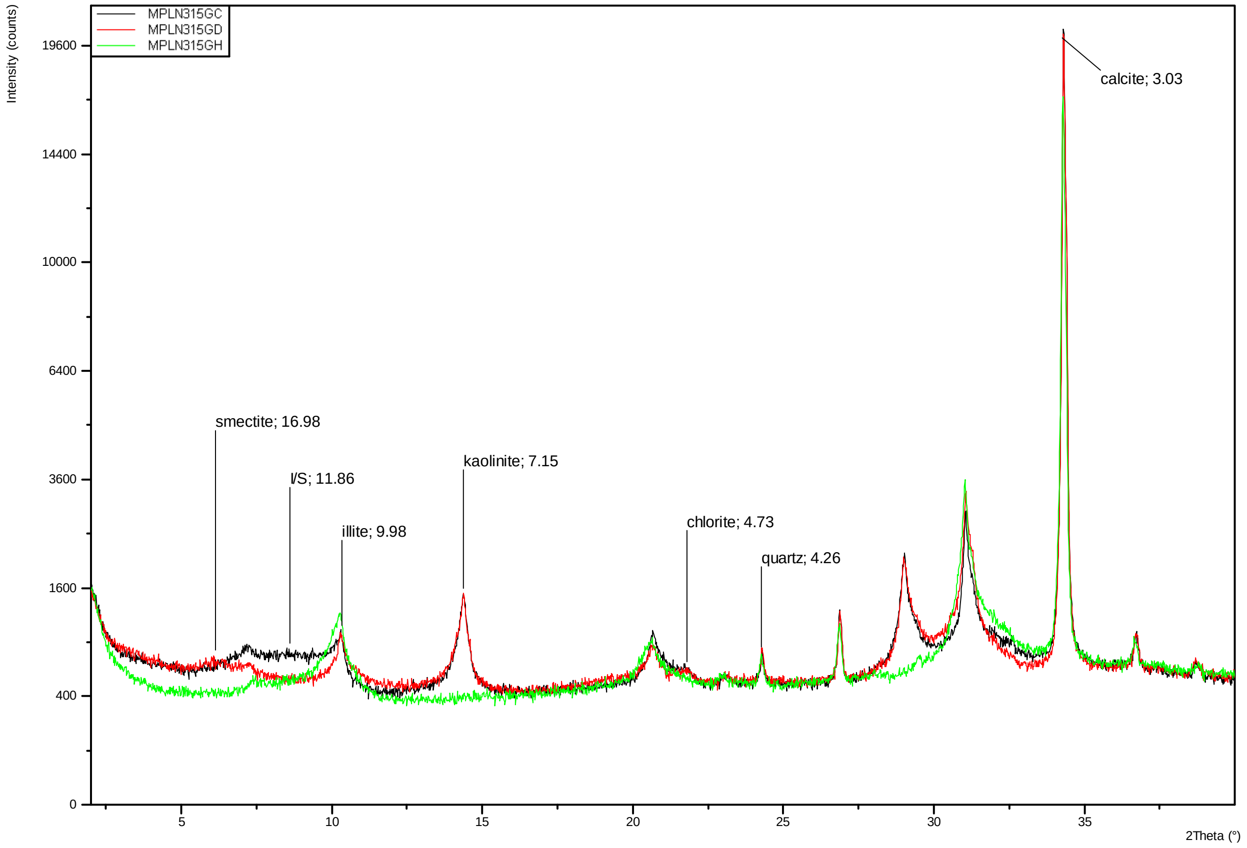


# Thetford, BH11, 7.00-7.45 m, whole-rock

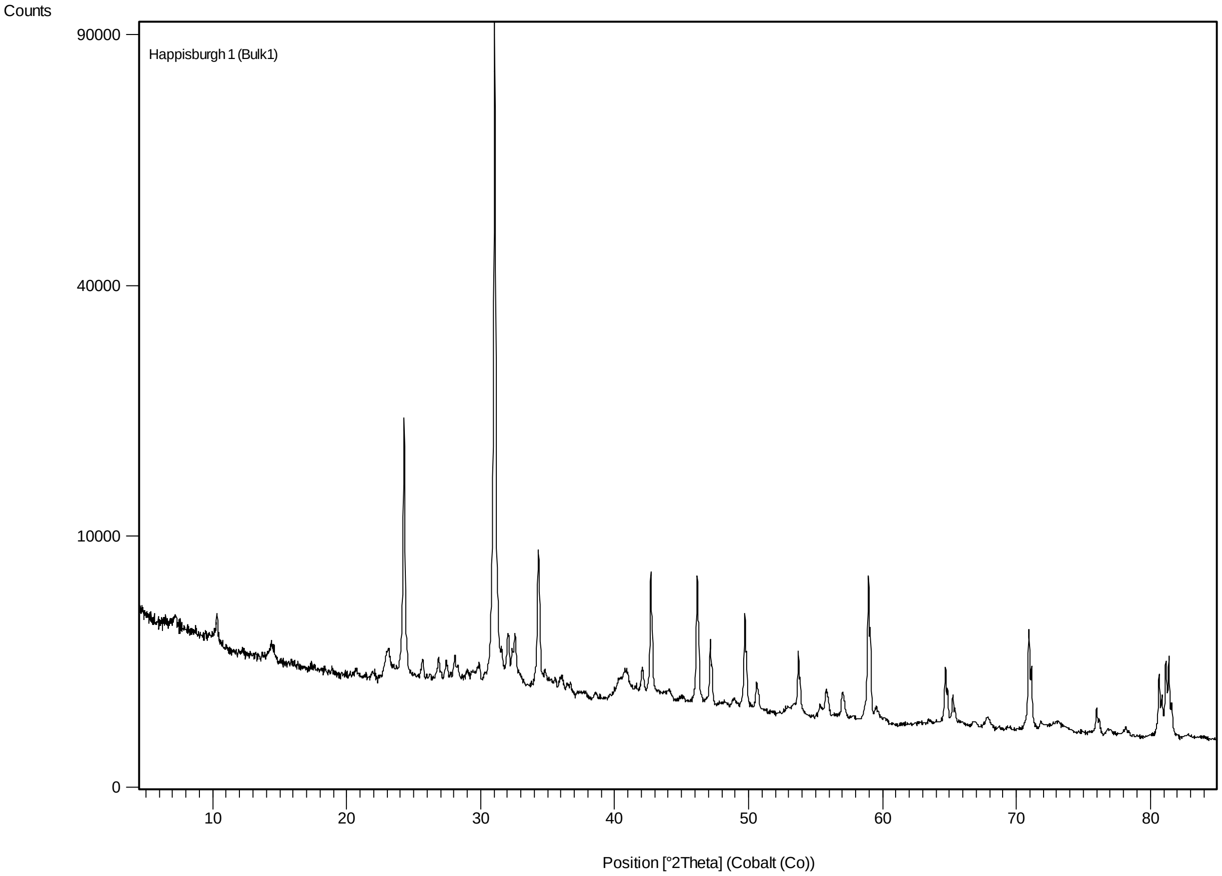


