The West Lothian Oil-Shale Formation: Results of a sedimentological study

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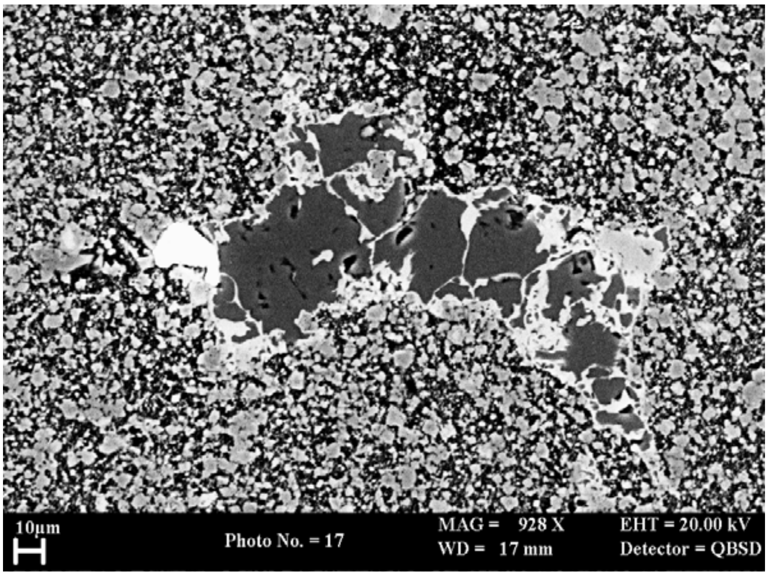

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Summary

This report summarises the results of a brief sedimentological study of the West Lothian Oil-Shale Formation. The work was carried out for the Midland Valley Integrated Surveys project (E1265S71 Task 01). The West Lothian Oil-Shale Formation is a Dinantian (Asbian-Brigantian) siliciclastic succession, up to 1120 m in thickness, that crops out locally in the West Lothian area of the Midland Valley of Scotland. The main aim of this study was to describe and interpret the sedimentology of a number of exposures of the West Lothian Oil-Shale Formation. The work comprised two phases of fieldwork (January-February 2002 and March 2003), Backscattered Scanning Electron Microscope (BSEM) analysis of 5 thin sections by A Milodowski, and reporting.

Ten sedimentary facies and one igneous facies were recognised from this study, representing predominantly lacustrine depositional conditions. Periods of lake development and expansion were marked by deposition of lacustrine limestones and desiccation-cracked mudstones, with lake maxima marked by the deposition of oil-shale facies. The lakes were generally filled by fine-grained siliciclastic (muddy) sediment, although minor channel systems fed coarser sediment (sand) into the lakes via small prograding delta systems.

BSEM analysis of material from borehole and outcrop were used to provide detailed analyses of the calcareous mudstone (‘marl’) facies and to address the issue of whether there was an igneous component to this facies. It was found that the igneous component was quite significant and predominantly comprises degraded and altered glass shards. These represent tuffaceous material ejected from nearby basic volcanic vents and reworked and incorporated into the lake sediments. Diagenetic alteration of this volcanic material typically resulted in the formation of calcite and other minerals including zeolite, chlorite and illite. It was found that not all the material selected were calcareous mudstones and that the diagenetic alteration to calcite gave other lithologies (e.g. mudstones and tuffaceous mudstones) an appreciable calcareous component, which led to their mis-identification in hand specimen.

1 Introduction

This report summarises the results of a brief sedimentological study of the West Lothian Oil-Shale Formation, carried out for the Midland Valley Integrated Surveys project (E1265S71 Task 01). The West Lothian Oil-Shale Formation is a Dinantian (Asbian-Brigantian) siliciclastic succession that crops out locally in the West Lothian area of the Midland Valley of Scotland. The base of the formation is taken at the base of the Humbie Shell Bed and the top is taken at the base of the Hurlet Limestone (Browne et al., 1999) (Figure 1). It is divided into a lower Calders Member and an upper Hopetoun Member, with the boundary between the two taken at the base of the Burdiehouse Limestone (Figure 1). The formation is laterally equivalent to the Aberlady Formation to the east and to the Bathgate Hills and Burntisland volcanic formations to the west and north (Browne et al., 1999) (Figure 1).

The West Lothian Oil-Shale Formation is up to 1120 m in thickness (Chisholm et al., 1989) and accumulated in a series of small north-south trending, tectonically and volcanically active sedimentary basins (George, 1958). During deposition of most of the formation the area was believed to have been land-locked to the north, south and south-west, although there was a link to a marine environment to the east (Loftus and Greensmith, 1988). When totally cut-off from the sea a series of standing bodies of water formed, referred to as Lake Cadell (Greensmith, 1968) (Figure 2). This led to a complex interaction between freshwater lacustrine, transitional lagoonal and fully marine conditions (Loftus, 1985).

The formation predominantly comprises an interbedded succession of oil-shales, ostracod-rich limestones, sideritic claystones and siltstones, fluvio-deltaic sandstones and calcareous mudstones, known in older literature as marls (Figure 3). The siliciclastic sediments form approximately 90% of the succession by thickness and are believed to be have been derived from both local sources and also from distant environments to the north-east (Greensmith, 1962, 1966; Loftus and Greensmith, 1988). At times, deposition of oil-shale, limestone, tuff, marl, dolomitic limestone (cementstone), ironstone, coal, palaeosol and marine mudstone also occur, but they are more sporadic in occurrence and constitute the remaining 10% of the formation. Oil-shale only forms about 3% of the succession and consist of highly kerogenous sediments ranging in thickness from a few centimetres to 5 m in a single seam. There are 11 workable oil-shale horizons that are widely distributed and can be traced in West Lothian, Midlothian and to a lesser extent Fife (Loftus and Greensmith, 1988) (Figure 3).

There has been much previous research carried out on the West Lothian Oil-Shale Formation and this short study cannot hope to capture the range and diversity of this previous work. Previous studies include George (1958), Tulloch and Walton (1958), Love (1959), Greensmith (1961, 1962, 1966, 1968), Moore (1968), Loftus (1985), Bateson and Haszeldine (1986), Fleet (1986), Loftus and Greensmith (1988), Parnell (1988), Chisholm et al. (1989), Raymond and Murchison (1991a, b, 1992) and Guirdham (1998).

The main aim of this short study was to describe and interpret the sedimentology of current exposures of the West Lothian Oil-Shale Formation (WLOSF). It is stressed that this report does not represent a comprehensive study of the formation. Fieldwork was carried out in January-February 2002 and March 2003. A number of previous publications suggested that the calcareous mudstone (‘marls’) within the WLOSF have a volcanic component (Cadell, 1901; Tulloch and Walton, 1958). Hence samples of this facies were collected and SEM analysis undertaken in February 2005 by A Milodowski in order to address this issue.

2 Methodology

Fieldwork consisted of recording detailed descriptions of outcrops accompanied by sedimentary logging of representative parts of the succession and the collection of palaeocurrent data where possible (See Appendix 1 for sedimentological logs). Photomontages were constructed for a number of outcrop sections in order to illustrate the nature of the sedimentary structures and architectural elements. The localities chosen for study were provided by other team members from the Midland Valley Integrated Surveys Project and these are illustrated in Figure 4. The main exposures occur along streams in the West Lothian area (e.g. Mid Calder and Midhope Burn) and tend to be generally poor and discontinuous. Coastal exposures occur at South Queensferry (Figure 4). In addition to these, strata from the Gullane Formation (Strathclyde Group) were also briefly examined at Craigleith. Whilst they are not from the West Lothian Oil-Shale Formation, they also represent an opportunity to examine the oil-shale lithology.

Grain and clast size estimations were made semi-quantitatively by use of a x10 hand lens and comparative grain-size charts, using the scheme of Udden and Wentworth (see Pettijohn et al., 1987). The grain size divisions for the main rock types are illustrated in Figure 5. It can be seen that mud can be divided into clay and silt. It follows that the lithified product, mudstone, can be divided into claystone and siltstone. Hence the term mudstone, where used in this report, is not synonymous with claystone but is used as a general term for all mud-grade sedimentary rock (i.e. claystone, silty claystone and fine- and coarse-grained siltstone). These are distinguished where it was felt to be important to subdivide them further.

Following Collinson and Thompson (1989, p.111), the term conglomerate has been applied in this report to any rock containing at least 30% of clasts greater than 2 mm in size. Features of importance worth noting within the conglomerates include the presence and type of bedding, nature of bedding contacts, bed thickness, composition of the clasts, grain size of clasts and matrix, the degree of roundness, sorting, clast or matrix support, development and thickness of stratification, clast maximum particle size, clast long axis orientation, presence of imbrication and the presence and type of grading.

Grain-shape terminology follows Powers (1953) and sorting terminology is from Folk (1974). Bed and lamina thickness are described in accordance with Campbell (1967) and Ingram (1954). Bedform terminology follows the guidelines described in Ashley (1990).

As well as fieldwork, 5 samples of calcareous mudstone (‘marl’) were collected for detailed analysis (Table 1). Five polished thin sections of this facies were prepared for more detailed and higher resolution petrographic analysis by backscattered scanning electron microscopy (BSEM), using qualitative/semi-quantitative energy-dispersive X-ray microanalysis (EDXA) to aid mineral identification (Table 1).

BSEM analysis was performed on a LEO 435VP digital scanning electron microscope (SEM). The SEM instrument was fitted with a KE Developments four-element solid-state backscattered electron detector and an Oxford Instruments ISIS 300 digital energy-dispersive X-ray microanalysis (EDXA) system, allowing simultaneous observation of samples under SEM cathodo luminescence (CL), BSEM and EDXA. The EDXA system used a thin-window Si-Li solid-state X-ray detector and is capable of detecting elements from atomic number 4 (B) to atomic number 92 (U). Comparative BSEM-EDXA observations were made under 20 kV electron beam accelerating voltage and probe currents between 200-750 pA.

BSEM image brightness is related to the average atomic number and density of the phase being observed (Goldstein et al., 1981). Phases composed of high atomic number elements (e.g. heavy metal phases) appear bright, whilst low atomic number phases (e.g. quartz, organic compounds) appear dark. Therefore, BSEM can be used to observe and image the distribution of different phases on the basis of their chemical composition. Semi-quantitative microchemical information, obtained by observation of EDXA spectra recorded simultaneously during BSEM, was used to aid the identification of phases imaged under BSEM. Experience shows that for most elements (sodium to uranium) the EDXA detection limits are probably of the order of 0.5 weight percent under the analytical conditions employed (100 second livetime count times and deadtime of 30%).

3 Sedimentary Facies

During a field-based examination of the formation, ten sedimentary facies could be identified, dependant on a number of distinctive features, of which lithology, sedimentary structures, colour and faunal/floral content were the most important. In addition an igneous facies could also be identified. These facies are listed below:

1. Laminated Black Mudstone (Oil-Shale)
2. Laminated Grey Lacustrine Mudstone
3. Desiccation-Cracked Lacustrine Mudstone
4. Rooted Mudstone (Palaeosol)
5. Calcareous Lacustrine Mudstone
6. Lacustrine Limestone
7. Lake Shoreline Sandstone
8. Deltaic Siltstone and Sandstone
9. Channel10. Current Rippled Sheet Sandstone
11. Tuff

These facies are described and interpreted in the following sections.

3.1 LAMINATED BLACK MUDSTONE (OIL-SHALE)

3.1.1 Description

In hand specimen this facies comprises well laminated, dark grey to black claystone and silty claystone. The facies becomes extremely fissile when weathered, giving the rock a ‘paper shale’ appearance (Figure 6). The facies has a ‘ferruginous’ brown colour in places where weathered and the rubbing together of fresh surfaces reveals a brown streak. Siderite lenses and beds (up to 0.1 m thick) also occur in places and rare cherty-siliceous lenses have been recorded. The facies is highly variable in thickness, from a few centimetres to many metres, with 1-5 m being fairly typical. Within this facies beds can be defined that are less well laminated and have a more massive, ‘cannel coal’ type of appearance. Near the old workings of the Broxburn Shales along Linhouse Water, Mid Calder [NT 07918 67089], there are contorted beds of oil-shale. In detail these appear to contain numerous small thrusts and curved bedding/lamination planes. These appear to be compressionally generated deformational features.

Fauna and flora are common within this facies and include plant stems, fish fragments and ostracods (Figure 7). In places, e.g. [NT 06857 78212] individual beds contain lamina strewn with abundant ostracods (Figure 8). Four samples were examined for Ostracoda in order to provide biostratigraphical and palaeoenvironmental information (Wilkinson, 2005). The ostracods generally indicate a mid Asbian age, with some samples from Midhope Burn indicating a mid to late Asbian age. The samples commonly contain Bairiid ostracods (Wilkinson, 2005).

Thin section analysis by Parnell (1988) reveal that the oil-shales comprise a variable mixture of i) discrete yellow algal bodies, ii) laminar algal matter, iii) plant remains, iv) phosphatic fish remains and coprolites, v) shell fragments, particularly ostracods, vi) detrital siliciclastic grains, vii) early diagenetic carbonate minerals, and viii) authigenic minerals such as pyrite. Analysis of the facies indicates a total organic content (TOC) varying from 4.25-28.52 % wt (Parnell, 1988), although values up to 35% are quoted (Loftus and Greensmith, 1988). At this level of TOC, oil-shales can be regarded as organic-rich mudstones (ORM) and represent the immature equivalents of oil-prone petroleum source rocks (Fleet 1986).

3.1.2 Interpretation

Moore (1968) has interpreted the oil-shale facies as the deposits of stratified lakes in which algae, fungal/bacterial organic matter were preserved in the hypolimnion (i.e. the cold, deeper part of a thermally stratified lake). The recent detailed work of Parnell (1988) interprets the oil-shales as algal oozes that formed in shallow, stratified lakes characterised by anaerobic bottom conditions. These are thought to be ephemeral lakes, with maximum organic productivity during permanent or highstand lacustrine phases. Reduced lake levels were marked by the progradation of other facies across the top of the oil-shale, restricting oil-shale formation to only the most central parts of the lakes (Parnell 1988). Maximum organic productivity tends to occur where oxygen is deficient or depleted (Fleet 1986). Such conditions are most commonly present when degradation of organic matter creates an oxygen demand that exceeds supply (Fleet, 1986). Oxygen supply is created by circulating waters and is at a minimum where permanent stratification of the water body occurs (Fleet, 1986). Hence oxygen deficient conditions and oil-shale formation is favoured under stratified water conditions.

Whilst most interpretations favour a non-marine, lacustrine origin for this facies, Bairiid ostracods, described from the oil-shales, are considered to be indicative of marine conditions (Wilkinson, 2005). The palaeogeography envisaged for the WLOSF by Loftus and Greensmith (1988) suggests that at times there were barriers and lagoons separating a large lake (Lake Cadell) to the west from a marine connection to the south-east (Loftus and Greensmith, 1988). Hence Wilkinson (pers comm. 2005) suggests that this marine connection was present and marginal marine conditions were responsible for deposition of these ostracod-bearing oil-shales. Black shales described by Parnell (1988) from South Queensferry and Randerston contain both a marine fauna and the *Botryococcus* type bodies. These algal bodies do not occur in marine environments so the conclusion was reached that these beds must represent a marginal environment with restricted access to the sea. This is believed to occur intermittently rather than represent a permanent feature of this depositional setting. Analysis of biomarkers (C_{27}, C_{28} and C_{29} steranes) from oil-shales exposed in Mid Calder-Linhouse Water [NT 079 671] show that there was a consistent terrestrial input into the oil-shales (Bateson and Haszeldine, 1986).

3.2 LAMINATED GREY LACUSTRINE MUDSTONE

3.2.1 Description

This facies comprises claystone, silty claystone and fine siltstone, typically varying from a few centimetres to a metre or so in thickness (Figure 9). Lithologies are light to medium grey in colour, rarely dark grey, greyish brown or black and generally finely (mm scale) laminated. Calcareous laminae and nodules occur in places, typically forming layers of discontinuous lenses or nodules (Figure 10). These are more common where the facies occurs closely interbedded with the lacustrine limestone facies. Ironstone beds and nodules are also present as a minor component and rare cherty-siliceous lenses have been recorded. This facies is generally lacking in fauna and flora, although rare ostracods, fish fragments, burrows and plant fragments, including *Calamites* sp., have been recorded in places (Figure 11). This facies is generally interbedded with other facies, particularly laminated black mudstone (oil-shale), desiccation-cracked lacustrine mudstone and calcareous lacustrine mudstone and is gradational with them. A good example of this facies is exposed at South Queensferry [NT 1419 7854]. Here dark grey to black fissile mudstones from the upper part of the Pumpherston Shales are present (Figure 3). They are described as containing fish remains, ostracods, *Naiadites*, *Euestheria*, plant remains and coprolites (Maddox and Andrews, 1987).

3.2.2 Interpretation

Low energy depositional conditions are indicated for this facies on the basis of the fine grain size, the horizontally laminated sediment and the presence of ostracods. These features are characteristic of deposition in a lacustrine environment (Picard and High, 1972). The fine grain-size suggests that the sediment was transported into the lakes in suspension before settling onto the lake floor. Reducing conditions are indicated by the dark colour of the facies and by the preservation of organic material. The presence of plant material within the lacustrine facies is related to the influx of plant material washed in from nearby environments. Whilst the lack of rooting and features indicative of subaerial exposure (e.g. desiccation cracks) suggests deposition within a permanent, standing body of water, the transitional nature of this facies, as shown by the interbedding with desiccation-cracked mudstones, suggests an environment that fluctuated from perennial to ephemeral at times. Shallow water conditions are therefore quite likely. Parnell (1988) envisages a lateral change towards the lake margins where limestone, calcareous mudstone, laminated lacustrine muds and desiccation-cracked mudstone accumulated.

Stable isotope ($\delta^{13}C$) data from carbonate nodules measured from other Dinantian mudstones in south-west Scotland indicate that the nodular limestones formed from bacterial oxidation of organic matter during sulphate reduction and methanogenesis (Gluyas, 1986). It is thought likely that the nodules and lenses of carbonate present in this facies were formed in a similar manner. They probably occurred at horizons enriched in organic matter (Gluyas, 1986). Siderite forms diagenetically under conditions of low Eh, low salinity and reduced sulphide content. This can be achieved either in freshwater conditions or during diagenesis in marine sediments below the depth of sea-water sulphate diffusion and reduction (Curtis and Spears, 1968; Spears, 1987). Organic matter forms the principal source of carbon, dissolved in highly acidic peat waters. Siderite is precipitated when acidic waters containing iron migrate into less acidic but strongly reducing sediment.

3.3 DESICCATION-CRACKED LACUSTRINE MUDSTONE

3.3.1 Description

This facies comprises grey to dark grey, greenish grey and grey brown claystone, silty claystone and fine siltstone in beds up to about 1 m in thickness. This facies is typically transitional with other facies, particularly the laminated black mudstone (oil-shale) and laminated grey lacustrine mudstones. Calcareous lenses, nodules and thin beds are noticeable, sometimes forming as much as 35% of the succession, although these proportions are uncommon. Rare rippled sandy lenses are present and ironstone beds and nodules also occur as a minor component. Typically this facies is massive, although some remnant fine (mm scale) lamination can occur. The main characteristic of this facies, apart from the grain size, is the presence of common desiccation cracks (Figure 12). These are typically infilled with coarser silty material and lamina surfaces are often strewn with claystone clasts, forming intraclast breccia and conglomerate. When weathered this gives the rock an irregular, disrupted rubbly weathered appearance. This facies is generally lacking in fauna and flora, although rare ostracods and plant fragments have been recorded in places.

3.3.2 Interpretation

The facies is similar lithologically to the laminated grey lacustrine mudstone facies, and quiet water, lacustrine conditions are indicated. However, the presence of desiccation cracks indicates that this environment was characterised by periodic emergence and hence were probably ephemeral features. This allowed the sediment to dry and crack, forming a surface of broken mud clasts. Subsequent wetting of the substrate during lake level rise led to minor reworking of the sediment surface to form the intraclast breccias and conglomerates.

3.4 ROOTED MUDSTONE (PALAEOSOL)

3.4.1 Description

The facies is uncommon, but is characterised by the presence of visible roots and rhizocretions (Figure 13). Typically the facies comprises grey or brown silty claystone and siltstone, in units from 0.3-2.3 m thick, rarely rooting has been observed in sandstones. In places the facies has a bleached or mottled appearance (Figure 14) and extensive pedoturbation often results in a rubbly, destratified to massive appearance (Figure 15). Rooting, whilst noticeable, is generally not abundant. Ironstone nodules can also occur; these are sometimes concentrated towards the base of the facies. Desiccation cracks have also been noted in some examples of the facies (Figure 14). Where present they give the facies a vertical fabric, with crack infills of darker or coarser material.

3.4.2 Interpretation

The presence of rooting indicates soil formation, and hence this facies is interpreted as a palaeosol. Palaeosols are produced by the modification of other depositional facies by pedogenic processes. The three main pedogenic processes responsible for soil formation are weathering, the incorporation of organic matter into the soil, and the movement of material within the soil. The filling and abandonment of many of the depositional environments (e.g. lakes) is commonly associated with a shallowing of water depth with the result that plants colonise and vegetate the tops of these facies.

The grey palaeosols are a function of the presence of iron in a reduced, ferrous form (Fe^{2+}) and the preservation of organic material and indicates formation in almost permanently waterlogged, anaerobic reducing conditions. Brunification is a term to describe the development of brown colour in a soil, formed in part by the presence of hydrated iron oxides, which formed due to particle oxidation. The presence of desiccation cracks suggests better-drained conditions and indicates that, at times, these palaeosols dried out. Temporary hiatuses in sedimentation were marked by plant colonisation and rooting. However, the relatively minor amounts of rooting associated with this facies indicates fairly regular sedimentation on an actively aggrading sediment surface which reduced the amount of pedogenic modification. The type of palaeosol recognised here appears to have similar characteristics to those described as brunified alluvial soils (Duchaufour, 1982, p185-188). Alluvial soils are immature and are commonly developed on modern day alluvial and deltaic plains close to rivers where they are often flooded (Duchaufour, 1982; Besly and Fielding, 1989). They represent plant colonisation of an actively aggrading sediment surface and can be poorly drained (grey alluvial soil) or freely draining (brunified alluvial soil) (Duchaufour, 1982).