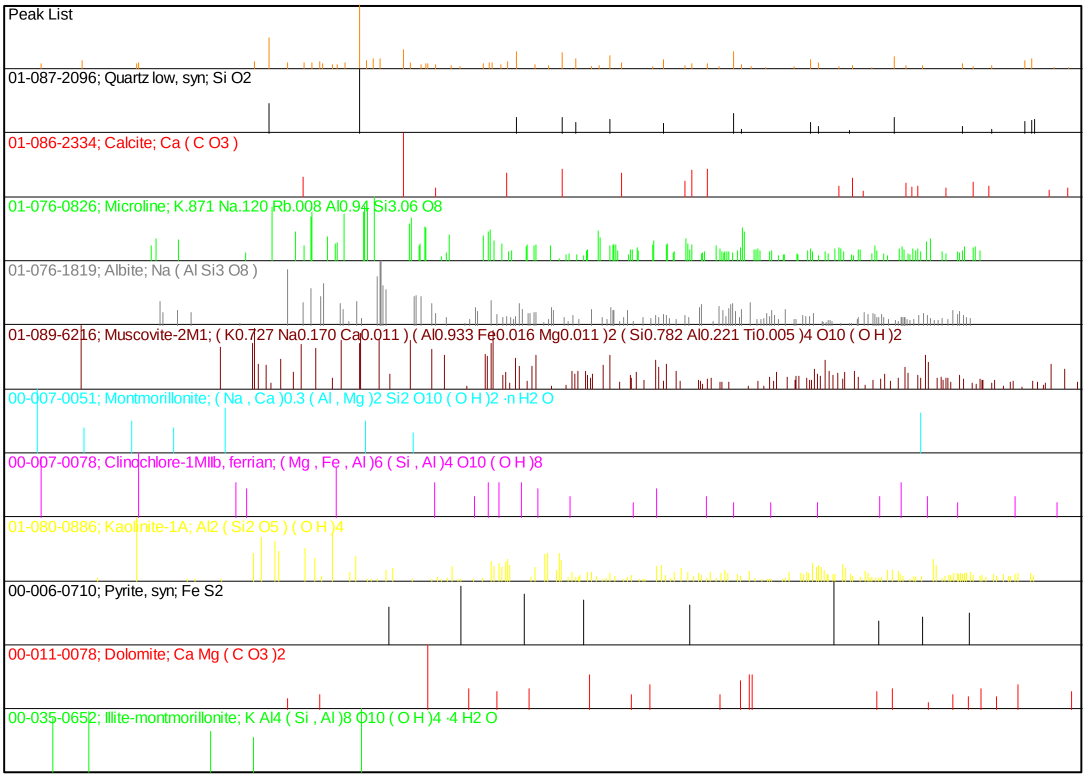


# Thetford, BH11, 7.00-7.45 m, <2 µm fraction

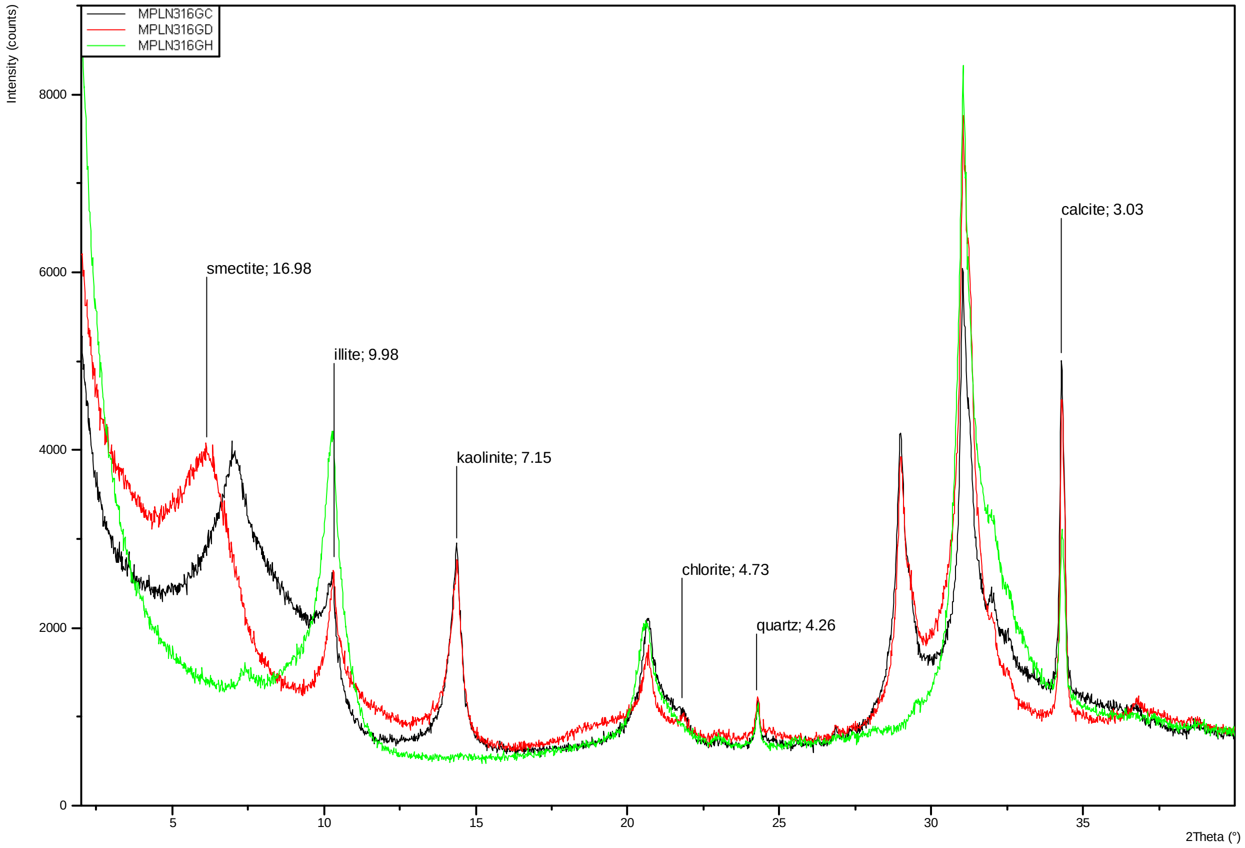