3.5 CALCAREOUS LACUSTRINE MUDSTONE

3.5.1 Description

Calcareous mudstone from the WLOSF has been previously described as marls (see Tulloch and Walton, 1958). In their glossary they describe a marl as 'Geologically a calcareous clay, but often used loosely to describe unbedded non-limy clays, particularly red clays or mudstones' They further describe the facies from the WLOSF as '. greenish marls and mudstones which may have been derived from volcanic debris …..' Tulloch and Walton, 1958, p.10). The definition of a marl elsewhere is generally quite vague, although it is generally described as a calcareous mudrock. An internet search found one specific definition: "a rock consisting of 35% to 65% clay and 35% to 65% lime mud" (see http://paleodb.org/public/tips/lithtips.html). However, the BGS Rock Classification Scheme does not recognise (or even mention) marl and hence it is recommended that its use should be discontinued (see Hallsworth and Knox, 1999). Using the BGS scheme, all siliciclastic argillaceous sedimentary rocks should be classified as silicate-mudstone, with the terms silicate-claystone and silicate-siltstone used for mudstone with >50% clay and <50% clay respectively. Where there is an appreciable carbonate component a qualifier such as 'calcareous', 'calcitic' or 'dolomitic' can be used.

Calcareous lacustrine mudstone facies occurs interbedded gradationally with other lacustrine facies. The facies is generally less than 0.2 m in thickness and comprises claystone or silty claystone. They are typically grey to dark grey or brown and massive to weakly laminated (Figs 16 and 17). They typically weather to a lighter colour than surrounding mudstones. Desiccation cracks have been noted in this facies and rare ostracods also occur. The mud grade component of the rock makes detailed field-based assessment difficult and the recognition of the facies is based on the fact that it comprises a mudstone with a recognisable calcareous component. However, detailed BSEM analysis suggests that the lithologies characterised as marls actually comprise a variety of different lithologies, and that the calcareous component originates in different ways (see section 4).

In thin section the more calcareous lithologies comprise laminated dolomicrite and dolomitic mudstone. Other calcareous mudstones are more muddy (argillaceous), with carbonate being present as later (secondary) replacement of lithic clasts.

3.5.2 Interpretation

The fine grain size and the intimate association between this facies and the other siliciclastic lacustrine facies indicates a similar origin, i.e. as a lake deposit. The pure calcareous mudstones represent deposition of carbonate in a lacustrine setting. However, in other so-called calcareous mudstones, the carbonate can be regarded as largely secondary, originating by replacement of ferromagnesian minerals. This is discussed in detail in Section 4. Parnell (1988) suggests that the mudstone and calcareous mudstone ('marls') represents the deposits of lake margin mudflats and carbonate mudflats formed as the lake dried out. This is in keeping with the evidence for desiccation cracks in the calcareous mudstones.

3.6 LACUSTRINE LIMESTONE

3.6.1 Description

This facies shows a large degree of variability, from massive limestones to sandy limestone, muddy limestone and well-developed microbial limestones. Typically the limestone is dolomitic, well bedded and is variable in thickness, up to about 1 m or so. More commonly it forms interbedded successions of dolomite and desiccation cracked mudstone. The Burdiehouse Limestone has been documented as comprising up to 6 beds, from 0.16 to 0.2 m thick (Loftus and Greensmith, 1988). The limestone typically occurs interbedded with the desiccation cracked mudstone facies and limestone commonly infills desiccation cracks. Some limestone beds also contain desiccation cracks (Figure 18) and some bedding surfaces can be strewn with clasts of limestone and mudstone, probably the result of desiccation processes.

Limestone of this facies is typically fine-grained, grey-brown, with a yellow brown honeycomb weathering pattern. Some of the limestone is fairly pure (i.e. lacking in siliciclastic material), other beds have a noticeable sandy or muddy component. They contain a varied fauna, including fish fragments, ostracods, *Naiadites*, *Lingula* and *Schizodus* (Figure 19). The sandy limestone beds are fine- to medium-grained, grey-brown, wavy laminated with current ripple cross-lamination. Rib and furrow cross-lamination measured from a number of examples appear to be directed towards the south-west and west. One instance of a sandy limestone has common visible quartz grains and probable ostracods, and possible ooliths or coated grains. In places abundant ooliths or coated grains up to 0.5 mm across occur. These are spherical to elliptical in form, some with concentric internal lamination.

This facies also includes microbial limestone. At South Queensferry this facies is well exposed on the foreshore, where it comprises a c.1 m thick limestone bed [NT 14175 78542] (Maddox and Andrews, 1987). This forms part of the Calders Member of the formation. In its lower part the limestone is interbedded with black fissile mudstone from the Pumpherston Shales and it is overlain by white, bleached, possibly wave ripple cross-laminated, fine-grained sandstone of the Port Neuk Sandstone (Figure 3). The limestone is dolomitic, grey (buff-yellow weathering) and contains well-developed very thinly to thick lamination (Figure 20). One bed of limestone shows evidence for syn-sedimentary collapse (foundering) into the underlying black mudstone. In its upper part, the limestone shows well developed laminated bulbous microbial domal forms, with a macrostructure (terminology of Grey, 1989) of up to 0.10 to 0.15 m wide and 0.04 m high (Figure 21). Other literature describes these features as laterally linked hemispheroidal stromatolites (e.g. see Maddox and Andrews, 1987). Cameron et al. (1998) also record oncolites and stromatolites from the WLOSF and a number of microbial limestones were found at outcrop by this study. These are typically very fine- to fine-grained, with well developed 'stromatolitic' lamination. One example, 0.2 m thick, has slightly enterolithic, mounded lamination in a very fine-grained limestone.

3.6.2 Interpretation

Loftus (1985) proposes that these carbonates were deposited in a closed system of freshwater lakes fed by runoff in a wet tropical climate. These lakes were broad, with gently sloping margins characterised by abundant vegetation. The faunas are predominantly non marine, although certain faunas (e.g. *Lingula*, *Schizodus*) suggest that, at times, marginal marine conditions may have formed. Carbonate sediment is known to increase in thickness towards the basin margin, indicating a probable shoreline position for the accumulation of thick carbonates (Loftus and Greensmith, 1988; Parnell, 1988). The Burdiehouse Limestone was suggested to have been deposited as a calcite or aragonite micrite on the lake floor during precipitation events (Loftus, 1984). High rates of evaporation are envisaged in this closed lake setting, thus encouraging early dolomitisation of the calcmicrite. The source of carbonate may be linked to leaching of basaltic terrains, which are present locally (Walkden et al., 1994).

The thickly laminated to very thinly bedded limestone and hemispheroidal stromatolites are interpreted as microbial structures formed in a lacustrine setting. The lamination reflects either seasonal growth, periodic sedimentation or both (Riding, 2000). Maddox and Andrews (1987) discuss the depositional environment of the microbial limestone facies and propose a shallow stromatolitic mudflat setting, varying from sublittoral to supralittoral. The bulbous microbial domal forms are characteristic features of stromatolitic bioherms and biostromes from sublittoral to littoral settings in lakes (Dean and Fouch, 1983; Casanova, 1986; Cohen et al., 1997; Guirdham et al., 2003). The best modern analogues are stromatolites forming in the modern East African Rift Valley lakes (see Casanova, 1986; Cohen et al., 1997). Here microbial carbonates represent littoral and sublittoral zone stromatolites growing in up to 20 m of water (Casanova, 1986; Cohen et al., 1997). These microbial carbonates formed in volcanically isolated shallow sub-basins where lavas and tuffs provided stable substrates for stromatolite nucleation, and their weathering may have enhanced Ca^{2+} ion activity to promote carbonate precipitation (Casanova, 1986; Cohen et al., 1997; Guirdham et al., 2003).

3.7 LAKE SHORELINE SANDSTONE

3.7.1 Description

This facies has only been recognised in the succession exposed at South Queensferry [NT 1418 7854], where beds of sandstone (equivalent to the basal part of the Port Neuk Sandstone) occur immediately above the microbial limestone described in Section 3.6. Sandstone beds are fine-grained, light grey to white and appear to be extremely siliceous and well cemented. They occur in beds from 0.1-0.5 m in thickness, with sharp bases and sharp to upward-fining tops. Wave ripple cross-lamination is ubiquitous; these are generally symmetrical with some minor asymmetry (Figure 22). Ripple crests trend east-west. Synaeresis cracks also occur on bed bases.

3.7.2 Interpretation

The presence of wave ripple cross-lamination suggests a shallow water origin for this facies. As these sandstones overlie the littoral to sublittoral zone microbial carbonates it is suggested that they represent a lake margin facies, where reworking along the shoreline has produced a siliceous, clean sandstone in which most of the fines have been removed. More saline conditions are indicated by the presence of synaeresis cracks which are formed subaqueously by the loss of sediment pore water due to salinity changes. An increase in salinity in the lake may be the result of either the influx of more saline water or due to high rates of evaporation.

3.8 DELTAIC SILTSTONE AND SANDSTONE

3.8.1 Description

Only two examples of this facies were identified by this study. The best is exposed along the Linhouse Water at Mid Calder [NT 07902 67156]. It comprises an upwards-coarsening succession, 6.5 m thick, with siltstone passing upwards into silty sandstone and sandstone (Figure 23). The base of the succession is not exposed but the first lithology recorded is grey siltstone. This passes upwards into 1 m of laminated grey siltstone, with up to 20 % current ripple cross-laminated sandy laminae and beds of sandstone up to 0.22 m in thickness. The beds of sandstone are grey to off-white or grey-brown, ferruginous fine- and fine- to medium-grained, often silty, with common plant debris, some mica, and burrowed in places. Current ripple cross-lamination is directed towards the north-west.

Within the lower siltstone-dominated lithologies of this facies studied at Calder Wood a number of small-scale faults are present (Figure 23). Faults are typically less than 0.5 m in length and dip towards the north-west at angles of up to 78°, they are listric and show evidence for thickened packages of strata in the hangingwall of faults and the tops show planar truncation across both the hangingwall and the footwall sections (Figure 24).

The upper part of this facies at Calder Wood comprises fine- to medium-grained flat laminated sandstone, approximately 2 m in thickness. It is truncated at the top by an erosively based sandstone, with over 1 m of relief on the basal erosion surface (Figure 25). Lining the base of this sandstone is a discontinuous layer of mudstone clasts (clast size typically up to 2x2 cm). The sandstone is medium- to coarse-grained and poorly sorted. The top of this facies is not exposed, but at least 5 m has been recorded.

The upper part of this facies is also exposed further upstream along Linhouse Water at [307820 666880]. Here the facies comprises 1.5 m of fine- to medium-grained sandstone with primary current lineation, oriented east-west. Interbedded sandstone beds with current ripple cross-lamination indicate a flow directed towards the west. Numerous ironstone nodules occur in the upper part of the sandstone. This is overlain gradationally by 0.4 m of rooted light grey silty claystone.

3.8.2 Interpretation

This facies is interpreted as the deposits of a fluvially dominated delta that resulted from the progradation of a fluvial system into a lake. Similar facies were identified by Maddox (1986) and Maddox and Andrews (1987) in their study of oil-shale facies at Burntisland, Fife. The facies can be subdivided into separate components on the basis of sand-silt content and bounding surfaces; these are prodelta, distal bar, mouth bar and distributary channel. The lowermost siltstone-dominated part represents a lacustrine deposit, in which mud settled from suspension. The prodelta marks the first input of sand into the lake and is marked by siltstones with thin sandy laminae. The distal bar marks the switch from predominantly silt- to sand-dominated deposition and the mouth bar represents the area of shoaling in the proximal parts of a lacustrine delta system. The mouth bar comprises the 2 m thick flat-laminated sandstone. Above this is an erosively based channel. This probably represents the feeder distributary channel which prograded across the top of the mouth bar.

The faults present in the prodelta-distal bar environment in the example from Linhouse Water [NT 07902 67156] are probably syn-sedimentary in origin. The dip direction of the faults is to the north-west and is suggested to have formed by collapse of the unstable delta front in this direction. The dip direction of the faults matches those of current ripple cross-lamination and suggests that, at least in this example, sediment was fed into the lake from the south-east.

Whilst the shape of the facies as a whole is likely to be lobate, feeder distributary channels probably form laterally restricted, ribbon-like sands. In the other example of the sand-dominated upper part of this facies along Linhouse Water [NT 07820 66880], a channel is absent and a rooted silty claystone is present, representing a palaeosol which developed on top. This indicates infilling of the lake and development of near-emergent conditions.

3.9 CHANNEL

3.9.1 Description

This facies can be divided into 2 main types:

- Major stacked channel
- Minor channel

Major stacked channels are relatively uncommon but examples are present at Craigleith [NT 22708 74741] and along Linhouse Water, Calder Wood [NT 07471 66087]. These sandbodies are characterised by thick successions of sandstone (more than 10 m or so in thickness) which can be subdivided by prominent internal erosion surfaces spaced every few metres or so vertically (Figure 26). Beds of pebbly conglomerate generally overlie these erosion surfaces, forming lags (Figure 26). The sandbodies typically comprise medium to coarse-grained sandstones, with some poorly sorted pebbly sandstones. Clasts are typically granule to medium pebble in size, rarely up to large pebble; the largest one recorded was 3.4 x 1.5 cm. Pebbles predominantly comprise intraformational material, typically mudstone clasts, but also ironstone. Extraformational clasts include quartzite, purple clasts of probable volcanic material and chert. Also present in minor amounts are fine-grained sandstone and siltstone. Bedsets vary from 0.05-0.65 m thickness, with sharp or erosive contacts common. The main sedimentary structures are unidirectional sets of cross-bedding, some of which have low angle foresets and can be flaggy. Sets are up to 0.2 m thick. No reliable palaeocurrent data was collected for this facies. There are also rare sets of cross-lamination; sandstone beds can also be massive. Plant debris is also fairly common within this facies, concentrated on cross-bedding foresets.

Minor channels tend to be more common, with examples noted along Midhope Burn at [NT 07523 78599] and [NT 07833 78923] and along Linhouse Water in Calder Wood at [NT 07504 66030] and [NT 07466 66067]. They form upwards-fining, erosively based units typically from 2-7 m in thickness. In one example the base is quite irregular, with a stepped form marking the basal erosion surface (Figure 27). They are typically heterolithic and comprise interbedded sandstone, silty sandstone, siltstone and silty claystone. Sandstone tends to be more common in the lower part of the facies; it typically forms up to about 60% of the succession. The sandstone typically comprises brown fine- to medium- and medium-grained sandstone. Plant debris is common, as is current ripple cross-lamination. Siltstone is grey and micaceous, weakly laminated to massive. Silty claystone tends to be dominant at the top of the facies and is grey, with some ironstone nodules. Cut-and-fill structures have been recorded from these channels (Figure 28). Large-scale, low-angle inclined bedding tends to be a common feature within this facies. This bedding can be wedge-shaped or concave in form and can occupy the full thickness of the facies (Figure 29). Accurate palaeocurrent data is hard to obtain for this facies but the channel in Midhope Burn [NT 07523 78599] has current ripple cross-lamination directed towards the west. However, this is only one example and it should be stressed that this is not necessarily representative for other channel facies within the formation. A detailed analysis of the clast types or the heavy mineral suites might provide further information of the provenance of this facies.

3.9.2 Interpretation

The prominent basal erosion surface associated with this facies type indicates that flow was channelised. The internal erosion surfaces present within the stacked, major channels represent repeated episodes of channel scouring. This could be a linked to periods of in-channel erosion related to flooding or barform or bedform migration, to erosion by multi-channel systems or to later channels migrating back across the same general area and eroding into their former deposits. The thick, stacked channel sandbodies are likely to have produced channel belts many kilometres in width and represent major channels. At times of high flow most of these river channels would have been submerged and it is suggested that they would have been of low sinuosity. At times, fairly high energy discharge was likely, capable of transporting a range of sediment grain sizes, including pebbly material. The sedimentary structures are all indicative of unidirectional, current-generated bedforms, formed from turbulent flows. Downstream-migrating sandy bedforms form the dominant fill of the channels. Unfortunately the absence of any palaeocurrent data for this facies precludes any analysis of the source of the clastic sediment.

The heterolithically-filled minor channels show good evidence for discharge variations and must have carried a combination of bedload and suspended sediment load. Fully turbulent unidirectional currents are indicated but, compared to the major stacked channels, they were probably significantly lower in energy as indicated by the dominance of finer grain sizes and smaller scale sedimentary structures. The greater amount of mud reflects alternations in flow conditions in the channels, with high energy conditions responsible for transportation and deposition of sand and low energy conditions leading to the draping of bedforms and barforms. The low-angle inclined bedding is interpreted to have formed from incremental deposition on inclined point bar surfaces, formed within meandering channel systems, with the muds representing low energy drapes on the point bar surfaces.

3.10 CURRENT-RIPPLED SHEET SANDSTONE

3.10.1 Description

This facies is not particularly common within the formation but comprises laterally continuous, thin sheet sandstone beds. Similar facies are well-exposed in the underlying Gullane Formation (Figure 30). In the WLOSF they are typically light grey to grey-brown, fine- to medium-grained sandstone. Beds have sharp bases and tops although they can sometimes show upwards-fining (Figure 31). They are generally between 0.1-0.2 m in thickness, although they range from 0.02-0.5 m. Unidirectional sedimentary structures are common, typically comprising current ripple cross-lamination, occasional small sets of cross-bedding and some climbing ripples with low angle of climb. Current ripple rib and furrow measured from a sheet sandstone was directed towards the west. Some disrupted slightly convoluted lamination can also occur, probably related to minor dewatering. Rare simple vertical burrows have also been recorded in this facies.

3.10.2 Interpretation

The sheet-like, laterally continuous form of these beds indicates deposition from unconfined, turbulent, tractional flows. Waning flows are indicated by the fining-upward profiles, with cross-lamination produced by unidirectional currents. Deposition from weak or distal flows is indicated by the thickness of beds. Deposition is interpreted to have been into standing bodies of water, as suggested by the planar nature of bed bases. This facies is likely to represent the deposits of either crevasse splay or sheetflood events.

3.11 TUFF

3.11.1 Description

This facies comprises a minor component within the WLOSF. Where recorded, e.g. at [NT 05749 77920], it comprises hard, dark grey, silt-grade tuff, in beds up to 3 m in thickness. The tuff contains common sedimentary clasts, and grey silty claystone, very fine-grained sandstone, grey marl and black mudstone clasts can typically be recognised (Figure 32). Clasts are generally rounded and flattened with occasional mica flakes. Some of the sandstone clasts have irregular, ragged forms. Pyrite also forms a visible, but very minor component.

3.11.2 Interpretation

Tuffs are well known within the WLOSF and have been interpreted as penecontemporaneous fall-out of pyroclastic fragments ejected from vents or fissures, which were then reworked under water (Durant, 1994; Guirdham et al., 2003). The dominant pyroclastic fragment size is typically of ash grade (<2 mm). The presence of common sedimentary clasts clearly indicates reworking of a sedimentary succession, i.e. incorporating country rock into the tuff. The irregular, ragged nature to some of the sandstone clasts suggests that they may have been semi-consolidated in form. It is suggested that these tuffs represent ash-fall and ash-flow deposits. Glass or devitrified glass tends to be an important constituent of these types of pyroclastic rocks.

4 BSEM Analysis

Previous work has suggested that the calcareous mudstone ('marl') facies may have been derived from volcanic debris (Tulloch and Walton, 1958). There has been little petrological work carried out on the calcareous mudstones previously (see Teall, 1925) so an SEM study was carried out to characterise the mineralogy and texture of the calcareous mudstones and to determine whether there is a volcanic detrital component. Five polished thin sections of calcareous mudstone facies were prepared for more detailed and higher resolution petrographic analysis by BSEM, using qualitative/semi-quantitative EDXA to aid mineral identification (Table 1).

4.1 SAMPLE DESCRIPTIONS

In the following section the main characteristics of each of the thin sections samples is described. A rock name is also assigned to each sample, using the BGS Dictionary Rock_Name_Type. In some instances the BGS Dictionary is not as comprehensive as the BGS rock classification scheme for sedimentary rocks (Hallsworth and Knox, 1999) so a further, more refined rock name can be assigned to the sample, listed under the heading Rock Type.

4.1.1 Sample NJN94: Midhope Burn [NT 05721 77856]

Rock Type: Calcareous-claystone or tuffaceous calcareous claystone
BGS_Dic_Rock_Name_Type: Tuffaceous-mudstone (TFAMST) or Mudstone, calcareous (CAMDST)
Hand specimen description: Weakly calcareous, light greenish grey to greenish grey claystone. The rock lacks any primary lamination.
Thin section description: The main features of this sample are illustrated in Figures 33 to 37. This sample predominantly comprises illite, forming a fine-grained matrix in which crystals are typically less than 2 μm across (i.e. clay grade). Within this matrix reworked, amorphous organic material is common and chlorite and kaolinite is present in small proportions. The sample lacks any discernable lamination. There also appears to be a mottled fabric which may represent the results of burrowing.

Randomly scattered within the matrix are numerous remnants of former lithic clasts and ghosted outlines of clasts, forming up to 30 % of the lithology in places. Clasts are highly variable in size, ranging from 50-400 μm in diameter (very fine sand to medium sand grains). Some of the lithic clasts appear to be rounded. These clasts have largely been replaced by chlorite and calcite, with chlorite typically forming the rims, although intergrown calcite and chlorite occurs in some examples. The presence of calcite gives the sample a weakly calcareous nature. Numerous small crystals (2-10 µm in size) of authigenic titanium oxide (TiO_2), probably anatase or brookite, occur, forming a weakly developed halo in the matrix around some of the altered clasts. One clast has a euhedral orthorhombic form, composed of chlorite, calcite and some minor TiO_2. Plagioclase and sodium feldspar crystals are also present. There is no quartz present in the sample. A shear fabric occurs in one part of the thin section.

The rounding shown by some clasts and the large amount of organic material indicates a water-lain sedimentary origin for this rock. Although now an illite-rich claystone, it shows evidence for extensive alteration and replacement of large lithic clasts and was clearly originally much coarser-grained than at present. The calcareous nature of the lithology is a secondary alteration product rather than an original depositional feature. Calcite precipitation was probably enhanced locally by leaching of Ca^{2+} from the lithic clasts. Chlorite is a well known alteration product, especially of volcanic rock fragments, and the calcite-chlorite-TiO_2 mineralogy that comprises most clasts probably occurs due to replacement of an original igneous-derived ferromagnesian mineral or ferromagnesian rock. The plagioclase and sodium feldspars are detrital but are also suggested to derive from an igneous source. The euhedral orthorhombic form to one clast suggests that it was once a single crystal, possibly a pyroxene, although the original mineralogy is not preserved. The lithic fragments are interpreted to be mostly of volcanic origin. The general absence of quartz indicates that the igneous material is likely to be a basic source.

4.1.2 Sample NJN95: Midhope Burn [NT 05721 77856]

Rock Type: Calcareous-mudstone or tuffaceous calcareous mudstone
BGS_Dic_Rock_Name_Type: Tuffaceous-mudstone (TFAMST)
Hand specimen description: In hand specimen this sample comprises a light greenish grey to greenish brown perhaps tuffaceous calcareous silty claystone. It is highly weathered, with some dark features, probably grains and lighter blebs or pellet like clasts.
Thin section description: The main features of this sample are illustrated in Figures 38 to 39. This sample is similar to NJN94, with ghost fabrics of former clasts, now replaced by calcite and chlorite. In thin section the sample is clearly clay dominated, with the matrix predominantly comprising illite, with minor calcite and chlorite. Organic material is present but in much lower proportions than in NJN94. There are numerous argillised lithic clasts; these form 20-30 % of this lithology. Some bioturbation also seems to be present. Clasts are highly irregular in form and are highly variable in size, ranging from 100-1000 µm (very fine to coarse sand size). Clasts are replaced by calcite, illite and (Mg rich) chlorite, with calcite typically forming a fringe around a chlorite core. These are best described as lithic fragments and it can be speculated that they are volcanic in origin. They were probably originally ferromagnesian minerals or ferromagnesian-rich rocks. Around some clasts is a darker zone that is more illite rich. These are interpreted to form by the weathering of the clasts which liberates the more mobile element potassium, which combines to form illite.

This sample has many features in common with Sample NJN94 and is predominantly a mudstone characterised by a well-developed secondary, altered fabric. However, as with NJN94, clasts are dominated by a mineralogy of calcite and chlorite, indicating the probable replacement of original basic igneous material. Hence it is interpreted that this rock formed by the incorporation of tuffaceous material into the water-lain sediment and can best be described as a tuffaceous mudstone.

4.1.3 Sample NJN96: Midhope Burn [NT 05761 77917]

Rock Type: Calcareous-mudstone or ?volcaniclastic calcareous mudstone
BGS_Dic_Rock_Name_Type: Tuffaceous-mudstone (TFAMST)
Hand specimen description: In hand specimen it comprises a greenish grey massive, very weakly calcareous silty claystone.
Thin section description: The main features of this sample are illustrated in Figures 40 to 41. In thin section it is clearly a mudrock, comprising largely chlorite and illite. It has been extensively homogenised

and altered, although a number of ghost of lithic clasts are visible. These comprise largely chlorite, with some calcite. The matrix comprises largely illite, with some chlorite and minor calcite. The sample lacks dolomite.

This lithology can be classified as a mudstone. Using the same argument proposed for Sample NJN94, the clasts are thought to be replacements of probable basic volcanic material. The low number of clasts indicates that it is more suitable to describe this rock as a volcaniclastic calcareous mudstone.

4.1.4 Sample NJN97 [NT 06194 71497]

Uphall BH. R03 (NT07SE 1086), 20.9 m

Rock Type: Dolomite-mudstone
BGS_Dic_Rock_Name_Type: Dolomite-mudstone (DLMDST)
Hand specimen description: This sample comprises a laminated, light brown calcareous silty claystone. The lamination is represented by subtle grain size changes from claystone to silty claystone, possibly up to siltstone. Some 1-2 mm thick black (oil-shale) mudstone interlaminae occur and soft sediment deformation of the laminae occurs in places. Lighter brown colour-mottled patches occur, some small faults present, possible mineral-filled (probably calcite) fractures. A sharp-based, graded is also present at the top of the sample.
Thin section description: The main features of this sample are illustrated in figures 42-46. In thin section under the BSEM the rock can be seen to be well-laminated, with laminae comprising alternations of dolomitic mudstone and dolomite. Laminae are on the order of 20-100 µm thick (0.02-0.1 mm). Rare exotic clasts are present in the sample, measuring up to 200 x 400 µm (0.2-0.4 mm, i.e. medium sand sized grains) across. There are rare circular features interpreted as replaced clasts, from 30 to 50 µm across, filled with quartz, dolomite or calcite. One clay-rich clast is partly replaced by barite.

Dolomitic mudstone laminae form 60-70 % of the rock, comprising finely interspersed dolomite crystals, clay minerals and amorphous organic material. The clay largely comprises illite and chlorite and these can occur as thin clay-rich layers. There are some possible diffuse clay-filled burrow structures. Very fine organic material occurs, forming nebulous, rounded shapes. They typically occur scattered in discrete laminae. These are probably fragments of plant cellular material.

Alternating with the dolomitic mudstone are dolomite laminae. The dolomite is very fine-grained, typically <5 µm particle size, with diffuse margins. This represents recrystallised micrite, possibly after dolomicrite. Some of the dolomite, which is patchy and irregular in shape, replaces the clay matrix. The dolomite is recrystallised but individual grains have late ankerite (calcium iron magnesium manganese carbonate) rims. There are some non-ferroan calcite laminae and discontinuous stringers, although these are not common. Calcite often occurs around organic material. One lamina has a basal, clast-rich layer overlain by dolomite, overlain by an organic-rich layer.

There is some pyrite mineralisation, cross-cut by ankerite. These are relicts of pyrite framboids (early bacterial origin) forming a thin, discontinuous lamina of pyrite framboids. There is a possible flame structure, resulting from dewatering. There are numerous mineral-filled fractures cross-cutting and sometimes displacing the lamination. BSEM analysis indicates a variety of different fills to the fractures, including ferroan dolomite, calcite and ankerite. Some of these fractures appear to be bedding controlled, with some fractures stopping at bed boundaries. Ankerite veins post-date the dolomite-cemented fractures.

The dolomite layers may represent deposition during more evaporitic conditions, whereas the clay-rich layers represent periods of more detrital activity. The present mineralogy is clearly replacive, comprising dolomite and calcite intergrowths. The replacive dolomite has diffuse margins. The circular replaced grains may be after ostracods.

4.1.5 Sample NJN98 [NT 06313 71502]

Uphall BH. R13 (NT 07SE 1096), 20.85m

Rock Type: Dolostone
BGS_Dic_Rock_Name_Type: Dolostone (DOLO); a combination of dolomite-microstone (DLMCST) and dolomite-microsparstone (DLMSPT)
Hand specimen description: In hand specimen this comprises a light grey to light brownish grey silty claystone. It appears structureless, although a brecciated fabric appears to be present in places. The rock has a 'soapy' feel to it.
Thin section description: The main features of this sample are illustrated in Figures 47 to 52. In thin section the sample is more coarse-grained than NJN97 and generally not as well laminated. Crystals of dolomicrite (<4 µm) and dolomicrosparite (4-32 µm) occur, hence it can be classified as both dolomite-microstone and dolomite microsparstone. Therefore it is best termed a dolostone. There is coarse patchy ferroan dolomite present in places. In addition there appears to be very little fracturing.

There are numerous lithic clasts present in this sample. EDXA analysis indicates that they comprise calcite intergrown with a hydrous silicate mineral with sodium, aluminium and calcium. This is suggested to be a zeolite mineral. Both the secondary calcite and the zeolite are typically anhedral in form, but the original clast shapes have a distinctive angular, shard like form to them. The zeolite-calcite replaced clasts appear to occupy a diffuse bed, 3000 µm or so in thickness. Here the clasts appear to occupy about 5% of lithology. Some examples of the zeolite-calcite appear to have been largely resorbed back into the dolomite groundmass by replacement processes. These are obvious because the dolomite has a different fabric, indicating that possibly not all are replaced glass. Dolomite-replaced clasts also occur. Some sphalerite is present in places, occurring with zeolite-calcite. This is later than the zeolite and calcite.

Zeolites typically occur in amygdales and vesicles in basic extrusive rocks or can result as secondary minerals from the alteration of feldspars and aluminous mineral of igneous rocks. In this example the zeolite and calcite are probably replacing another mineral. The angular, shard like form to the clast suggests that the zeolite and calcite are probably replacing volcanic glass.

4.2 SUMMARY OF BSEM ANALYSIS

From the BSEM analysis it is clear that many different lithologies have previously been lumped together and described as 'marls'. The rock types identified by this study include dolomite (dolomicrite), calcareous mudstone, altered tuffite (tuffaceous mudstone) and volcaniclastic mudstone. Extensive diagenetic overprinting makes it difficult to determine original compositions and in many instances the breakdown of pre-existing minerals has led to the formation of secondary calcareous minerals that give these rocks a calcareous component. The fine grain size of these rocks, combined with the calcareous component clearly gives potential for confusion when trying to name these rock types in hand specimen.

The true calcareous mudstone shows many features typical of deposition as a sedimentary rock, such as lamination, the presence of plant fragments and shelly material. However, all lithologies show some evidence for the presence of larger lithic or vitric grains, with replacement of ferromagnesium minerals a common feature. Some of the replaced lithic grains have remnant crystal structures. In one example (NJN94), the orthorhombic shape is very reminiscent of a pyroxene mineral. This lithic grain has been altered to chlorite and titanium oxide, which are typical replacements of ferromagnesian minerals. In other examples the angular, shard like nature of many of these clasts suggests an origin as volcanic glass. The original mineralogy has typically been replaced by zeolite and calcite. Zeolites typically occur in amygdales and vesicles in basic extrusive rocks or can result as secondary minerals from the alteration of feldspars and aluminous mineral of igneous rocks.

Volcaniclastic rocks are well known within the WLOSF and typically form as penecontemporaneous fall-out of pyroclastic fragments ejected from vents or fissures, which were then reworked under water (Durant, 1994; Guirdham et al., 2003). According to Gillespie & Styles (1999), rocks that have more than 10 % by volume of volcanic debris can be described as volcaniclastic. The igneous fragments present in these samples are probably pyroclastic in origin, i.e. generated by disruption as a direct result of explosive volcanic action (Gillespie & Styles, 1999). Volcaniclastic sedimentary rocks that have 25-75 % pyroclastic fragments can be described as tuffaceous mudstones, whereas rocks that have <25 % pyroclastic fragments would be classified as volcaniclastic mudstones (Gillespie & Styles, 1999). The dominant pyroclastic fragment sizes recorded are typically of ash grade (<2 mm).

Glass fragments form by rapid cooling of igneous material following eruption. Glass or devitrified glass is often an important constituent of pyroclastic rocks known as ash-fall tuffs and ash-flow tuffs. Clearly there is an appreciable igneous component to these samples, with some (NJN94, 95 and 96) showing a greater component than the remainder. The large number of shard-like fragments found within the samples examined by this study points to a volcanic igneous origin for them, followed by incorporation into the background sedimentary lithology. The alteration products and the lack of quartz indicates a basic source for the volcanic material.

5 Depositional model and conclusions

The work presented here is not a comprehensive study of the West Lothian Oil-Shale Formation and did not consider the full oil-shale succession nor did it make use of all the available data sources e.g. borehole information. Hence is not possible to give a detailed palaeogeographic reconstruction of the area. Overall, the pattern of sedimentation agrees with that previously described by other authors, i.e. a predominantly lacustrine environment, with sedimentation dominated by deposition of fine-grained sediment from suspension. Carbonate deposition appears to mark the period of lake development and expansion, with oil-shale deposition taking place in the centre of the lakes during lake highstands. Some connection to intermittent marine waters is also suggested during the highstands. It is thought that the deposition of mudstones is linked to periods of open, through-flowing drainage, whereas deposition of calcareous mudstone is linked to the development of closed lakes. This is somewhat complicated by the lateral facies change that occurs towards the lake margins where limestone, calcareous mudstone, laminated lacustrine mud and desiccation-cracked mudstone accumulated. Oil-shale deposition was periodically interrupted by the progradation of small lake deltas, which infilled the lake and left shallow water, near emergent conditions across which immature (probably short-lived) soils developed. The single storey channels represent small scale meandering channels that possibly carried sediment to the lake deltas. The larger scale multi-storey channel systems represent periods when coarser clastic sediment was fed into the area; these are poorly understood in terms of their source area, channel type and controls.

Climatically, the oil-shales occur in a succession that marks the change from the semi-arid climate that typified the uppermost Devonian-lowermost Dinantian and the later humid tropical climate when the Coal Measures were deposited (Belt, 1975; Parnell, 1988; Andrews and Nabi, 1998). The lower parts of the WLOSF is marked by numerous beds of limestones, which tend to be less common in the upper parts, linked to a decrease in aridity (Parnell, 1988). Tectonic activity is thought to be an important control on oil-shale deposition, indicated by the fact that the region of oil-shales deposition coincides with the area of maximum subsidence in the Midland Valley (Greensmith, 1968).

The main contribution that this report makes to the understanding of the West Lothian Oil-Shale Formation is a better insight into the contribution that volcanic material makes to the finer-grained lake sediments. Clearly, nearby volcanic vents or fissures were active during the deposition of the oil-shales and supplied pyroclastic material which were then reworked under water and incorporated into the lake sediments. Much of this material was in the form of glass shards, which were later diagenetically altered, leaving ghosts of their original form. This breakdown typically involved the formation of calcite, which gave the resultant rock a calcareous component. This ultimately led to the mis-identification of some samples as ‘marls’.

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Subsystem	Series		Stage	Central Coalfield	Ayrshire	Fife	West Lothian	East Lothian	Groups
				Lithostratigraphical Units					
				Formations					Groups
Silesian	Westphalian	C	Bolsovian	Upper Coal Measures					Coal Measures
		B	Duckmantian	Middle Coal Measures					
		A	Langsettian	Lower Coal Measures					
	Namurian		Chokierian-Yeadonian	Passage Formation					Clackmannan Group
			Arnsbergian	Upper Limestone Formation					
			Pendleian	Limestone Coal Formation					
Dinantian	Viséan			Lower Limestone Formation					Bathgate Group
			Brigantian	Lawmuir Formation		Pathead Formation	West Lothian Oil Shale Formation	Aberlady Formation	
			Asbian	Kirkwood Formation		Sandy Craig Formation			
				Clyde Plateau Volcanic Formation		Pittenweem Formation			
			Arundian-Holkerian			Anstruther Formation	Gullane Formation		Strathclyde Group
						Fife Ness Formation	Arthur's Seat Volcanic Formation	Garleton Hills Volcanic Formation	
	Tournaisian		Chadian	Clyde Sandstone Formation				Ballagan Formation	Inverclyde Group
			Courceyan	Ballagan Formation					
				Kinnesswood Formation					

Figure 1. Classification of the Carboniferous strata in the Midland Valley of Scotland (redrawn from Browne et al., 1999).

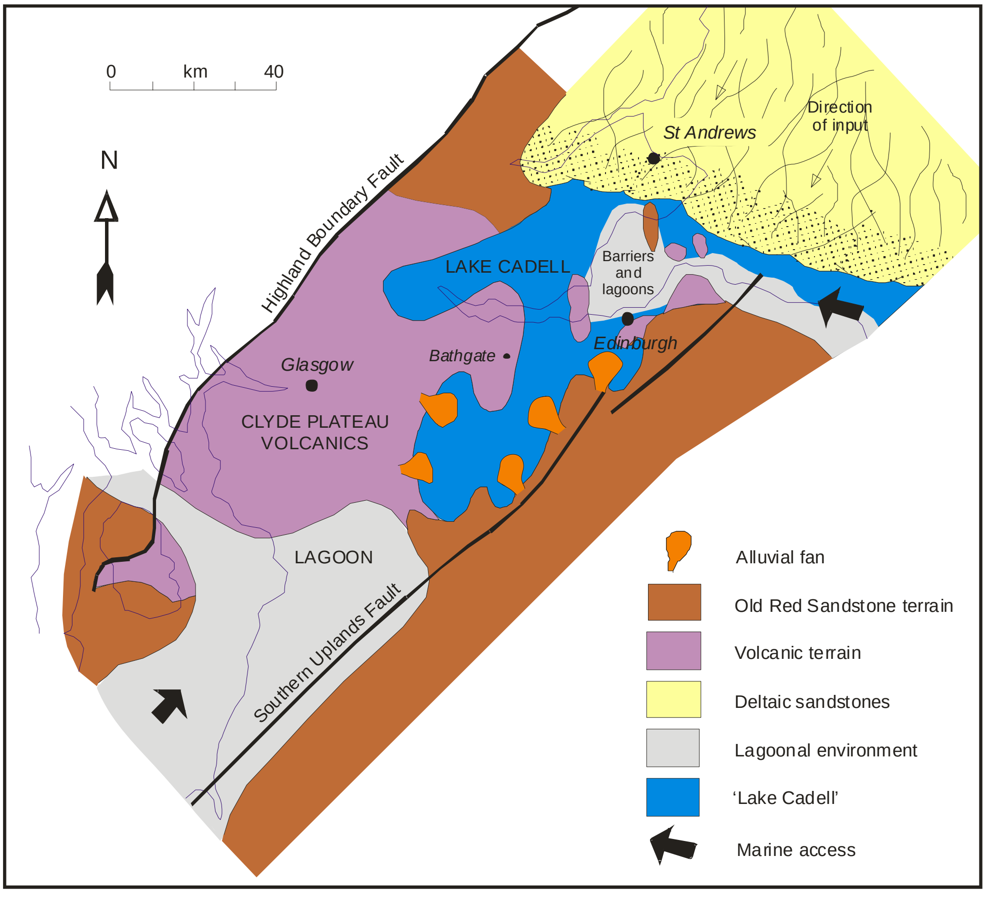


Figure 2. Envisaged palaeogeographical setting of the West Lothian Oil-Shale Formation at the time of deposition of the Burdiehouse Limestone (redrawn with modifications from Loftus & Greensmith, 1988).

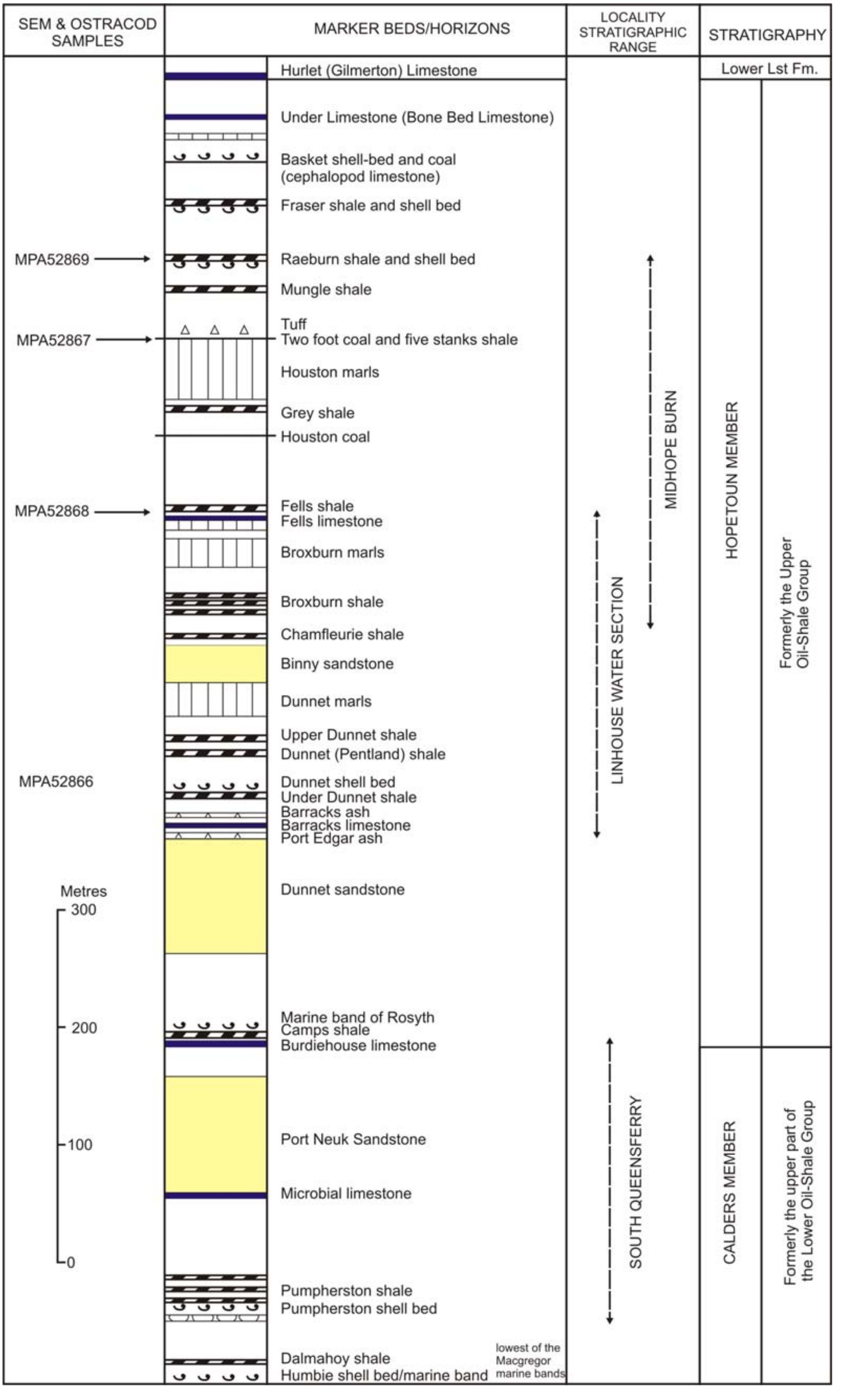


Figure 3. Detailed stratigraphy of the West Lothian Oil-Shale Formation, Midland Valley of Scotland. Redrawn with modifications from Cameron & McAdam (1978), Chisholm & Brand (1994), Browne et al. (1999), and Guirdham et al. (2003).