# Norfolk, Happisburgh 1, Bulk1, whole-rock

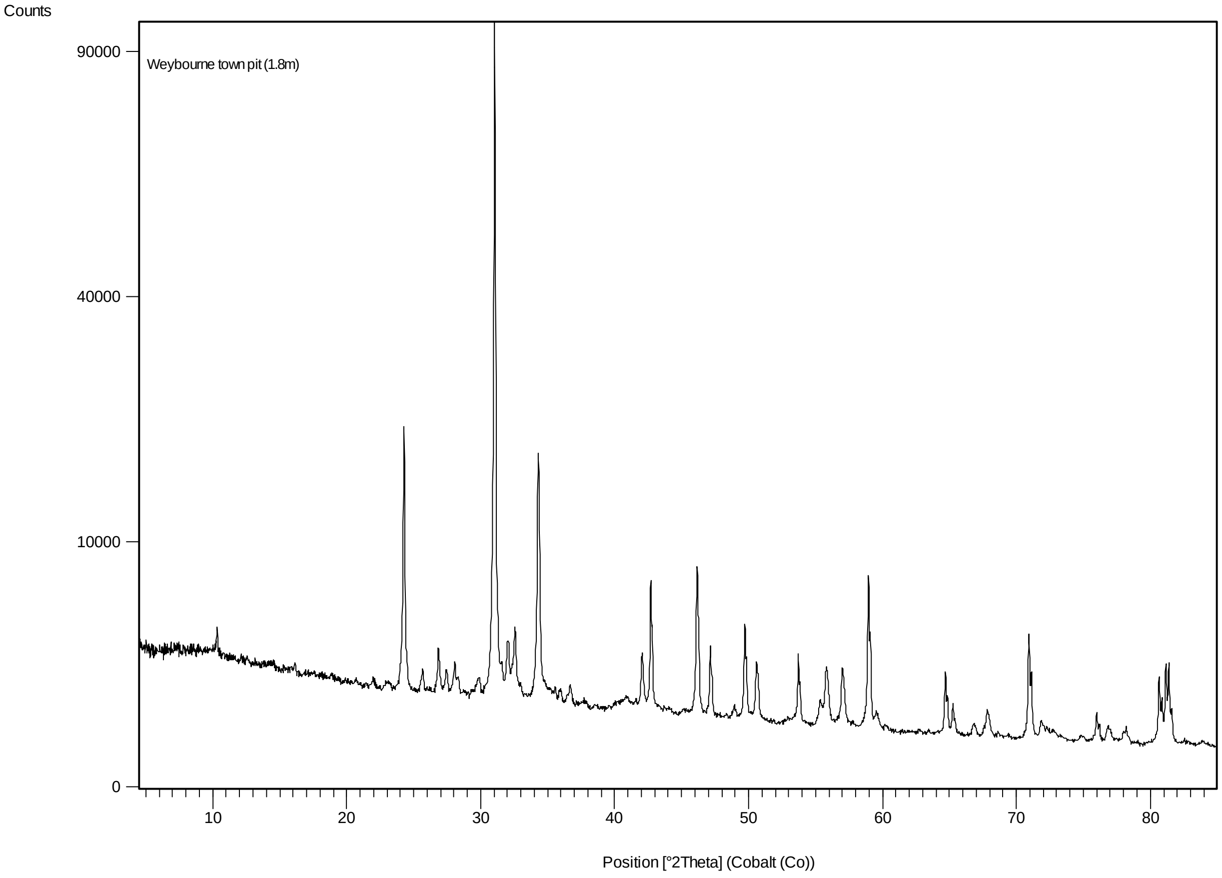


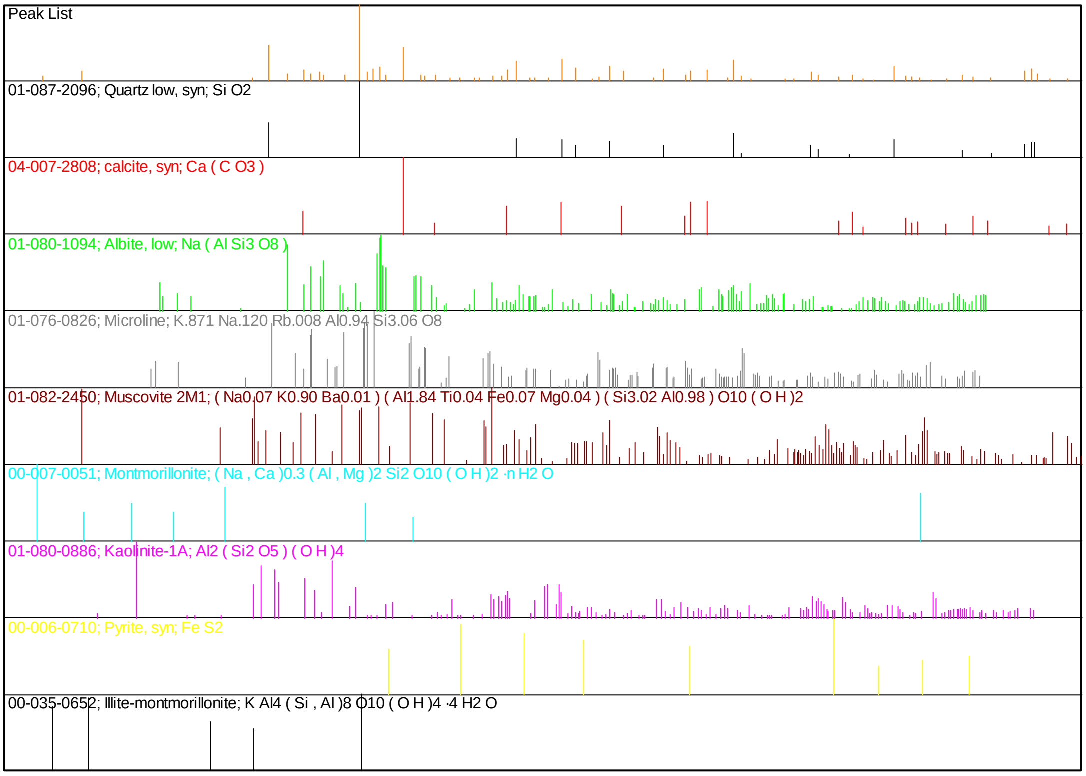


# Norfolk, Happisburgh 1, Bulk1, <2 µm fraction

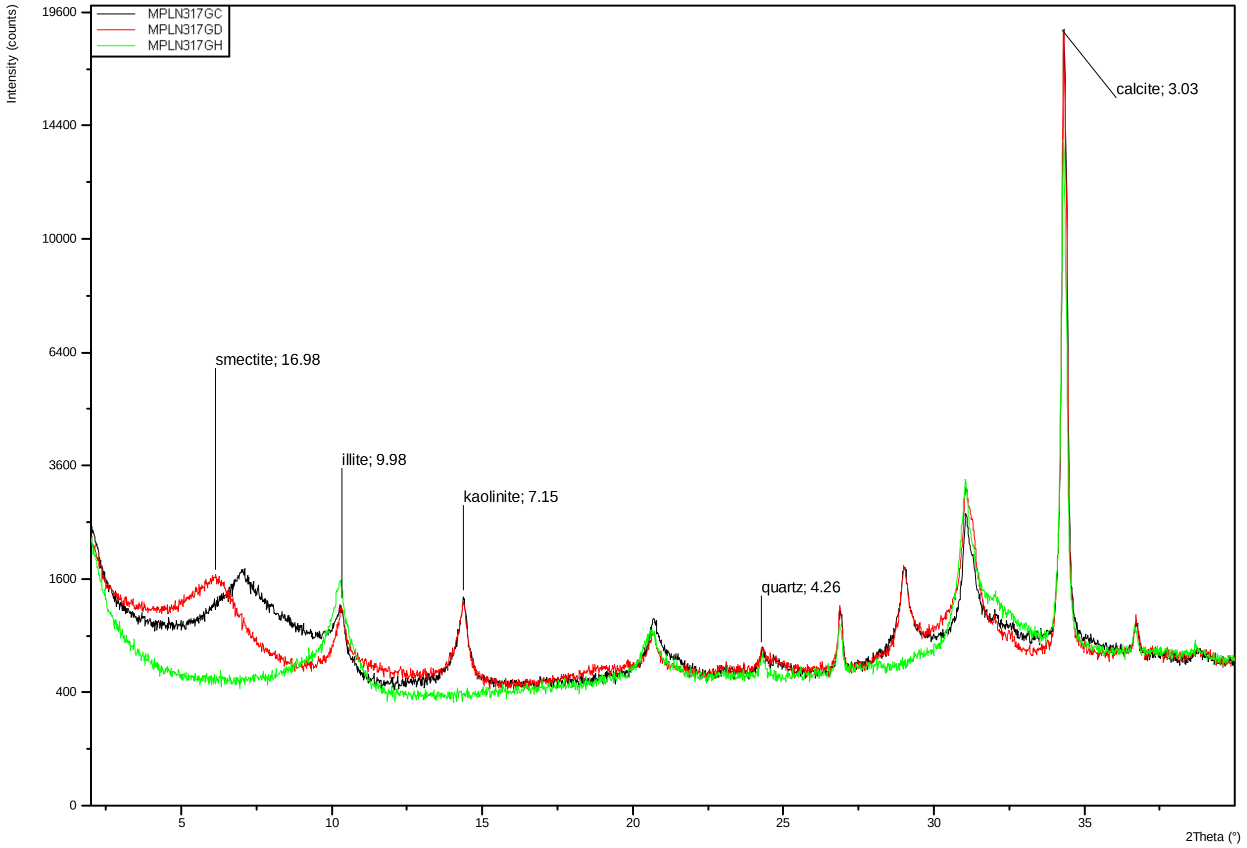


# Norfolk, Weybourne town pit 1, 1.8 m, whole-rock