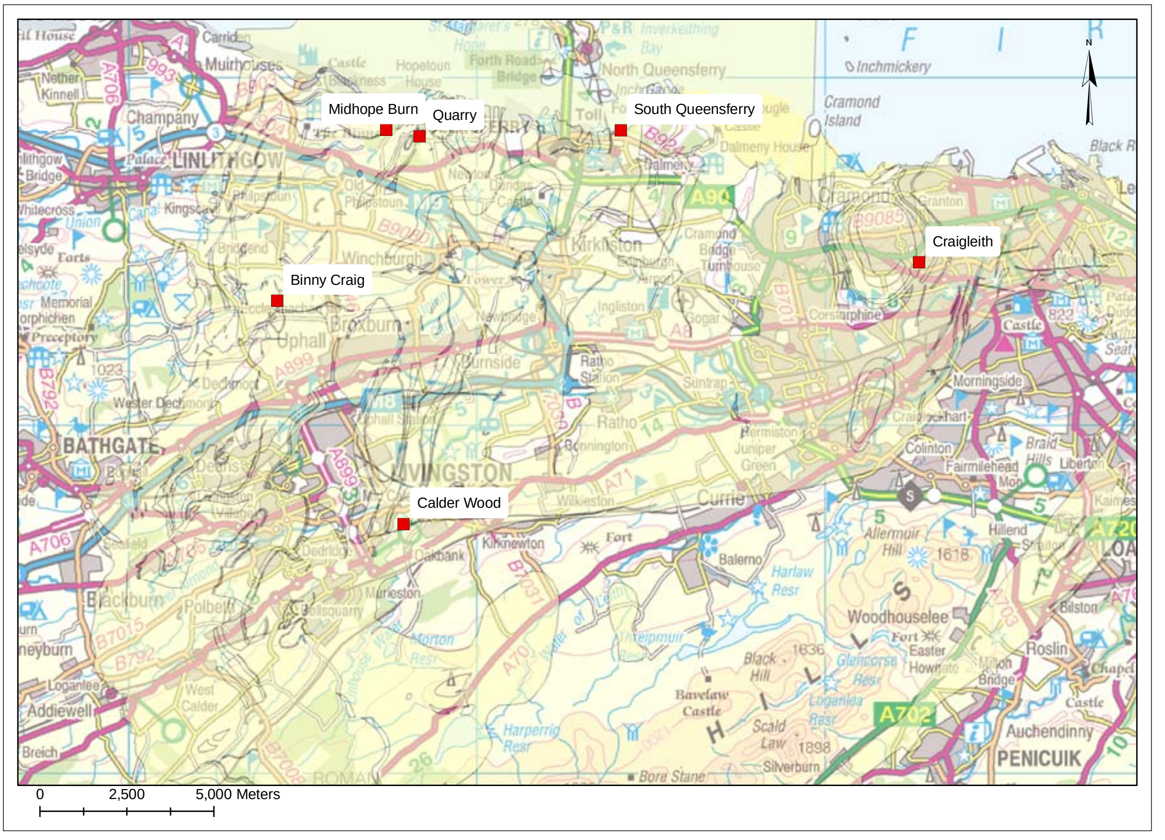


Figure 4. Location map of localities studied. The region coloured in yellow represents the area of outcropping Strathclyde Group. OS 250K map used with the permission of the Controller of Her Majesty's Stationery Office.Ordnance Survey licence number GD 272191/2007.

Phi (ϕ)	mm	WENTWORTH CLASS SIZE		
-12	4096			
			BOULDER	GRAVEL
-8	256			
		Large	COBBLE	
-7	128			
		Small		
-6	64			
		Very large	PEBBLE	
-5	32			
		Large		
-4	16			
		Medium		
-3	8			
		Small		
-2	4			
			GRANULE	
-1	2			
		Very coarse	SAND	SAND
0	1			
		Coarse		
1	0.5			
		Medium		
2	0.25			
		Fine		
3	0.125			
		Very fine		
4	0.0625	0.032 (BGS)		
			SILT	MUD
8	0.0039			
			CLAY	

Figure 5. Grain size scheme used in this report (redrawn from Pettijohn et al., 1987).

Figure 6. General view of the laminated black mudstone (oil-shale) facies.
Note the well laminated nature of the mudstone. Calder Wood [NT 07504 66030].

Figure 7. *Calamites* stems in an oil-shale.
Linhouse Water, Calder Wood, GR approximately [NT 0791 6713].

Figure 8. Ostracods in an oil-shale from the Gullane Formation (Strathclyde Group).
Craigleith Retail Park [NT 22702 74651].

Figure 9. General view of the Laminated Grey Lacustrine Mudstone facies. Note thin silty sandstone interbed (light grey) near the compass and ironstone beds (brown) – one at the top and one in the lower third of the photograph. Linhouse Water, Calder Wood [NT 07475 66063].

Figure 10. General view of the Laminated Grey Lacustrine Mudstone facies. This silty claystone contains well defined brown limestone lenses in the lower third of the photograph. Linhouse Water, Calder Wood, approx GR [NT 0781 6740].

Figure 11. Fish scales in the Laminated Grey Lacustrine Mudstone facies. Linhouse Water, Calder Wood, approximate GR [NT 07910 67200].

Figure 12. Desiccation-cracked Lacustrine Mudstone. Note the polygonal desiccation cracks infilled with slightly darker grey mudstone. Midhope Burn, approximately [NT 05870 77990].

Figure 13. Rooted Mudstone (Palaeosol) facies. This mudstone contains numerous narrow black roots. Midhope Burn, approximately [NT 05860 77990].

Figure 14. Rooted Mudstone (Palaeosol) facies with sand-filled desiccation cracks and brown mottling. Linhouse Water, Calder Wood [NT 07468 66067].

Figure 15. Rooted Mudstone (Palaeosol) facies with rubbly, destratified texture. This is the result of extensive pedoturbation. Linhouse Water, Calder Wood [NT 07468 66067].

Figure 16. General view of the Calcareous Lacustrine Mudstone facies. Two beds of light grey calcareous mudstone can be seen (arrowed). Linhouse Water, Calder Wood [NT 07810 67400].

Figure 17. Close up view of the Calcareous Lacustrine Mudstone facies showing a faint parallel lamination. Linhouse Water, Calder Wood [NT 07810 67400].

Figure 18. Lacustrine Limestone facies with desiccation cracks. Linhouse Water, Calder Wood [NT 07600 65822].

Figure 19. Lacustrine Limestone facies with shelly material concentrated towards the base of the bed. Linhouse Water, Calder Wood [NT 07600 65822].

Figure 20. Lacustrine Limestone facies: thickly laminated to very thinly bedded limestone and hemispheroidal stromatolites (arrowed). South Queensferry [NT 1418 7854].

Figure 21. Lacustrine Limestone facies: microbial limestone with bulbous microbial domal forms (= hemispheroidal stromatolites). South Queensferry [NT 1418 7854].

Figure 22. Wave rippled siliceous sandstone (Lake Shoreline Sandstone facies), from the basal part of the Port Neuk Sandstone, South Queensferry [NT 14180 78540].

Figure 23. Delta Siltstone and Sandstone facies showing distinct upwards-coarsening, with siltstone and silty sandstone in the lower half of the photograph (prodelta and distal bar environments) overlain by the sandstone-dominated mouth bar (above the geologist's head). Arrowed area shown in Figure 24. Locality: Linhouse Water, Calder Wood [NT 07902 67156].

Figure 24. Deposits of the prodelta and distal bar environments of the Deltaic Siltstone and Sandstone facies. A number of small scale syn-sedimentary faults (arrowed) dip at a steep angle from left to right. These are interpreted to have formed by gravity induced collapse of the delta front. Linhouse Water, Calder Wood [NT 07902 67156].

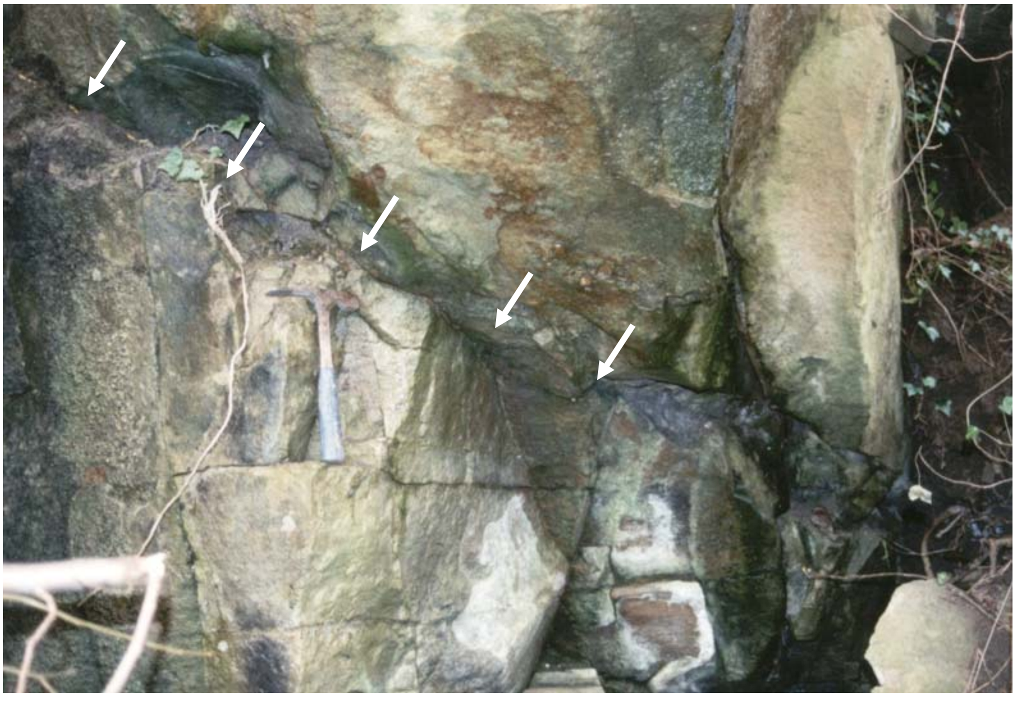


Figure 25. Distributary feeder channel in the upper part of a lake delta, Deltaic Siltstone and Sandstone facies. The base of the channel is erosive, marked by white arrows. Linhouse Water, Calder Wood [NT 07902 67156].

Figure 26. Major stacked channel, Channel facies. Coarse-grained to pebbly sandstone occurs just above the hammer head and lines an internal erosion surface (arrowed) that defines the base of a channel. Linhouse Water, Calder Wood [NT 0747 6609].

Figure 27. Basal erosion surface to a channel sandstone, minor channel, Channel facies. The surface (arrowed) is markedly stepped. Linhouse Water, Calder Wood [NT 07470 66070].

Figure 28. Cut-and-fill structure within an heterolithic minor channel deposit, Channel facies. The base of the scour is marked with arrows and the interbedded siltstone and sandstone immediately above forms the fill to the scour. This is suggested to have been generated by an in-channel scouring event. Linhouse Water, Calder Wood [NT 0746 6607].

Figure 29. Close up of minor heterolithic channel, Channel facies to show the detail of the wedge shaped bedding (W) and some folding of bedding (F). Linhouse Water, Calder Wood [NT 07500 66030].

Figure 30. Laterally continuous sheet sandstones (arrowed), Current-Rippled Sheet Sandstone facies . Note the soft sediment deformation features (arrowed). Gullane Formation (Strathclyde Group), Craigleith [NT 2271 7468].

Figure 31. Close up of the sheet sandstone facies, Current-Rippled Sheet Sandstone facies. They can be seen to be sharp-based and internally current ripple cross-laminated. Approx GR [NT 0747 6607].

Figure 32. Tuff facies. Note the numerous light grey to brown mudstone clasts incorporated into the tuff. Midhope Burn, [NT 0575 7792].

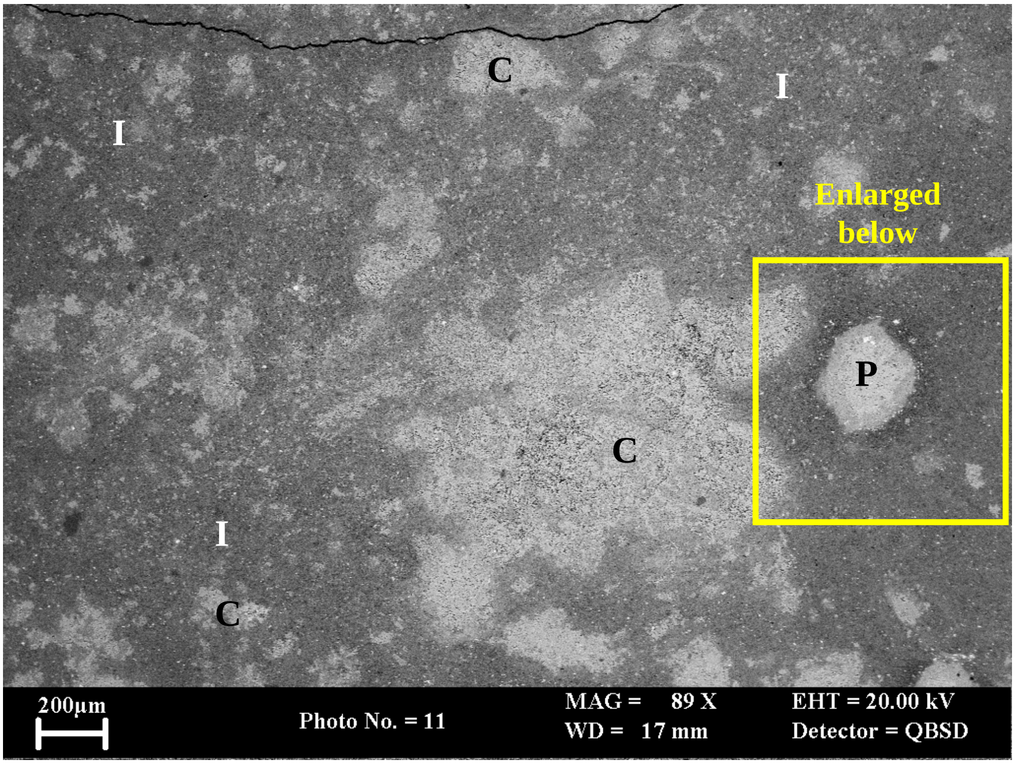


Figure 33. BSEM photomicrograph of thin section NJN94. Calcareous claystone. This low magnification image shows the ghosted nature of many of the lithic clasts, replaced by calcite (C) and illite (I). A possible pyroxene (P) is marked and enlarged below. Sample NJN94, Midhope Burn [NT 05721 77856]. MAG = magnification, EHT = accelerating beam voltage, WD = working distance, QBSD = Quadrant Back Scattering Detector

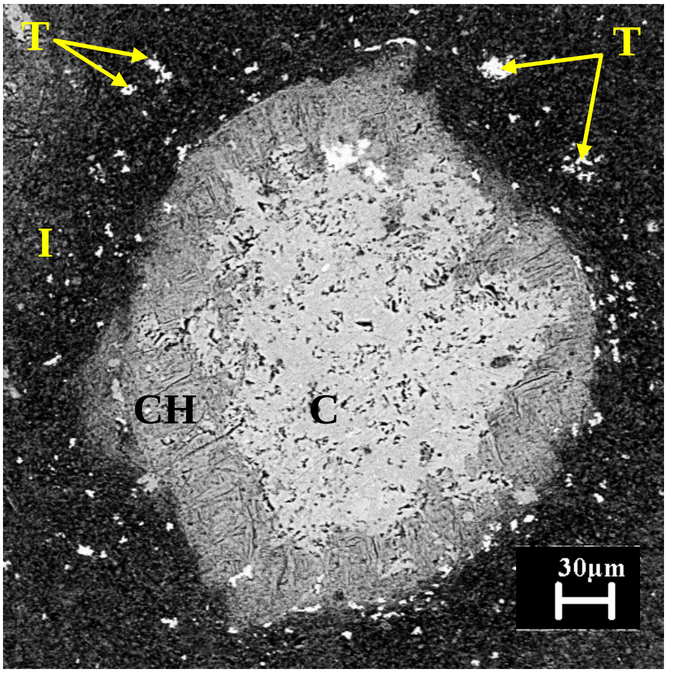


Figure 34. BSEM photomicrograph of thin section NJN94. Calcareous claystone. This shows the detail of one altered lithic clast, comprising calcite (C) and a rim of chlorite (CH). The fine-grained surrounding matrix comprises predominantly illite (I) and small bright crystals of titanium oxide (T). The orthorhombic shape of the clast and the alteration minerals suggests that this may have resulted from the replacement of a pyroxene. Sample NJN94, Midhope Burn [NT 05721 77856].

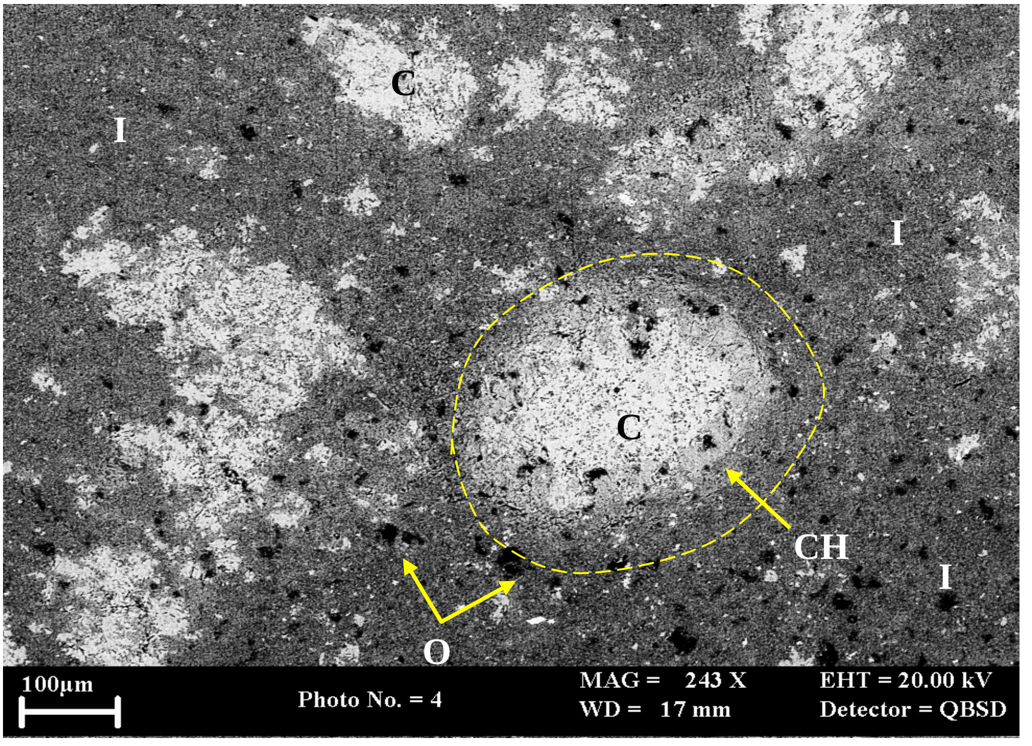


Figure 35. BSEM photomicrograph of thin section NJN94. Calcareous claystone. The fine-grained matrix comprises predominantly illite (I) and amorphous black organic material (O). Also present are ghosted remnants of former lithic clasts (one example circled), now comprising calcite (C) and chlorite (CH). Sample NJN94, Midhope Burn [NT 05721 77856].

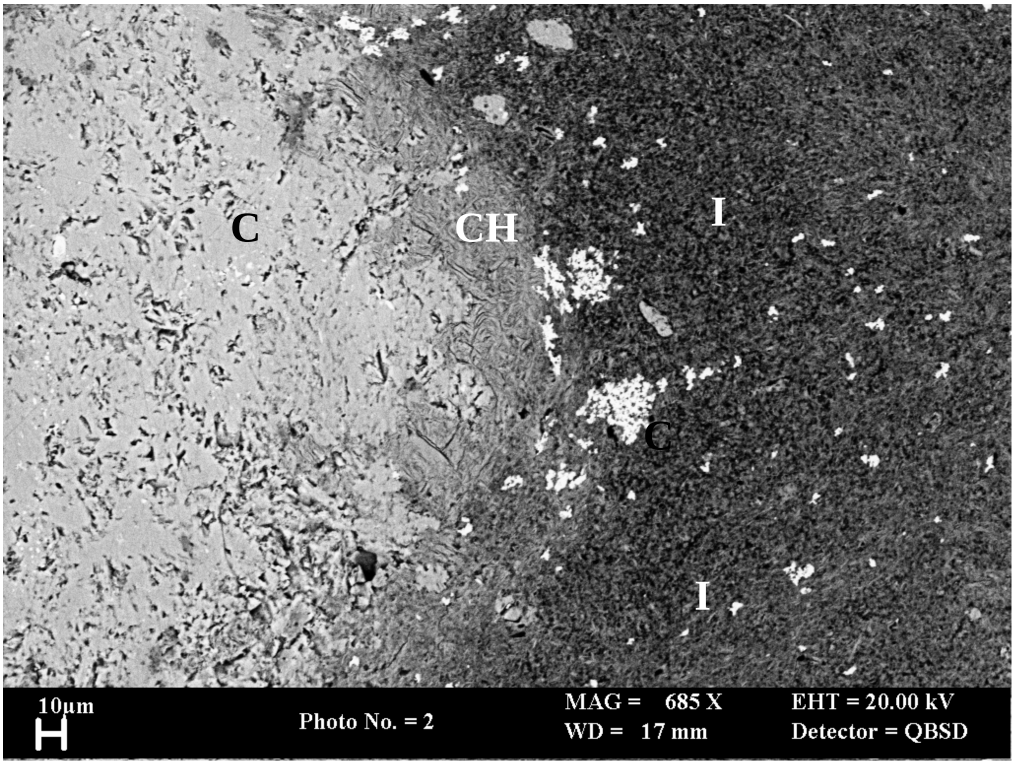


Figure 36. BSEM photomicrograph of thin section NJN94. Calcareous claystone. This shows the detail of one altered lithic clast, comprising calcite (C) and a rim of chlorite (CH). The fine-grained matrix to the right comprises predominantly illite (I) and amorphous black organic material. Sample NJN94, Midhope Burn [NT 05721 77856].