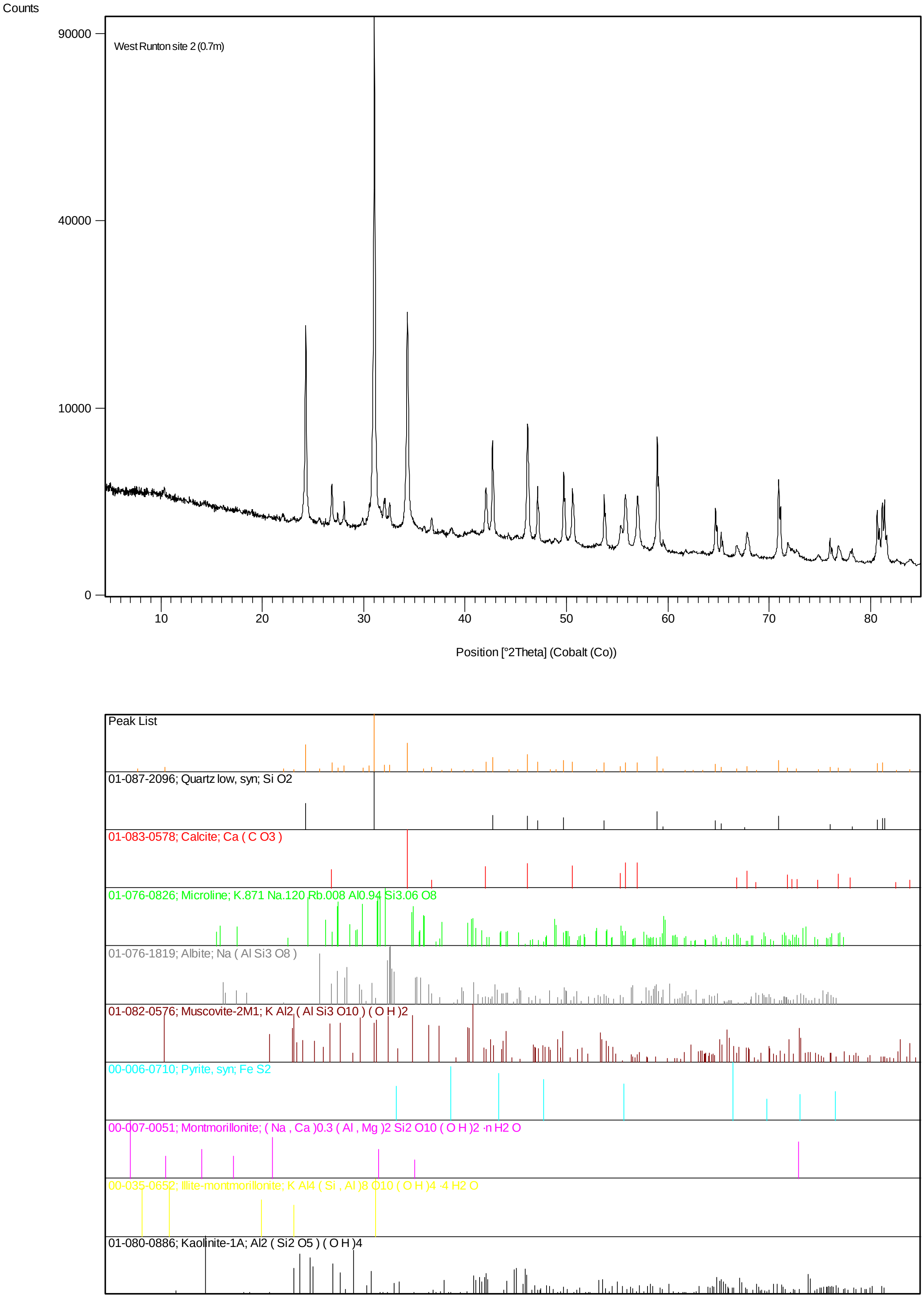




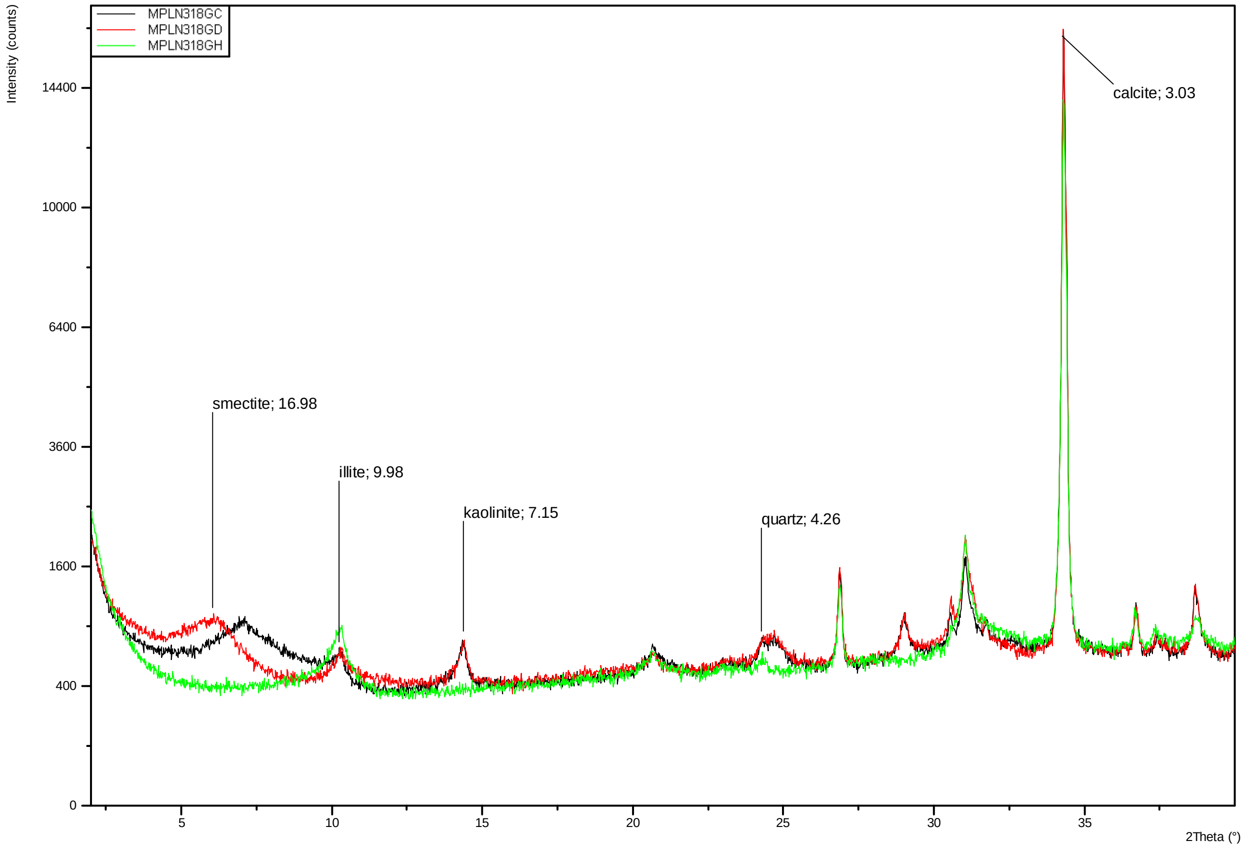
## Norfolk, Weybourne town pit 1, 1.8 m, <2 µm fraction