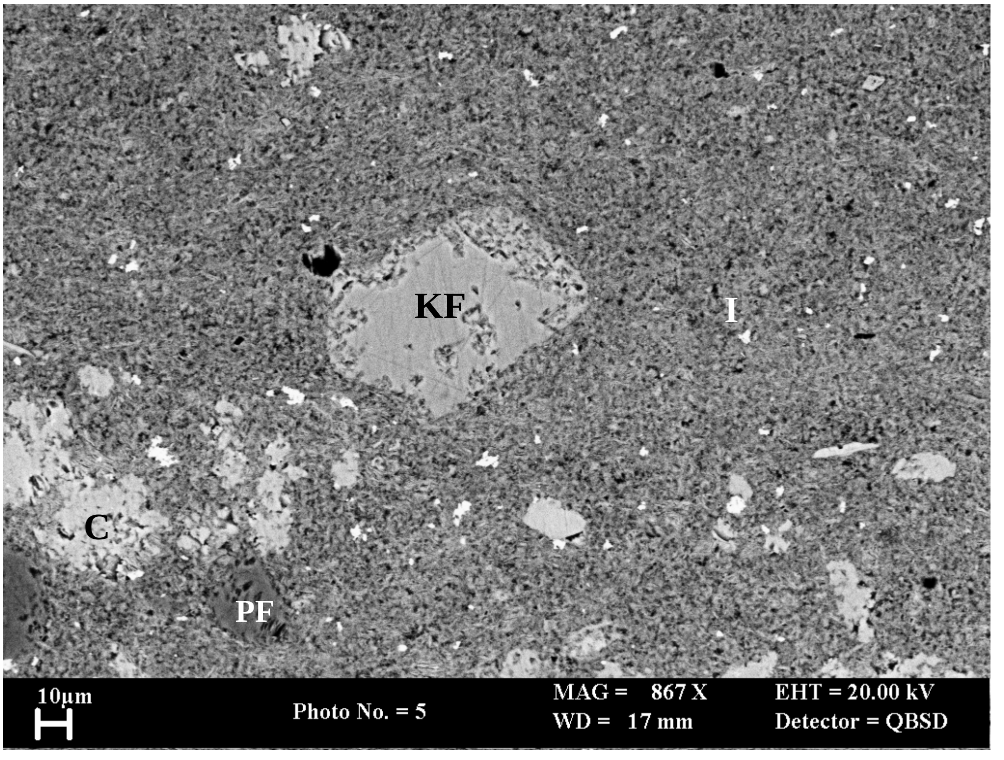


Figure 37. BSEM photomicrograph of thin section NJN94. Calcareous claystone. The fine-grained matrix comprises predominantly illite (I) and amorphous black organic material. Also present are grains of K feldspar (KF), plagioclase feldspar (PF) and calcite (C). Sample NJN94, Midhope Burn [NT 05721 77856].

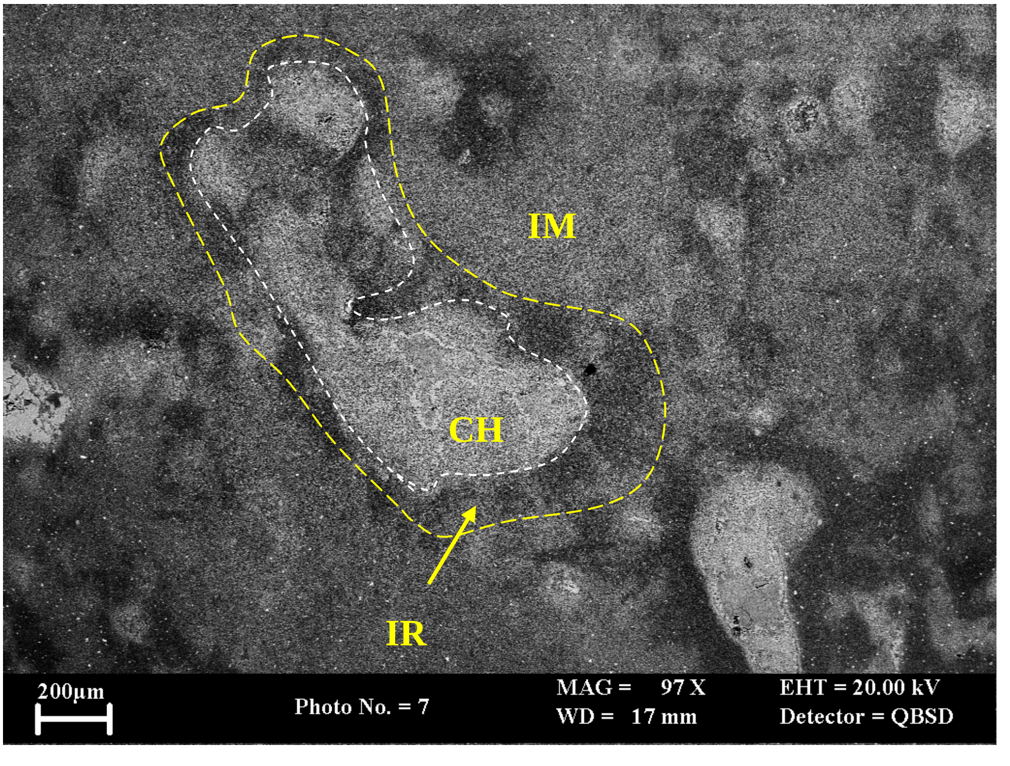


Figure 38. BSEM photomicrograph of thin section NJN95. Tuffaceous mudstone. This shows the nature of the diffuse irregularly-shaped 'ghost' like lithic clasts, enclosed by the dashed white line. This predominantly comprises replacive chlorite (CH). The fine-grained matrix mainly comprises illite (IM). Illite is also concentrated as a diffuse darker zone around the ghost of the clast (IR), enclosed by the dashed yellow line. Sample NJN95, Midhope Burn [NT 05721 77856].

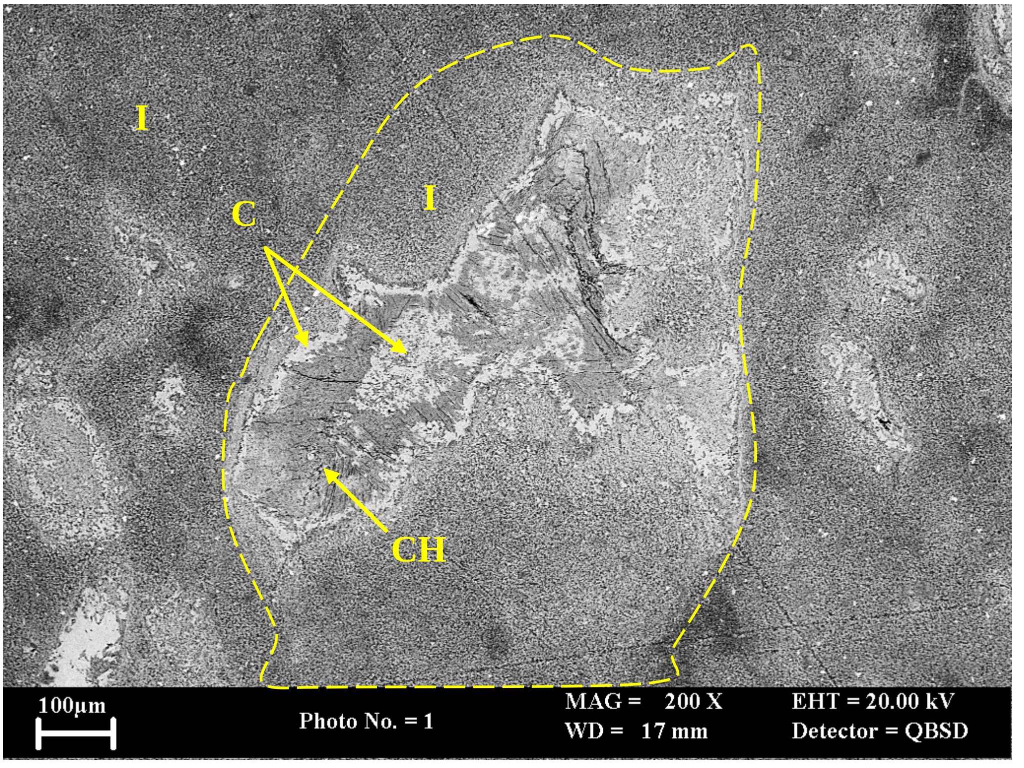


Figure 39. BSEM photomicrograph of thin section NJN95. Tuffaceous mudstone. This shows a ghost lithic clast (dashed line) replaced by illite (I), calcite (C) and chlorite (CH). Calcite typically forms a rim around the edge of the grain, but in this example also occurs intergrown with chlorite. The fine-grained matrix comprises predominantly illite (I). Sample NJN95, Midhope Burn [NT 05721 77856].

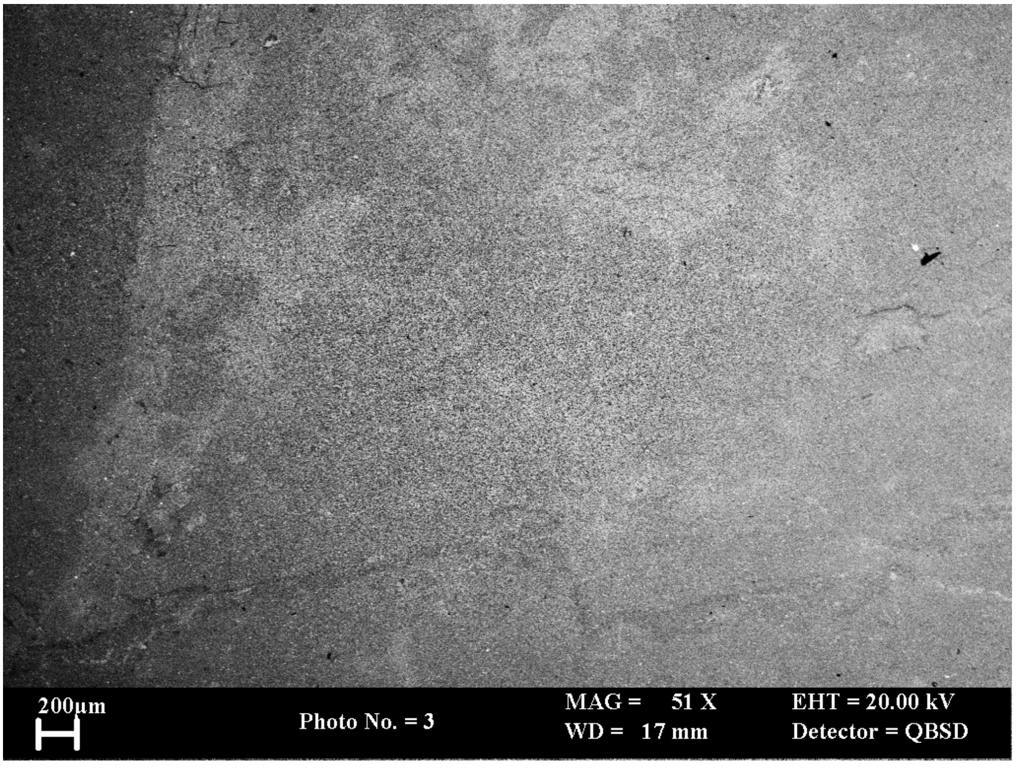


Figure 40. BSEM photomicrograph of thin section NJN96. Tuffaceous mudstone. This shows the homogenised nature of the lithology. The matrix comprises illite, with minor chlorite. Lighter patches have a higher proportion of calcite. Lithic clasts are largely absent from this field of view. Sample NJN96, Midhope Burn [NT 05761 77917].

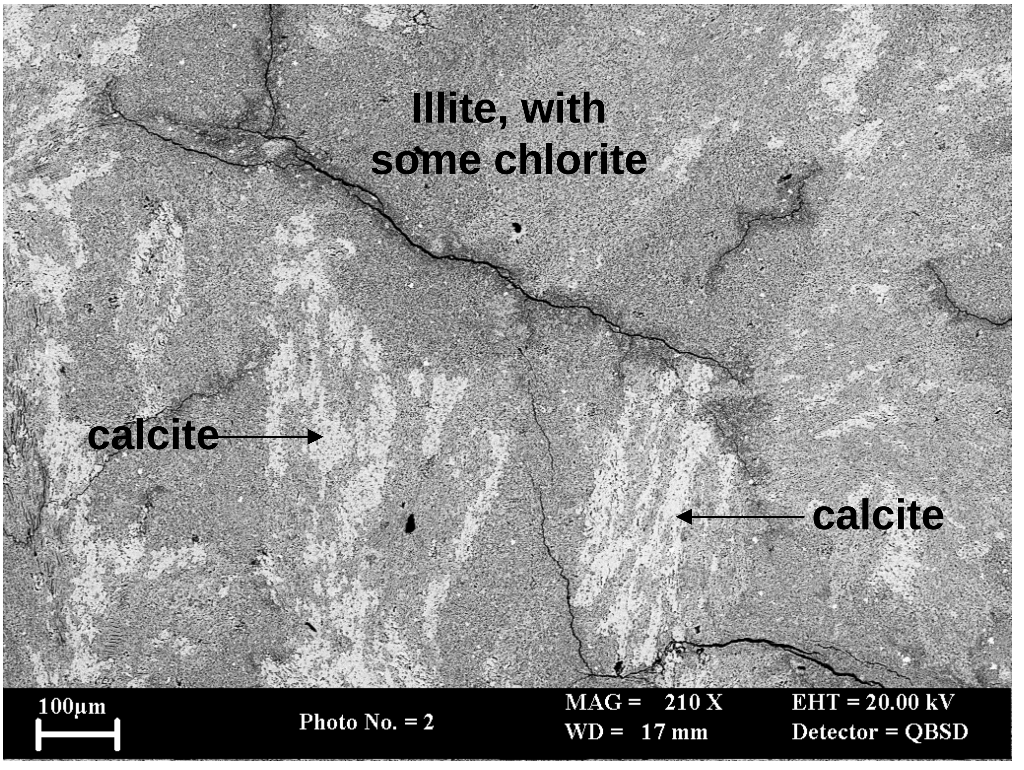


Figure 41. BSEM photomicrograph of thin section NJN96. Tuffaceous mudstone. The fine-grained matrix comprises predominantly illite and some chlorite. Patches of calcite may represent the former positions of highly degraded, replaced lithic clasts, probably of volcanic rock. Sample NJN96, Midhope Burn [NT 05761 77917].

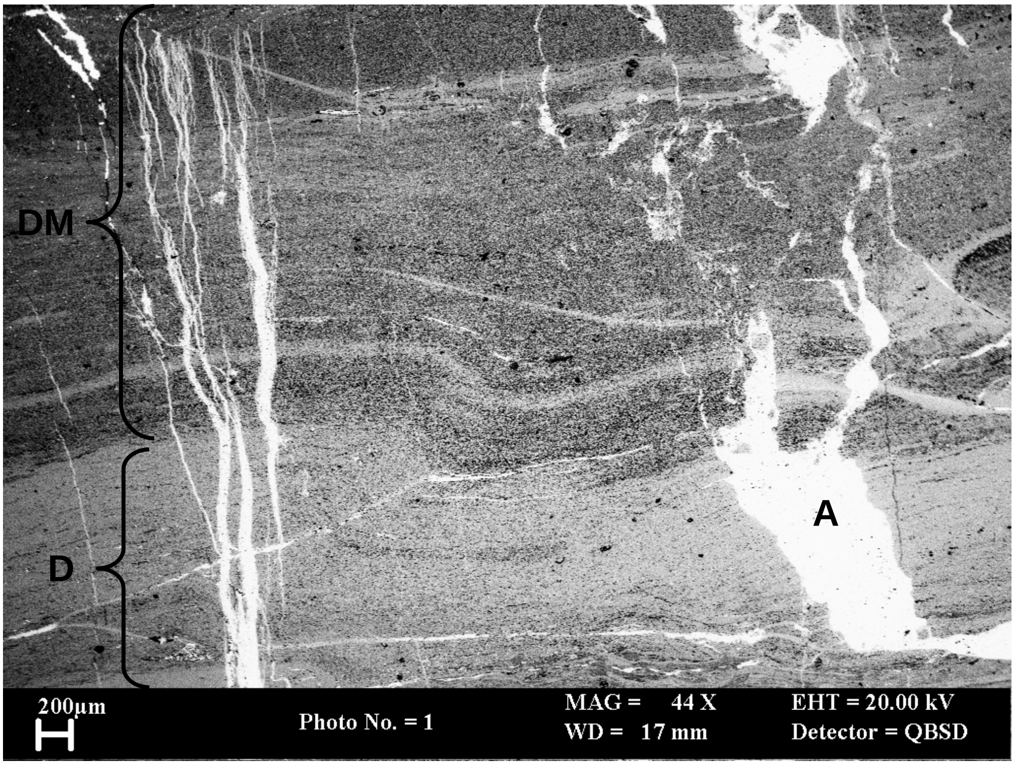


Figure 42. BSEM photomicrograph of thin section NJN97. Dolomite mudstone. The well laminated nature of this lithology can be clearly seen here, and is slightly convoluted in places. Laminae comprise alternations of dolomitic mudstone (dolomite with illite and chlorite) (DM) and dolomite (D). An ankerite filled fracture can also be seen (A). Sample NJN97, Uphall Bh R.03 [NT 05721 77856].

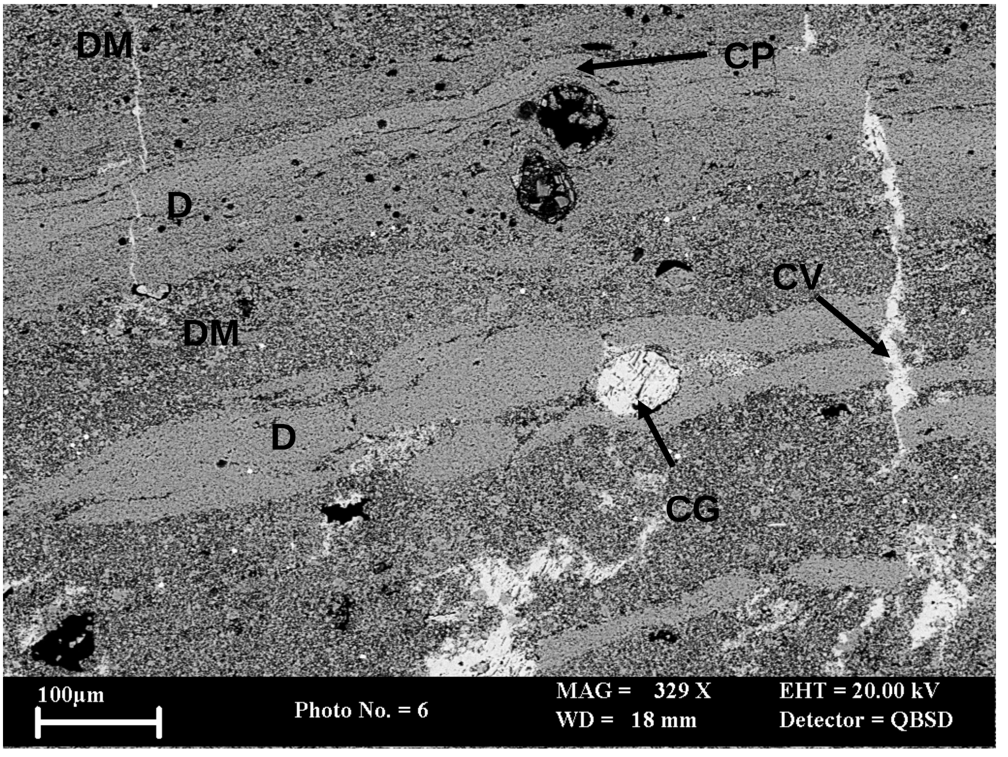


Figure 43. BSEM photomicrograph of thin section NJN97. Dolomite mudstone. The well-laminated nature of this lithology can be clearly demonstrated. Laminae comprise alternations of dolomitic mudstone (dolomite with illite and chlorite) (DM) and dolomite (D). Also visible are a calcite-filled vein (CV) and a calcite detrital grain (CG). The effects of compaction can also be seen around a now largely dissolved grain (CP). Sample NJN97, Uphall Bh R.03 [NT 05721 77856].

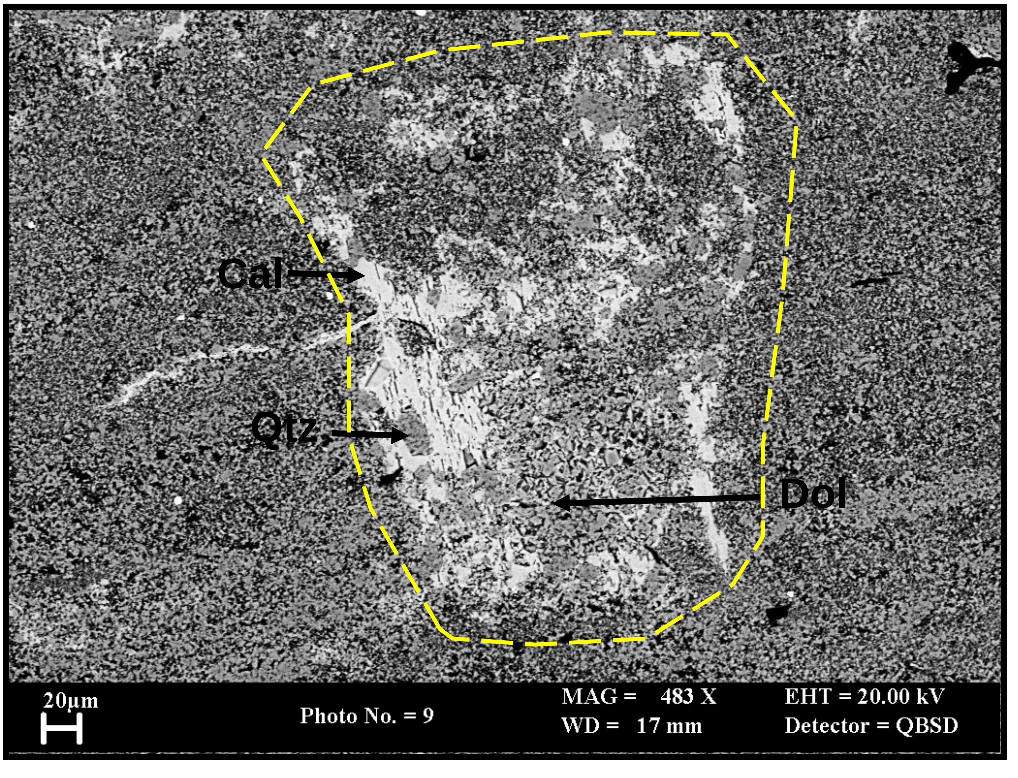


Figure 44. BSEM photomicrograph of thin section NJN97. Dolomite mudstone. This shows an exotic clast (outlined in yellow), now replaced by calcite (Cal), dolomite (Dol), with some remnant quartz (Qtz). Sample NJN97, Uphall Bh R.03 [NT 05721 77856].

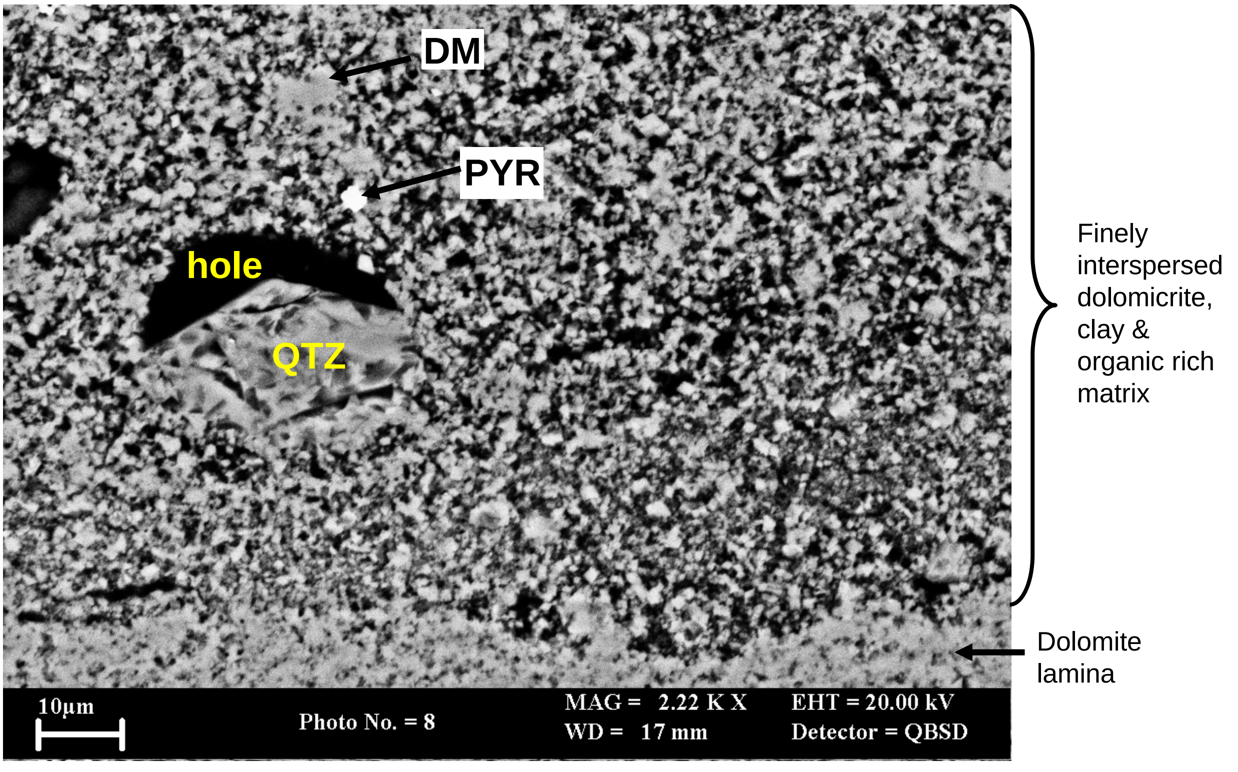


Figure 45. BSEM photomicrograph of thin section NJN97. Dolomite mudstone. This shows the fine detail of the lamination in this lithology, comprising alternations of finely interspersed dolomicrite, clay and organic rich matrix with dolomite. Also present is quartz (QTZ), pyrite (PYR) and dolomicro-sparite with an ankerite rim (DM). Sample NJN97, Uphall Bh R.03 [NT 05721 77856].

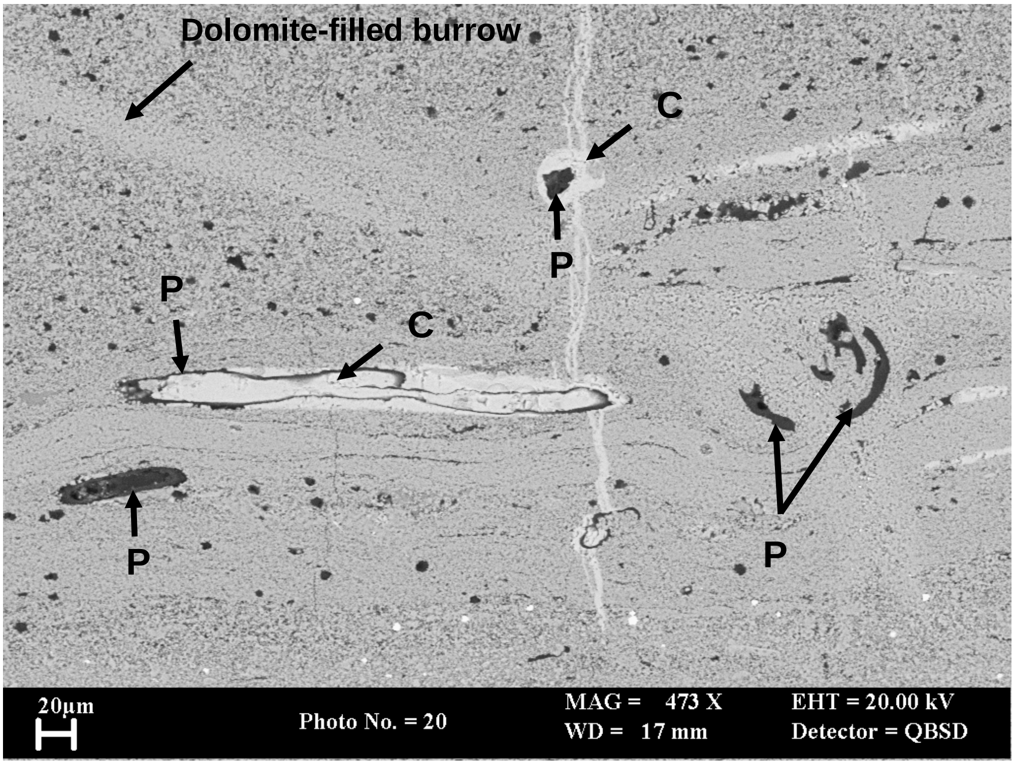


Figure 46. BSEM photomicrograph of thin section NJN97. Dolomite mudstone. The background lithology is largely a laminated dolomite, within which are numerous plant fragments (P). Also present associated with the plant material is secondary calcite (C) and a possible burrow structure, filled with dolomite. Sample NJN97, Uphall Bh R.03 [NT 05721 77856].

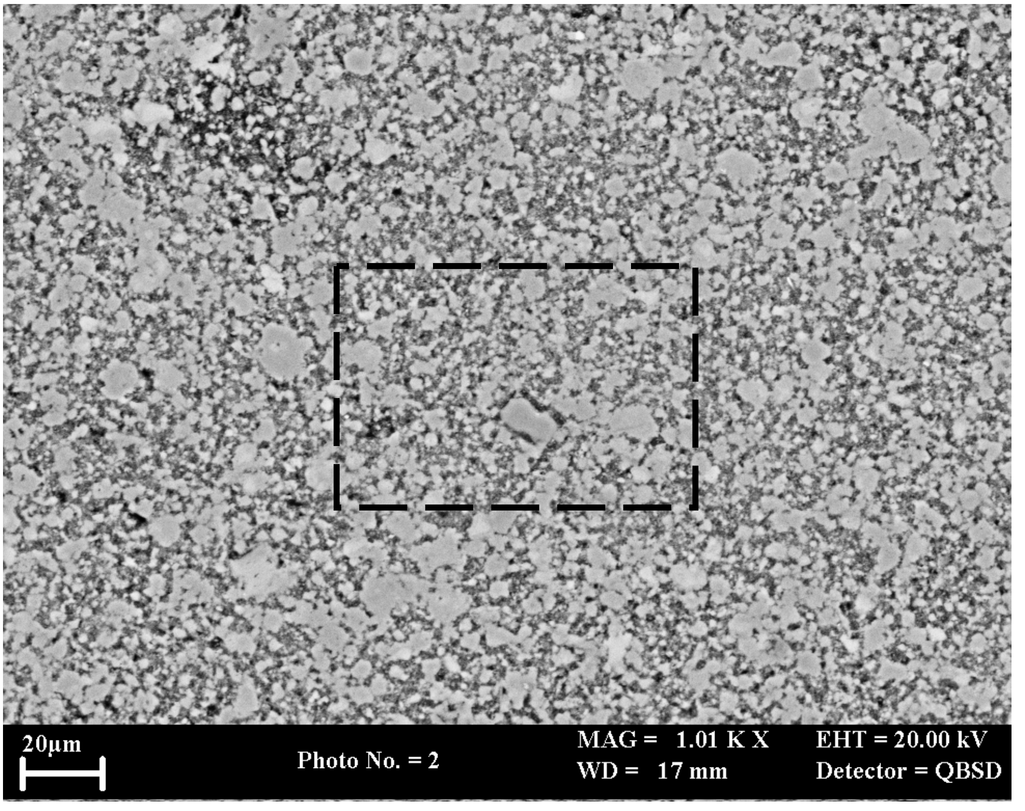


Figure 47. BSEM photomicrograph of thin section NJN98. Dolostone. This general view shows the largely structureless nature of the lithology. The marked section is enlarged in Figure 48 below. Sample NJN98, Uphall Bh.R13 [NT 06313 71502].

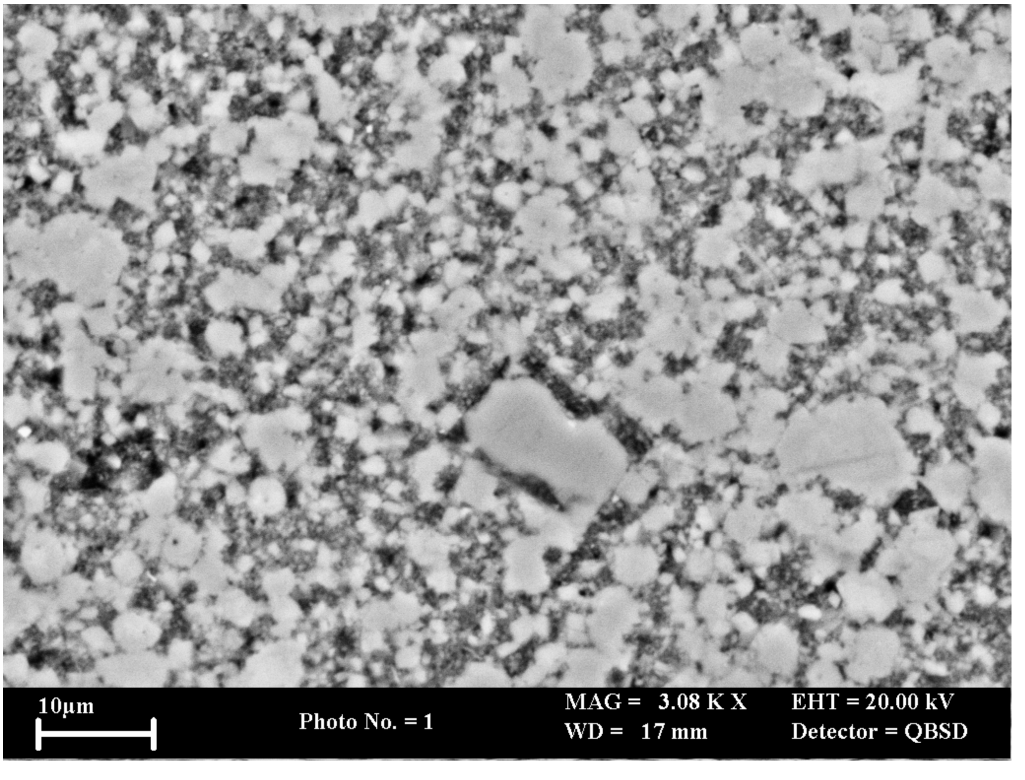


Figure 48. BSEM photomicrograph of thin section NJN98. Dolostone. Close up from Figure 47. This lithology comprises various sizes of relatively amorphous dolomicrosparite crystals with dolomicrite and illitic matrix. Sample NJN98, Uphall Bh.R13 [NT 06313 71502].

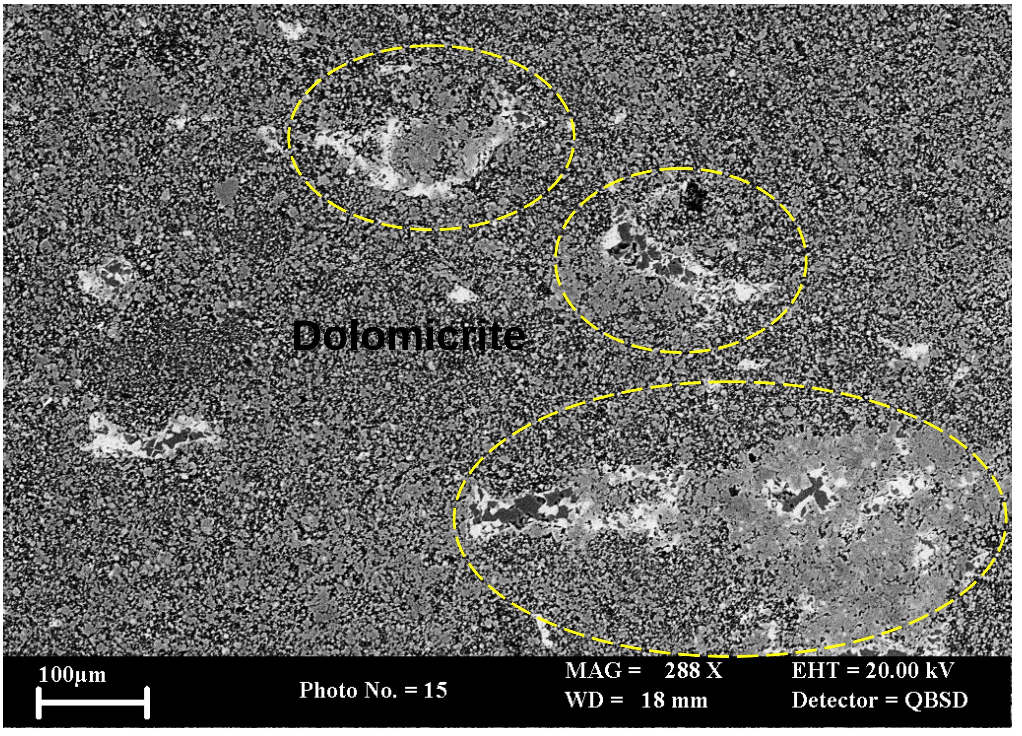


Figure 49. BSEM photomicrograph of thin section NJN98. Dolostone. This shows dolomite replacing an earlier replacement fabric dominated by zeolite (dark grey) and calcite (white). Note the more massive fabric shown by the later dolomite compared to the dolomicrite and dolomicrosparite that forms most of the matrix. Sample NJN98, Uphall Bh.R13 [NT 06313 71502].

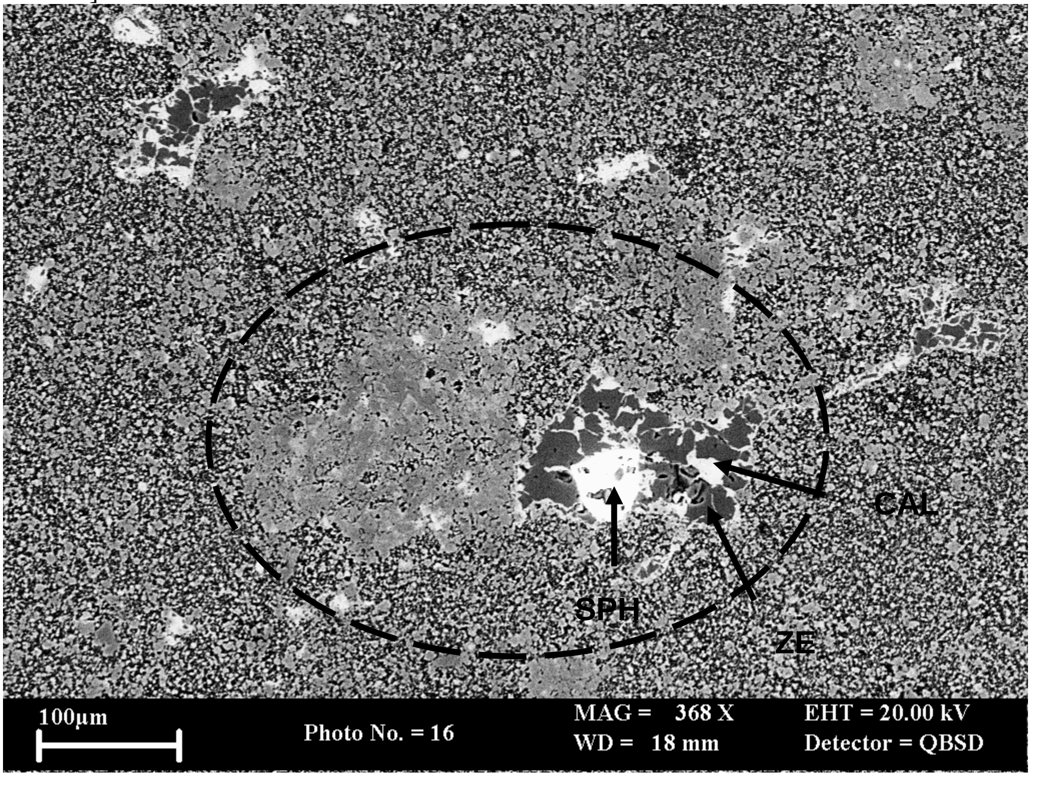
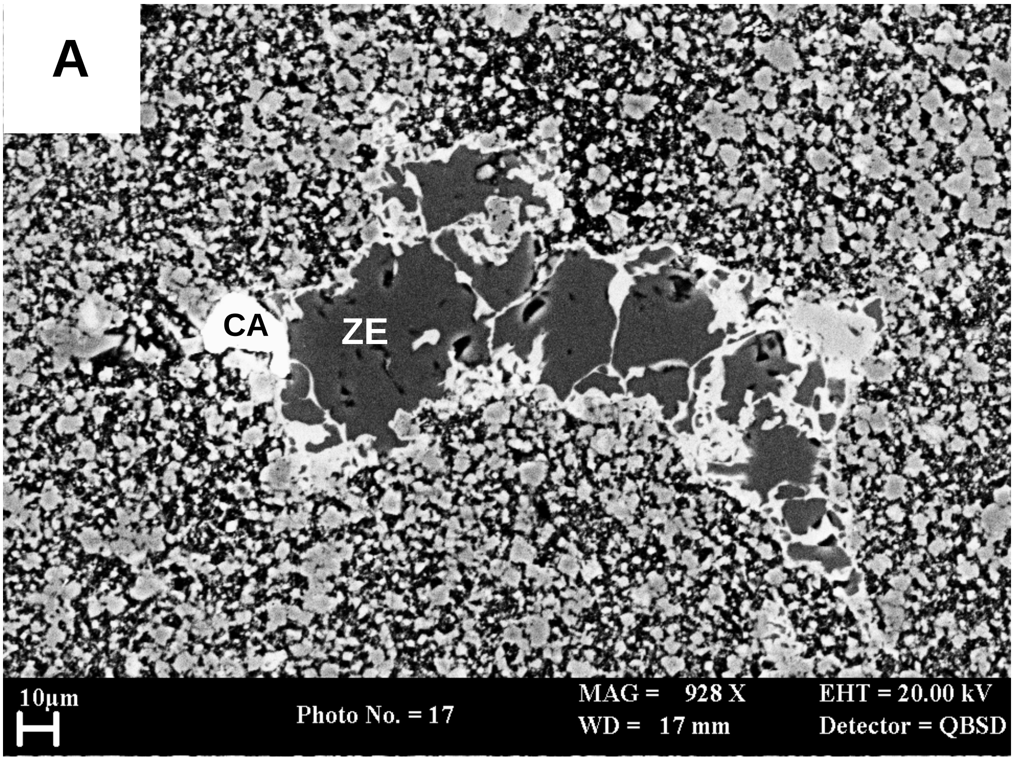


Figure 50. BSEM photomicrograph of sample NJN98. Dolostone. Dolomite replacing an earlier replacement fabric dominated by zeolite (dark grey, labelled ZE) and calcite (light grey to white, labelled CAL). Note the more massive fabric shown by the later dolomite compared to the dolomicrite and dolomicrosparite that forms most of the matrix. Late sphalerite (SPH) also occurs in association with the zeolite and calcite. Sample NJN98, Uphall Bh.R13 [NT 06313 71502].