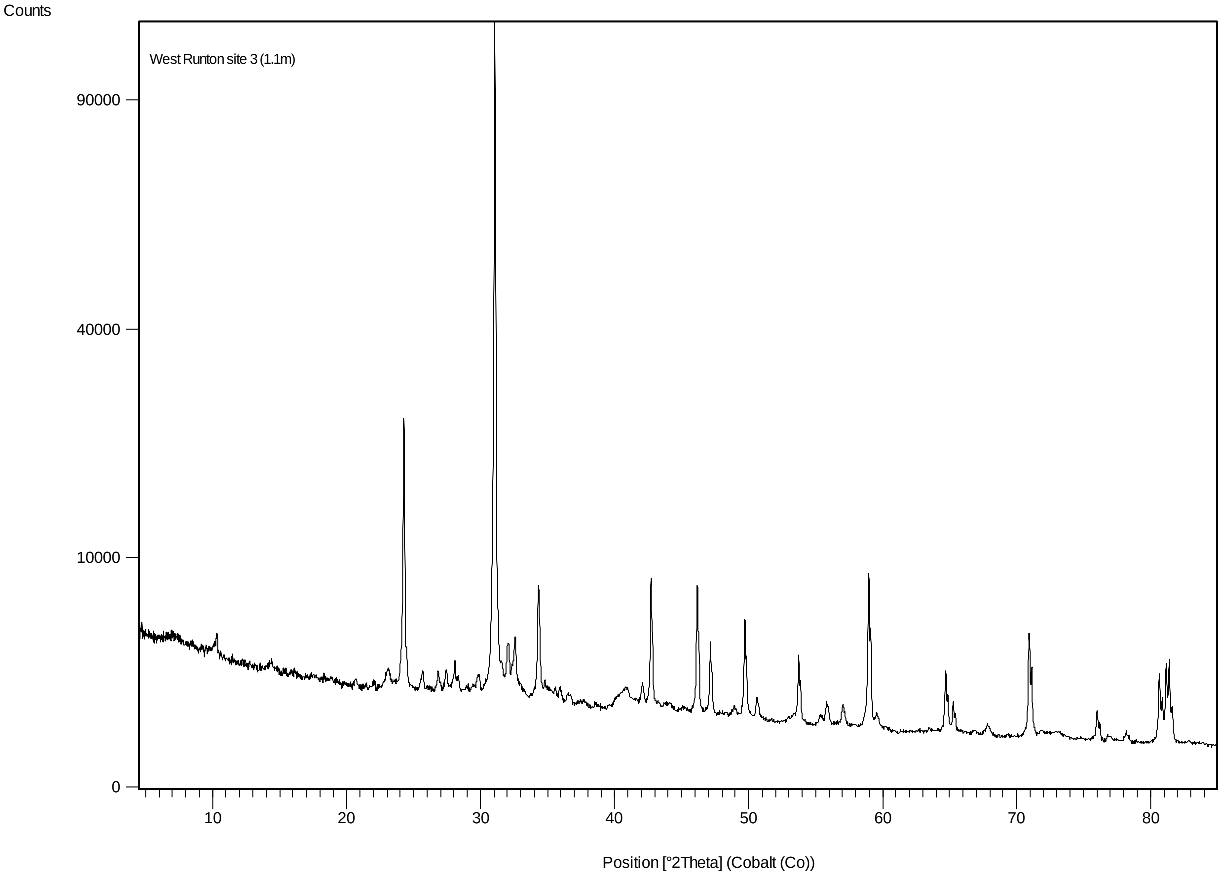
# Norfolk, West Runton site 2, 0.7 m, whole-rock