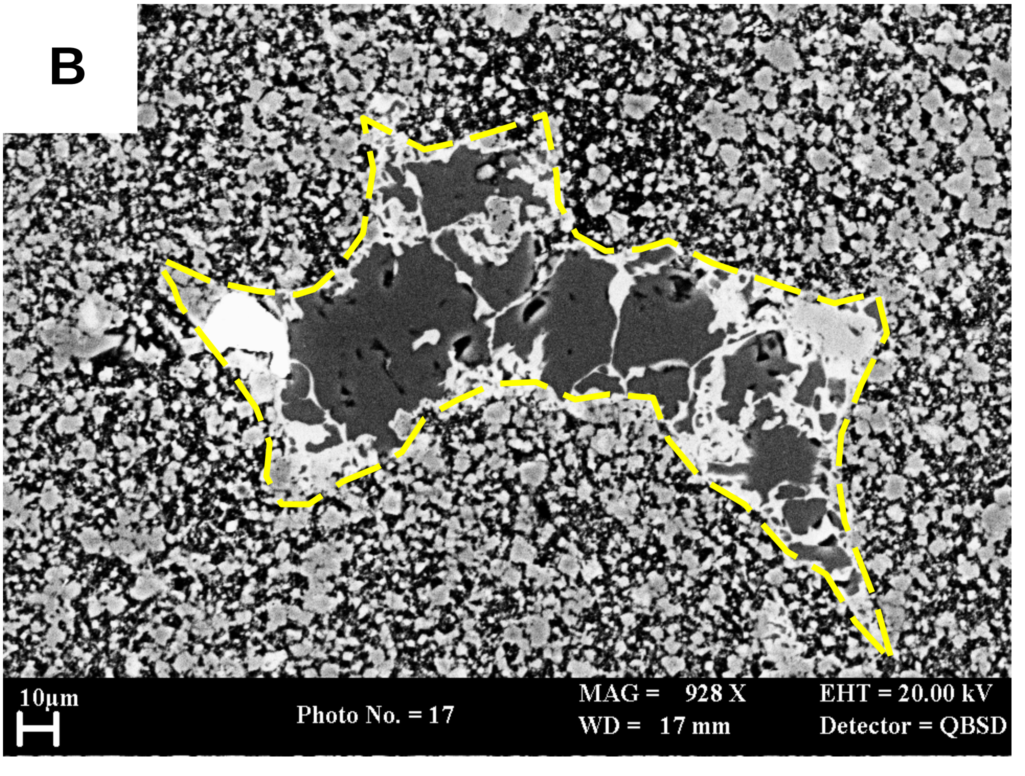


Figure 51. BSEM photomicrograph of thin section NJN98. Dolostone.

A. A lithic clast composed of calcite (CA) intergrown with a zeolite mineral (ZE) is present within a background matrix of dolomicrite and illite. The clast has a distinctive angular, shard like form to it.

B. As image A, with the angular nature of the clast outlined. Sample NJN98, Uphall Bh.R13 [NT 06313 71502].

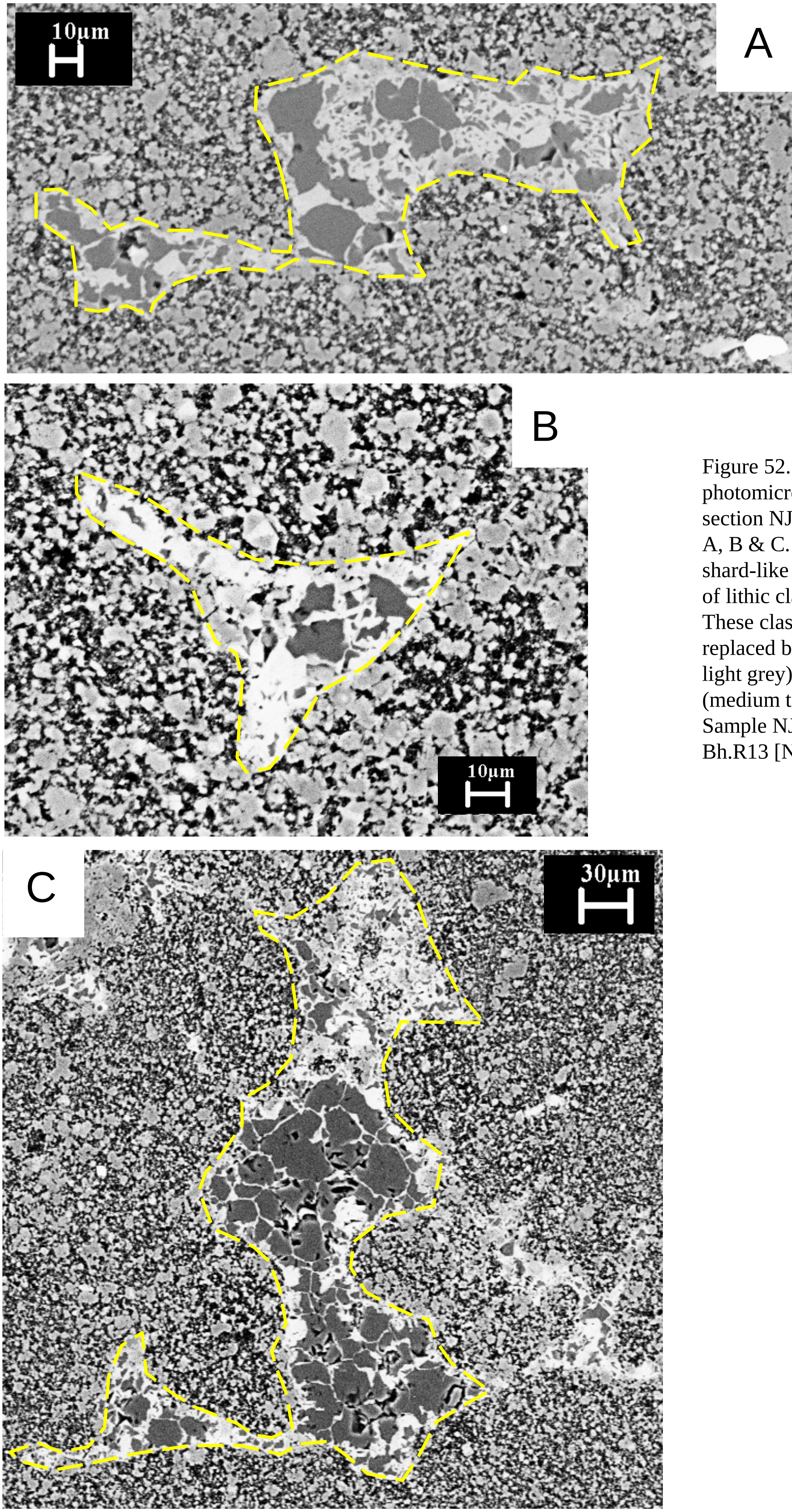


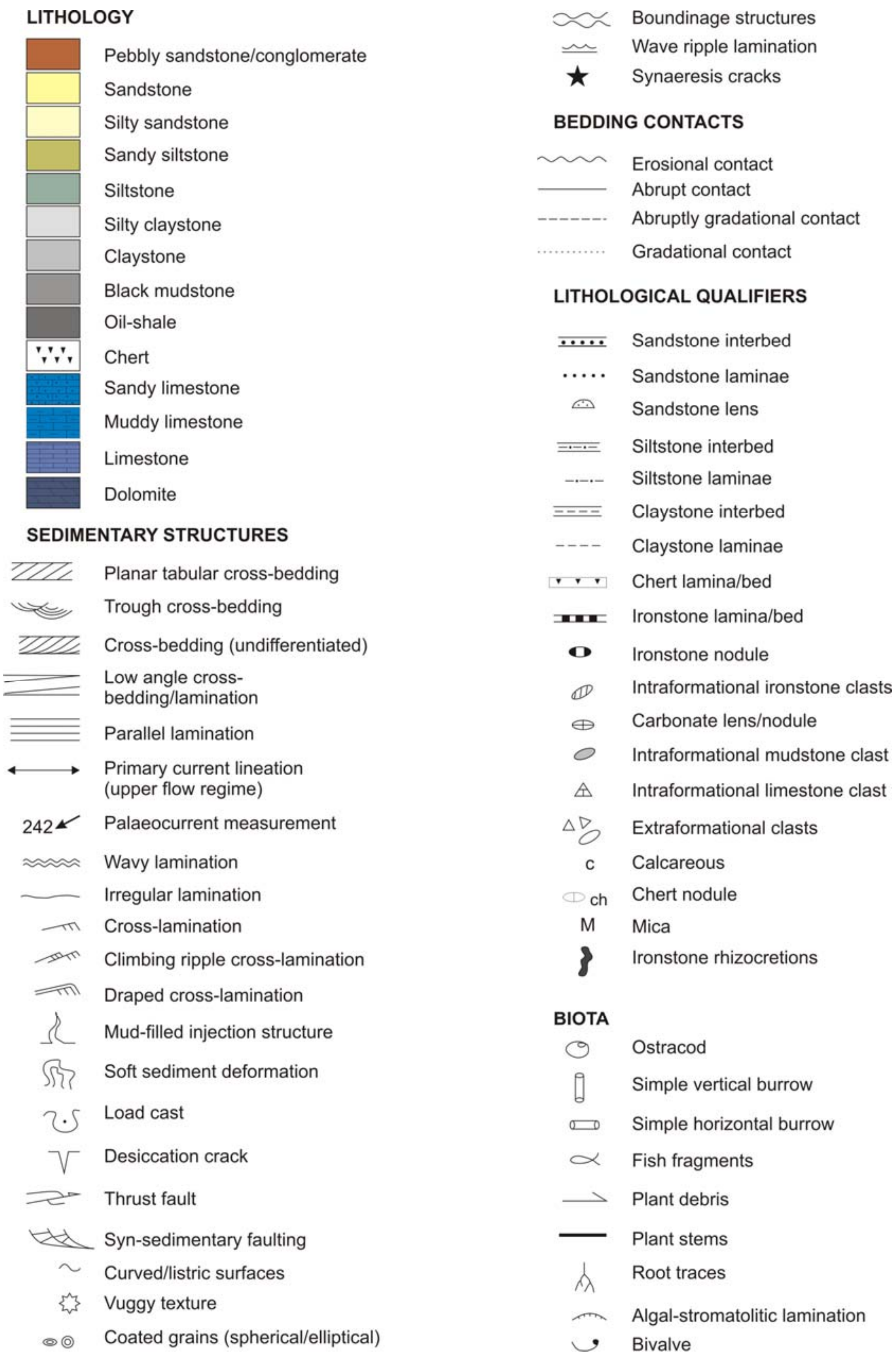
Figure 52. BSEM photomicrographs of thin section NJN98. Dolostone. A, B & C. The angular, shard-like nature of a number of lithic clasts is outlined. These clasts are now replaced by calcite (white to light grey) and zeolite (medium to dark grey). Sample NJN98, Uphall Bh.R13 [NT 06313 71502].

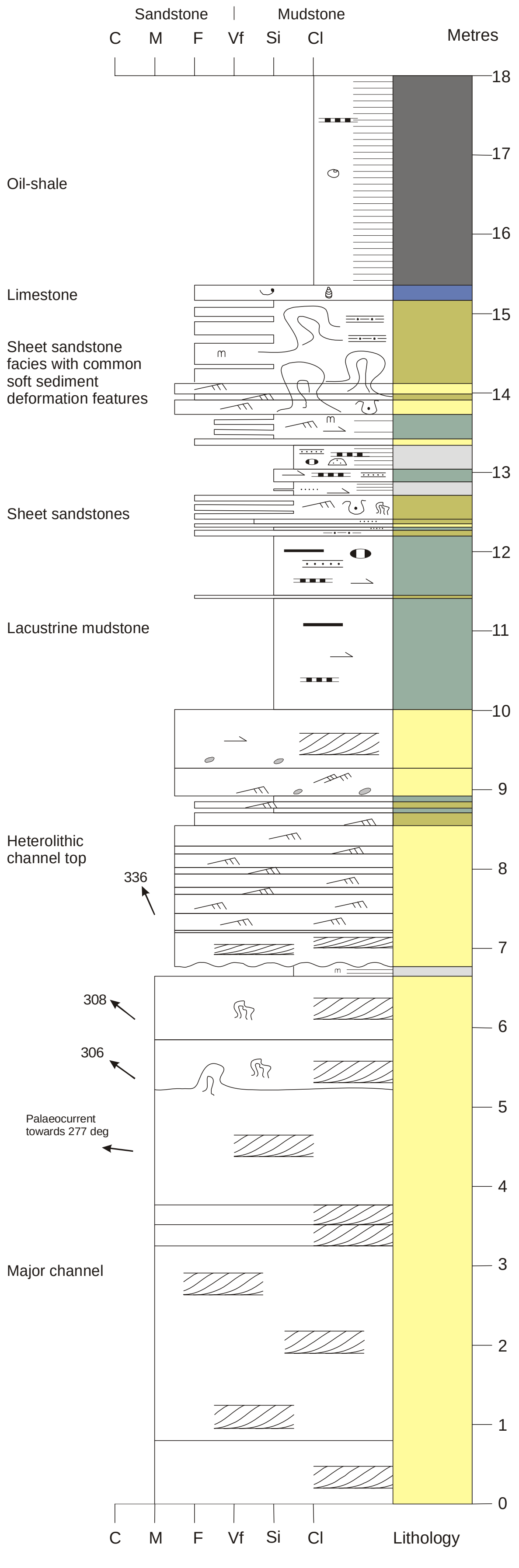
Collectors prefix	Collectors number	Locality name or SOBI Name	SOBI Borehole Reg.		Eastings	Northings	Location Information	RCS name or code (field identification)
			QS	Number				
NJN	97	Uphall Bh.R03	NT07SE	1086	306194	671497	Uphall Borehole R.03	Calcareous silicate-mudstone
NJN	98	Uphall Bh.R13	NT07SE	1096	306313	671502	Uphall Borehole R.13	Calcareous silicate-mudstone
NJN	94	Midhope Burn			305721	677856	Approximately 350 m upstream (WSW) of Binns Mill and 50 m NNE of A904 road	Calcareous silicate-mudstone
NJN	95	Midhope Burn			305721	677856	Approximately 350 m upstream (WSW) of Binns Mill and 50 m NNE of A904 road	Calcareous silicate-mudstone
NJN	96	Midhope Burn			305761	677917	Approximately 300 m upstream (WSW) of Binns Mill and 130 m NNE of A904 road	Calcareous silicate-mudstone

Table 1. Thin section metadata

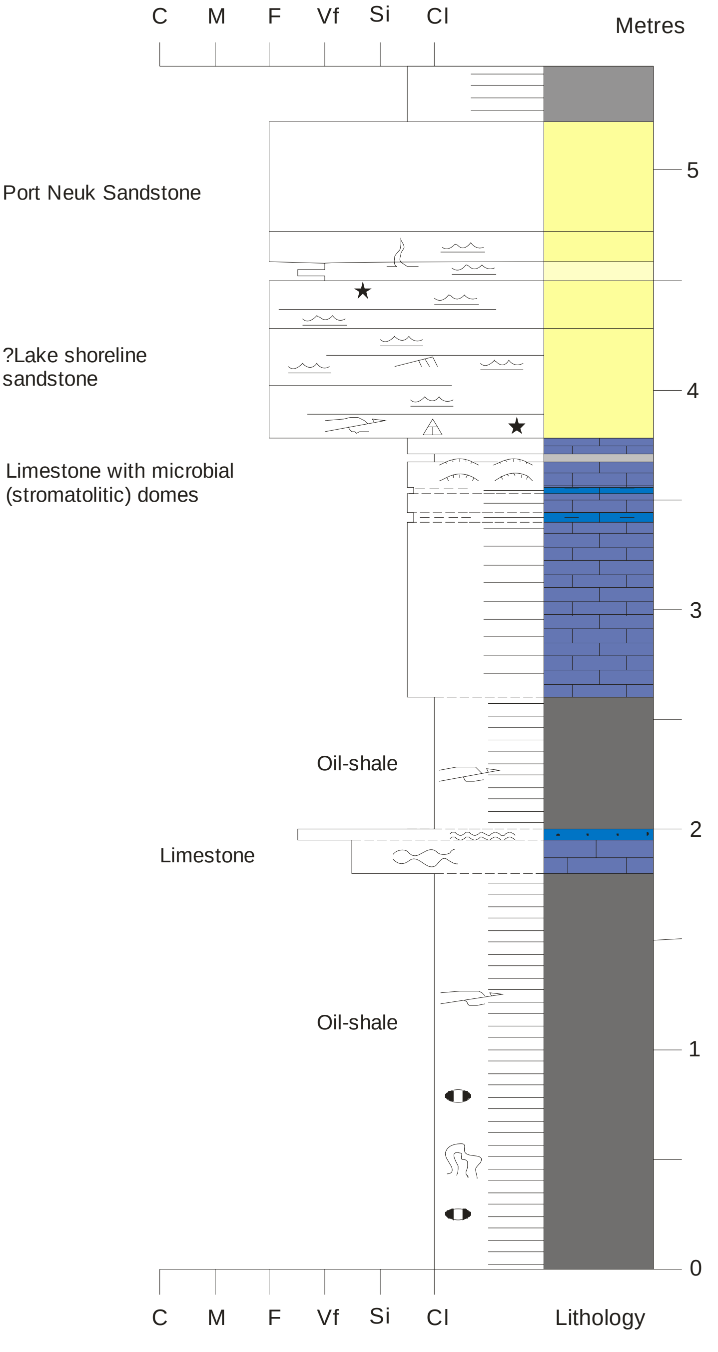
Appendix 1 Sedimentary logs

Key to sedimentary log symbols

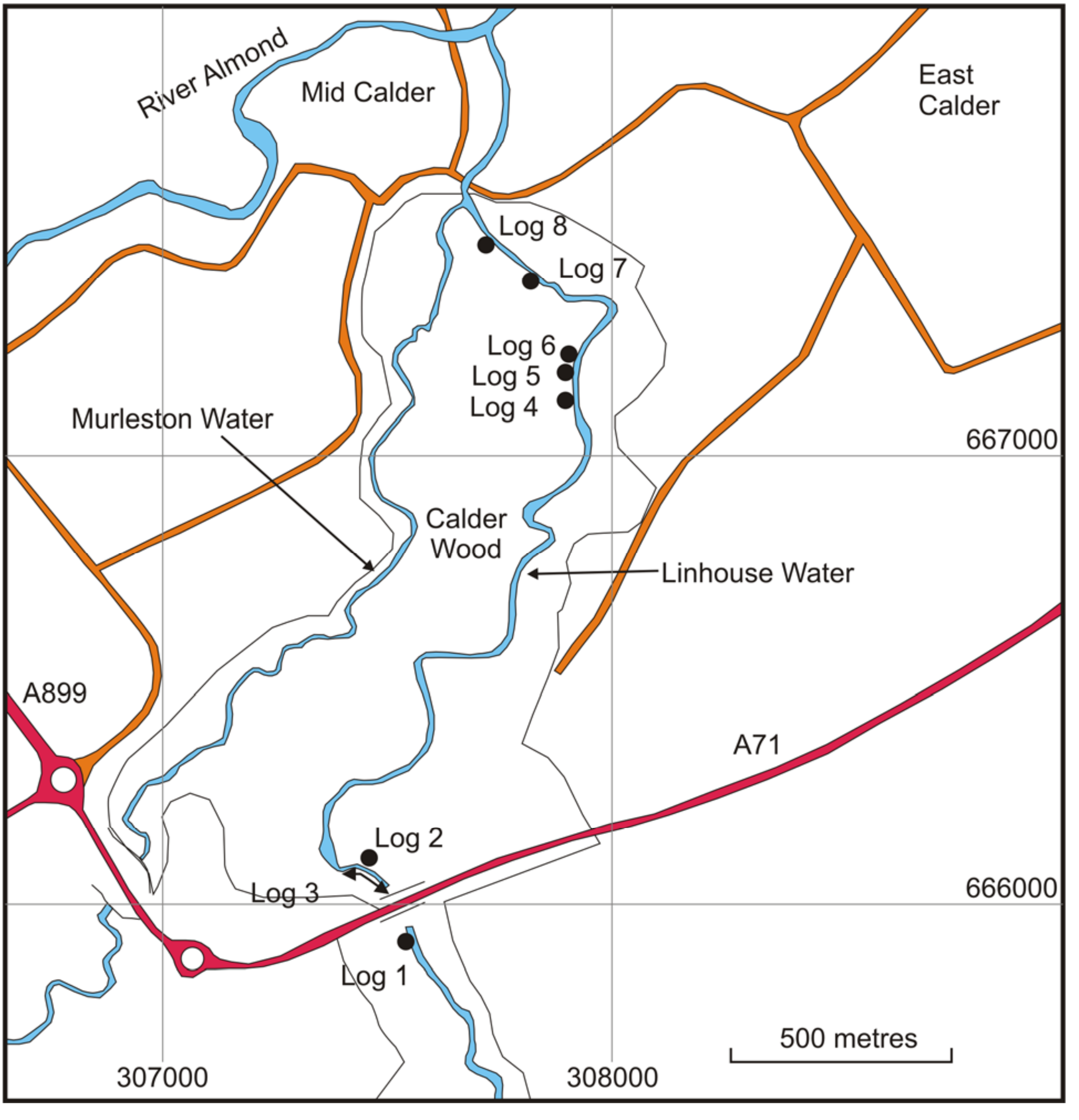




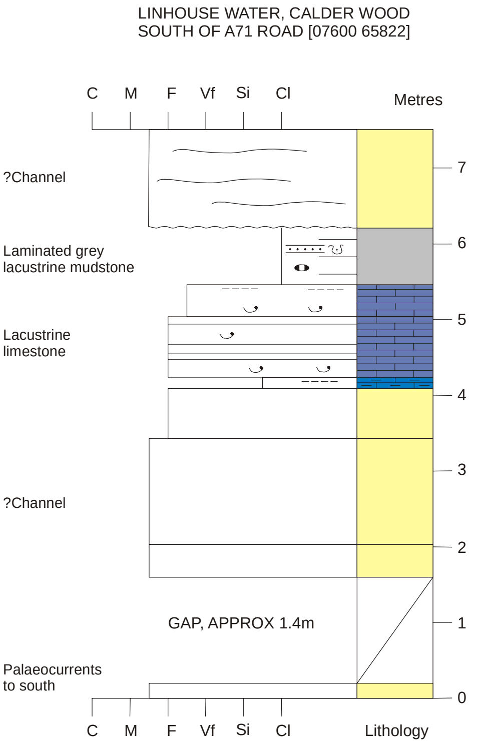
Sedimentary log of the Gullane Formation (Strathclyde Group) outcrops at Craigleith Retail Park [NT 2271 7468]