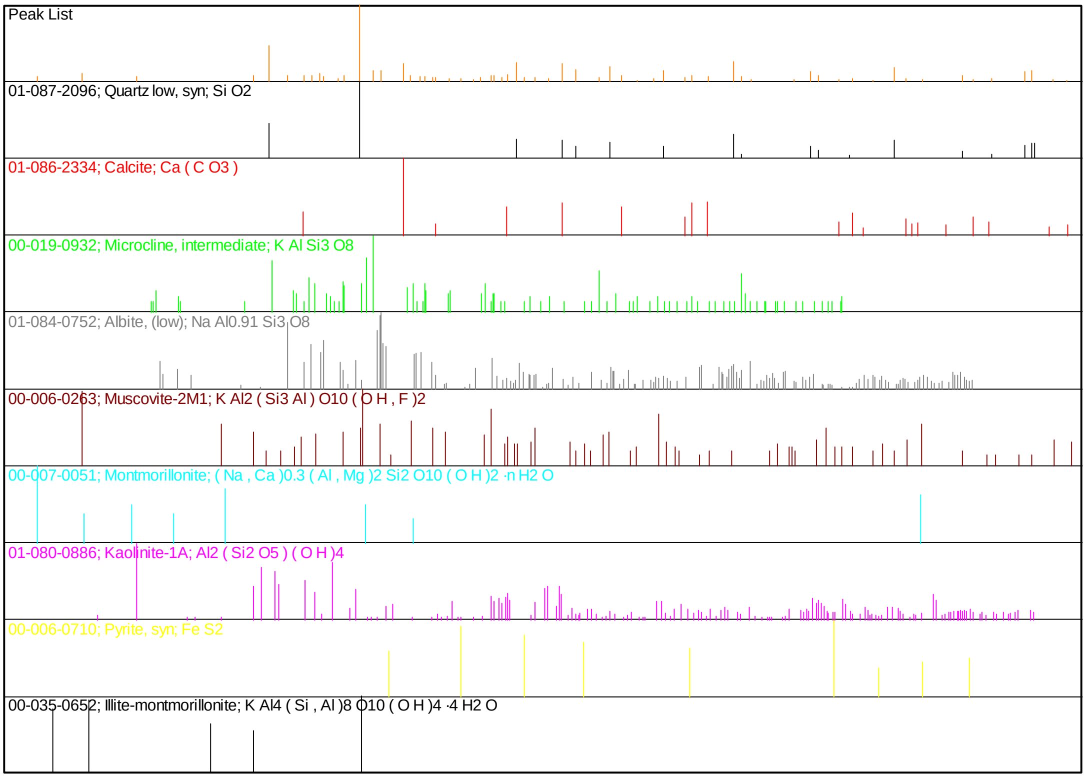


## Norfolk, West Runton site 2, 0.7 m, <2 µm fraction

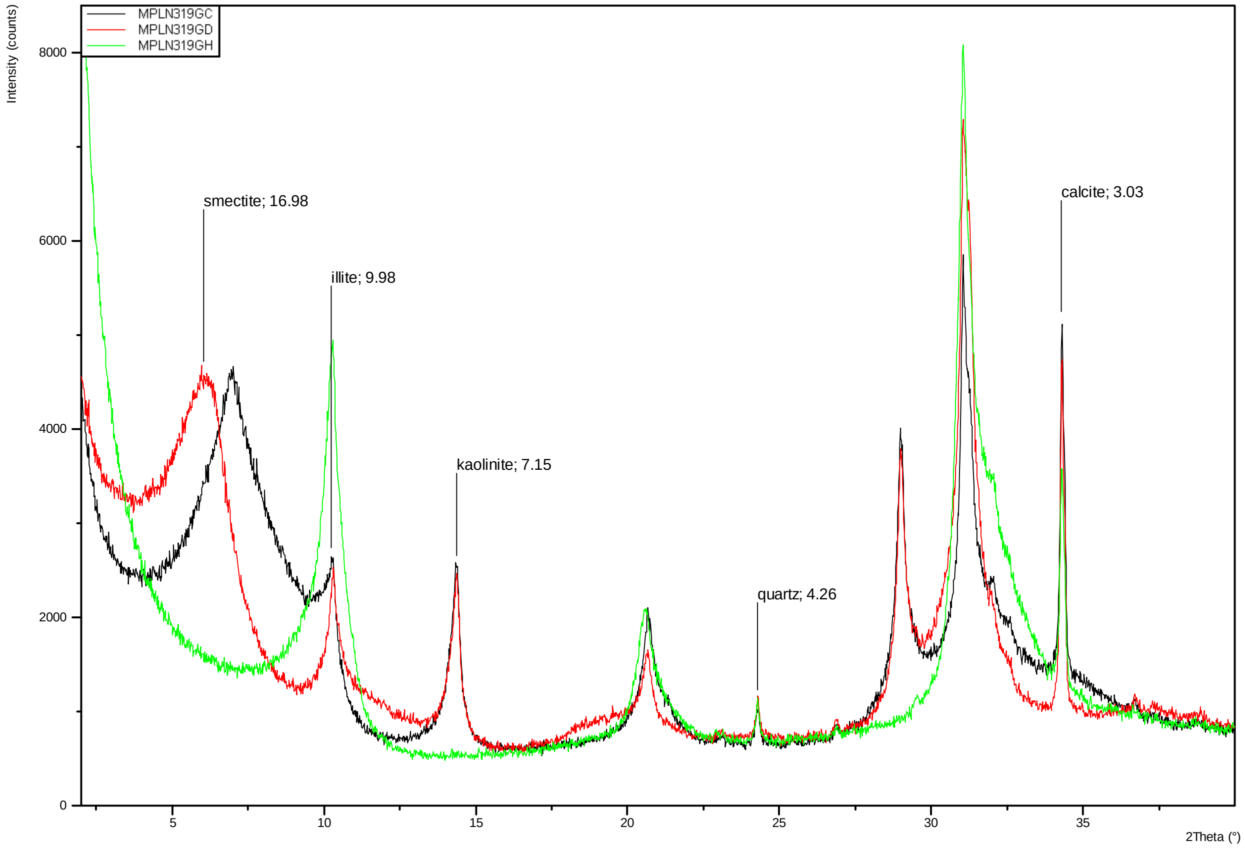


# Norfolk, West Runton site 3, 1.1 m, whole-rock

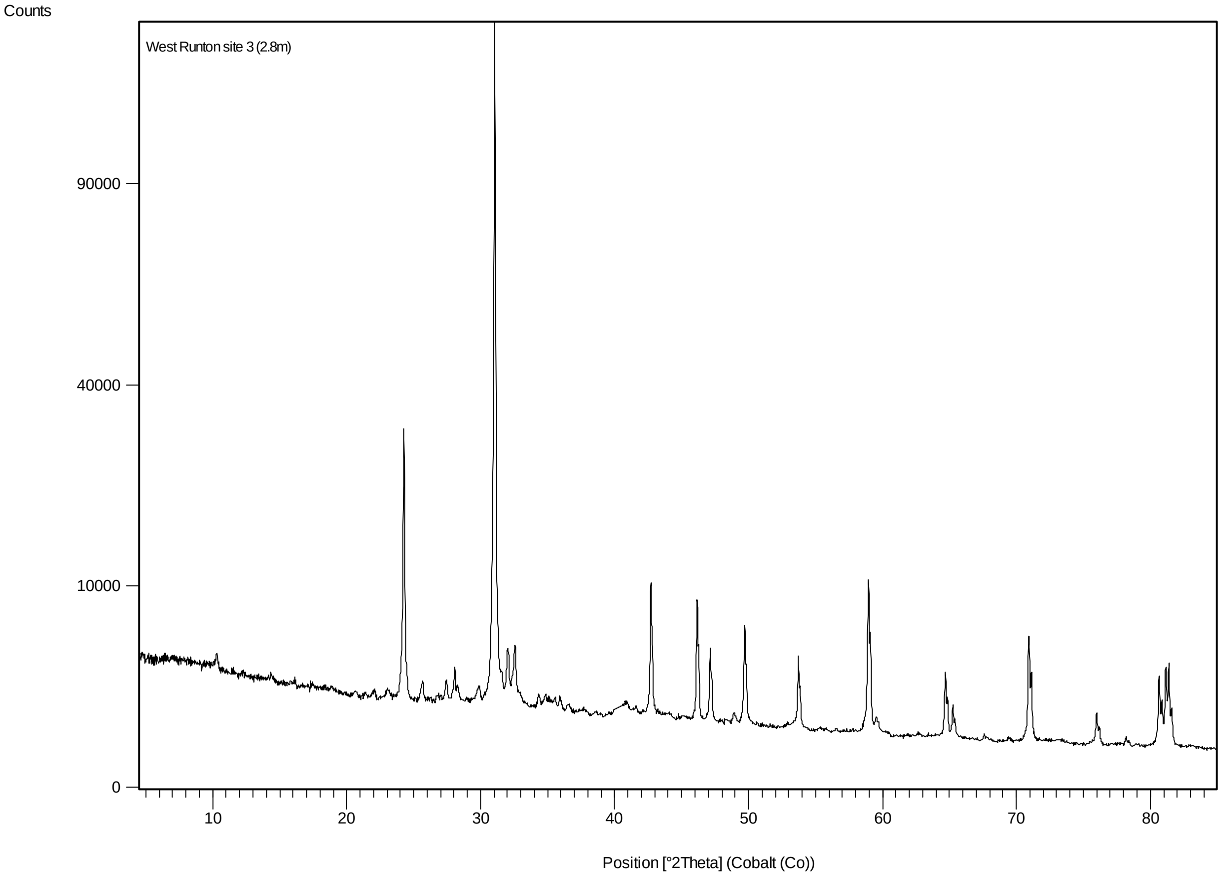


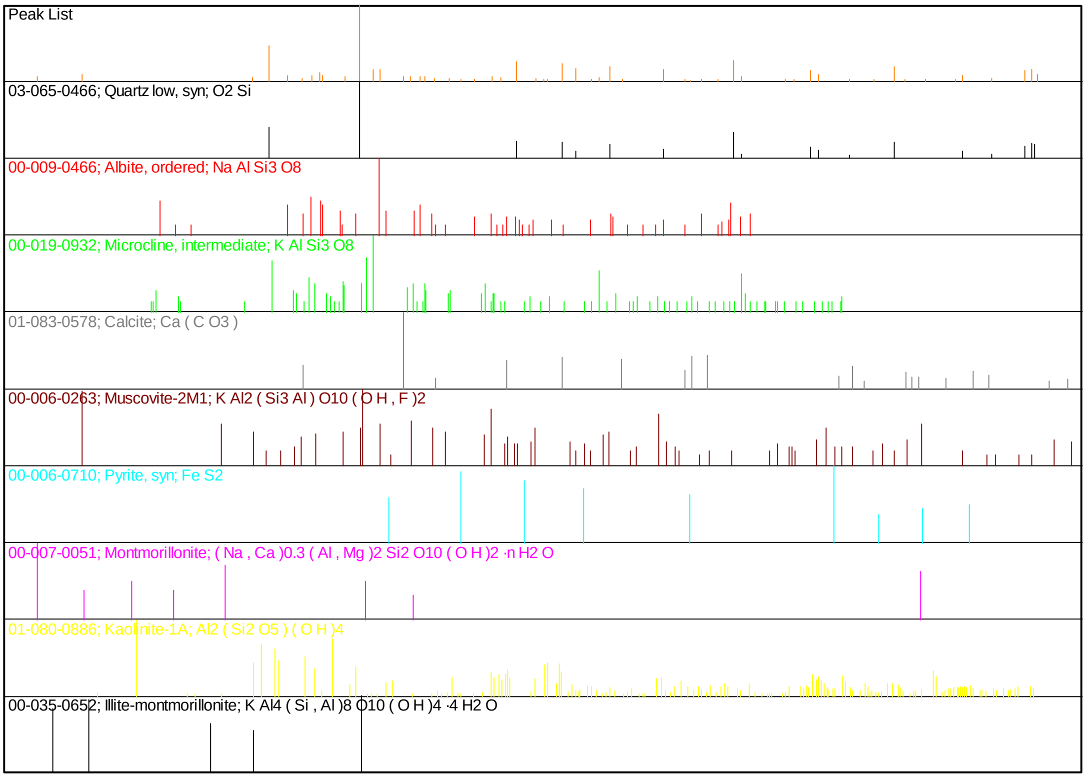


# Norfolk, West Runton site 3, 1.1 m, <2 µm fraction



# Norfolk, West Runton site 3, 2.8 m, whole-rock





## Norfolk, West Runton site 3, 2.8 m, <2 µm fraction