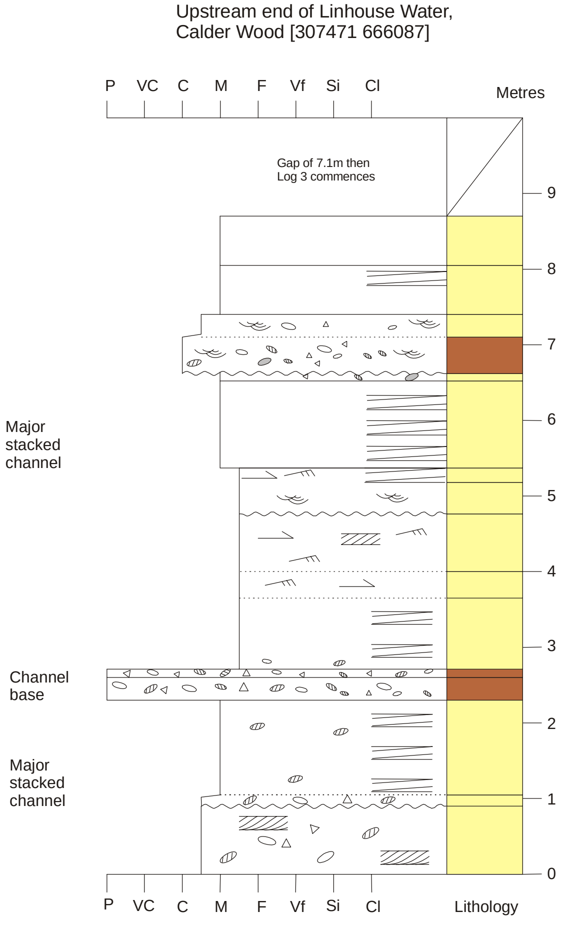
Sedimentary log of the WLOSF succession at South Queensferry [NT 14175 78542]



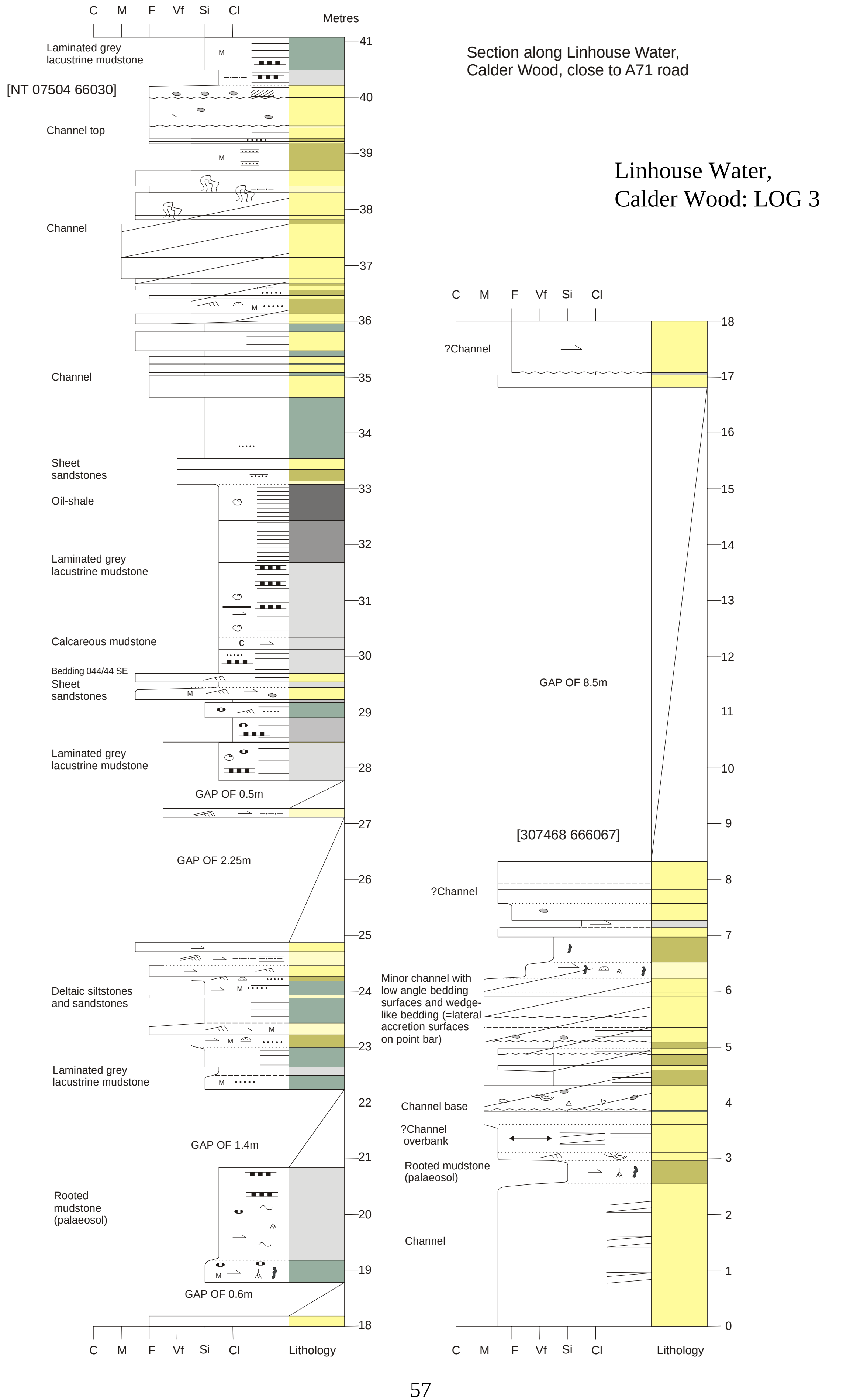
Location map to show the positions of the sedimentary logs from Linhouse Water, Calder Wood

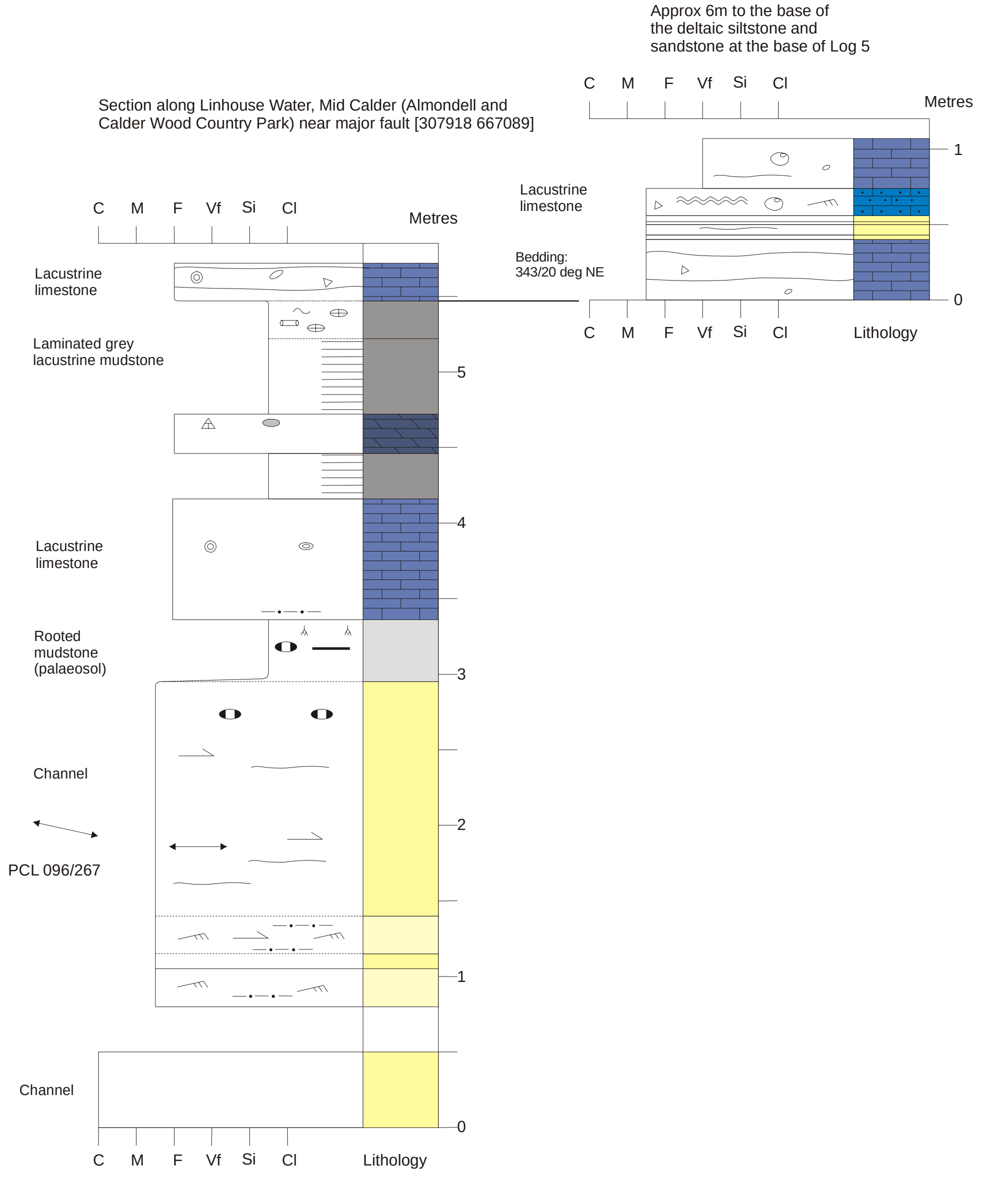


Linhouse Water, Calder Wood: LOG 1



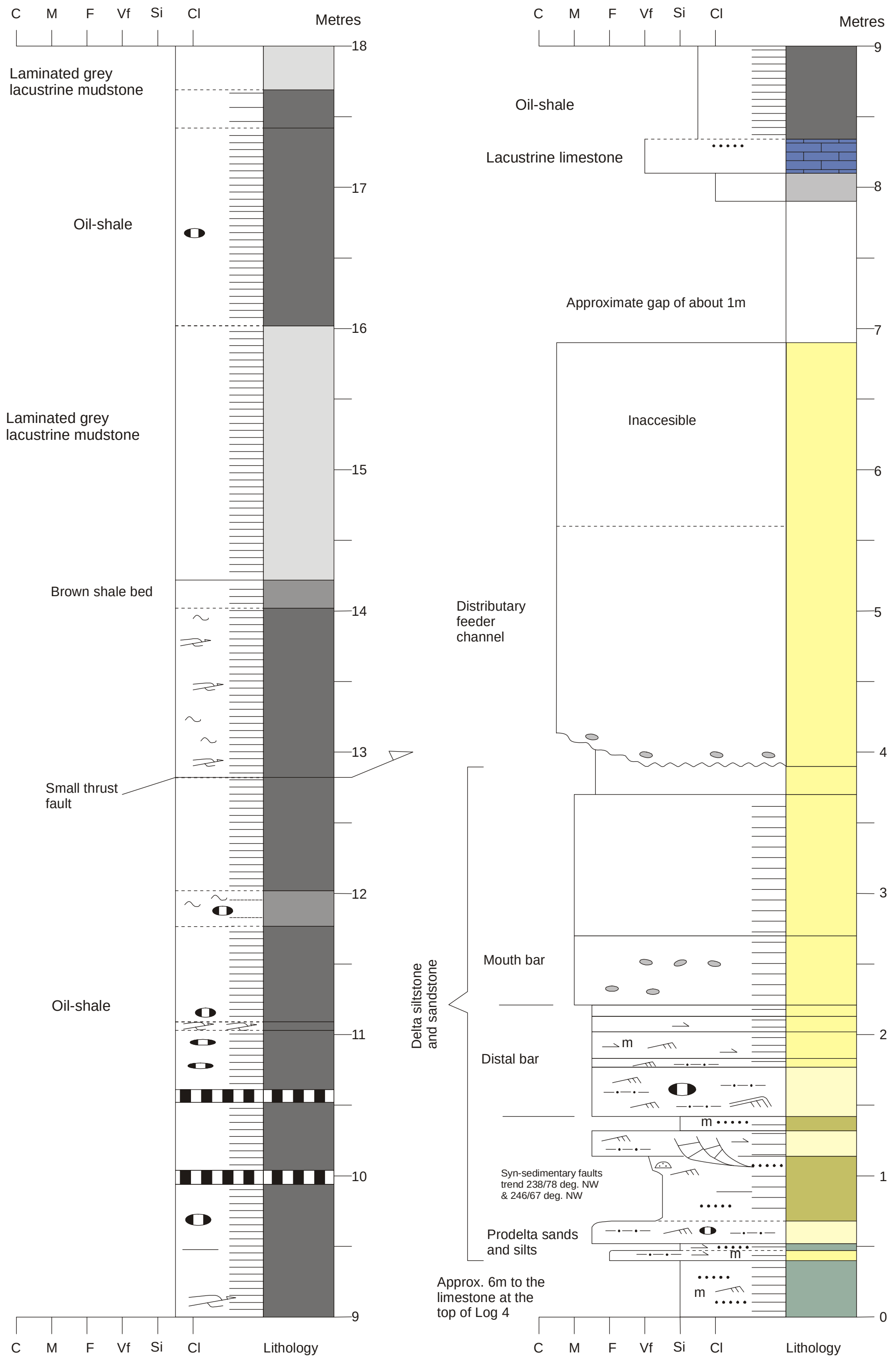
Linhouse Water, Calder Wood: LOG 2


Section along Linhouse Water, Calder Wood, close to A71 road
Linhouse Water, Calder Wood: LOG 3
C M F Vf Si Cl
Metres
Laminated grey lacustrine mudstone
[NT 07504 66030]
Channel top
Channel
Channel
Sheet sandstones
Oil-shale
Laminated grey lacustrine mudstone
Calcareous mudstone
Bedding 044/44 SE
Sheet sandstones
Laminated grey lacustrine mudstone
GAP OF 0.5m
GAP OF 2.25m
Deltaic siltstones and sandstones
Laminated grey lacustrine mudstone
GAP OF 1.4m
Rooted mudstone (palaeosol)
GAP OF 0.6m
Lithology
?Channel
GAP OF 8.5m
[307468 666067]
?Channel
Minor channel with low angle bedding surfaces and wedge-like bedding (=lateral accretion surfaces on point bar)
Channel base
?Channel overbank
Rooted mudstone (palaeosol)
Channel
Lithology

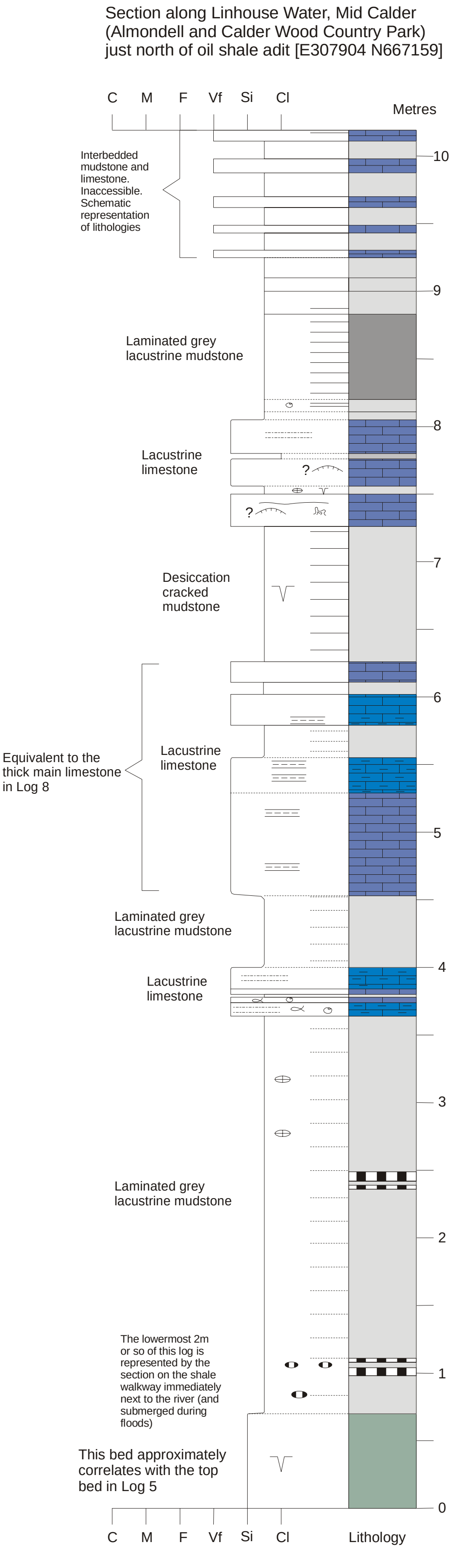


Linhouse Water, Calder Wood: LOG 4

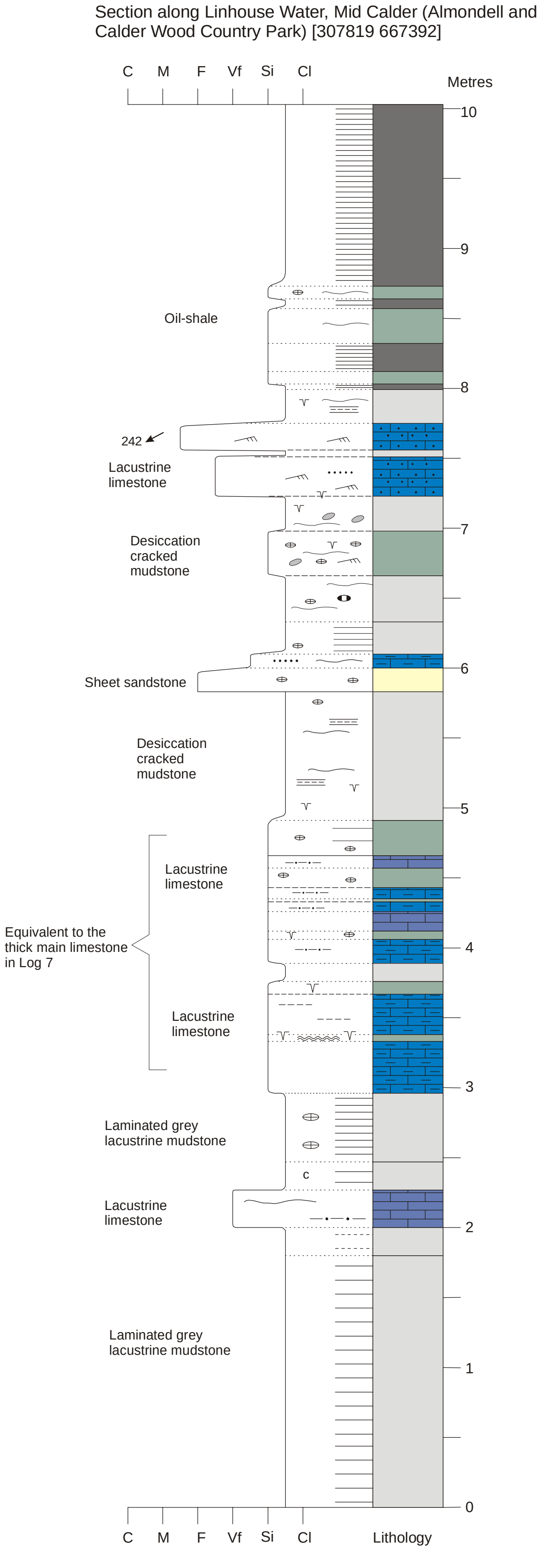
Section along Linhouse Water, Mid Calder (Almondell and Calder Wood Country Park) [307902 667156]



Linhouse Water, Calder Wood: LOG 5



Linhouse Water, Calder Wood: LOG 6



Linhouse Water, Calder Wood: LOG 7

Linhouse Water, Calder Wood: LOG 8