**Appendix F. Borehole lithostratigraphic descriptions**

Six borehole cores were examined in this study from the Yorkshire Sub-Basin. Salterford Farm and Woolsthorpe Bridge were drilled by the British Coal Board and are now housed at the British Geological Survey, and capture the Cadeby Formation of Cycle 1 (EZ1). SM4 Gough, SM7 Mortar Hill, SM11 Dove’s Nest and SM14b Woodsmith Mine North Shaft were drilled by Sirius Minerals PLC and between them capture the evaporites of Cycle 2 (EZ2) up to the top of Cycle 5 (EZ5). Below are brief lithological descriptions of the boreholes.

**Borehole SM4 Gough [NZ 946001]**

Borehole SM4 has a total depth of 1669.91 m bRT, passing through Zechstein cycles 2 to 5. At its base SM4 terminates in the Kirkham Abbey Formation of EZ2, a 0.87 m thick limestone. The Fordon Evaporite formation of EZ2 is 231.23 m thick and composed of halite, polyhalite and anhydrite in the lower ~200 m, and predominantly halite in the upper ~35 m. The 0.64 m thick Grey Salt Clay mudstone marks EZ2/3 boundary, and is topped by the Brotherton Limestone (47.82 m), the Billingham Anhydrite (11.47 m), and Boulby Sylvinite/Halite (49.31 m) formations. The Carnallitic Marl (15.73 m) marks the EZ3/4 boundary and is topped by the dolomitic Upgang (0.63 m), Sherburn Anhydrite (6.53 m), Sneaton Halite (14.95 m), Sneaton Potash (8.46 m), and Sneaton Halite (5.79 m) formations. The top of the borehole passes up into the Sleights Siltstone formation of EZ5, marking the boundary between EZ4/5. A total of 17 samples were taken from SM4 from the Fordon Evaporite Formation through to the Sleights Siltstone.

**SM7 Mortar Hall [NZ 899068]**

Borehole SM7 has a total depth of 1626.84 m bRT. The 259.43 m cored covers the upper part of the Kirkham Abbey Formation (198.3 m thick), which is overlain by the thick polyhalite succession of the Fordon Evaporite Formation (223.28 m). The EZ2/3 boundary is marked by the mudstone of the Grey Salt Clay (0.92 m), which is overlain by the limestone of the Brotherton Formation (16.93 m). 10 samples of black argillaceous mudstone and grey mudstone from the EZ2/3 boundary, and one sample of argillaceous halite, were taken over a depth range of 6.32 m between 1382.41 m and 1388.73 m, corresponding to the Fordon Evaporites Formation, Grauer Salzton, and Brotherton Formation, across the EZ2/3 boundary.

**Borehole SM11 Dove’s Nest [NZ 894053]**

With a total depth of 1582.54 m bRT, borehole SM11 is the borehole sampled to the highest resolution in this study. At its base, SM11 terminates in the Fordon Evaporite Formation of EZ2, a 134.14 m thick sequence of halite, sulphatic halite, polyhalite, anhydrite and halite/sylvinite. At the boundary between EZ2/3, the Grey Salt Clay, a 0.9 m thick interval of argillaceous limestone/dolomitic mudstone, separates the Fordon Evaporite Formation from the Brotherton Formation. The Brotherton Formation represents the carbonate phase of EZ3 and comprises 46.4 m of dolomitic limestone. The evaporative phase of EZ3 is represented by a total of 66.3 m of the Billingham Anhydrite (19.65 m), Boulby Halite (Units B & A) (43.3 m), Boulby Potash (Unit C) (2.15 m) and Boulby Halite (Unit D) (1.2 m). The Carnallitic Marl Formation, a 23.44 m thick hygroscopic reddish brown mudstone, lies at the boundary between EZ3/4. On top of this lies the 0.7 m thick dolomite of the Upgang Formation, the Sherburn Anhydrite (8.26 m), Sneaton Halite (Units B & A) (16.30 m), the Sneaton Potash (Unit C) (2.9 m) and Sneaton Halite (Units E & D) (20.65 m). The start of EZ5 is marked by the mudstone/siltstone of the Sleights Siltstone, which is topped by the final part of the Zechstein, the Littlebeck Anhydrite (0.9 m). SM11 then passes up into the Roxby Formation, and up into the Triassic through to the topsoil. A total of 126 samples were collected from SM11 ranging from the Fordon Evaporite Formation through to the Bröckelshiefer.

**Borehole SM14b Woodsmith Mine North Shaft [TA 054892]**

Borehole SM14b is the shortest length of borehole core sampled in this study, although originally drilled to a depth of 1627.27 m bRT. Available for sampling was under 10m of the upper part of the Fordon Evaporite Formation (EZ2), the Grey Salt Clay (EZ3), and the lower part of the Brotherton Formation (EZ3), fortunately capturing the EZ2/3. Of the original 368.52 m of core extracted, 9.67 m of the Fordon Evaporite Formation through to the lower part of the Brotherton Formation from which 9 samples were taken.

**Salterford Farm (Oxton) [SK 605528]**

Salterford Farm borehole was drilled in 1961 near the village of Oxton in Nottinghamshire for the National Coal Board by Foraky Ltd, now housed at the British Geological Survey, Nottinghamshire. Of interest are the approximately 157 m of Permian-Triassic sediments drilled, including the Basal Permian Breccia and a 155 m thick sequence of Permian-Triassic sandstone, dolomite and marls. The 6 samples taken from Salterford Farm borehole were taken from a 19 m long interval through the Lower Permian Marl. Samples SF445, SF455 and SF465 are of grey to mid-grey mudstone, silty dolomite, with bands approaching impure dolomitic limestone. Samples SF475 and SFYFP6373 are of unlaminated massive grey silty dolomitic mudstone. Sample SFYFP6873 from Fredric Godwin’s hand sample collection is from the boundary between the Lower Permian Marl and Basal Permian Breccia.

**Woolsthorpe Bridge [SK 843348]**

One borehole core hand sample was available at 544.45 m, a red fine-grained mudstone, of the Cadeby Formation. Woolsthorpe Bridge Borehole commences with 2.45 m of brick red, micaceous siltstone with mudstone laminae equating with the former ‘Lower Marl’ division and is known to contain a typical Zechstein miospore assemblage (Warrington, 1980; Berridge et al., 1999) containing *Crustaesporites* cf. *globosus*, *Klausipollenites schaubergeri* and *Lueckisporites* *virkkiae*. The overlying bed is correlatable with the ‘Lower Magnesian Limestone’, consisting of 2.55 m of brick red, laminated, micaceous, calcareous sandstone with common small siliceous pebbles.

**Outcrop Descriptions**

At outcrop in the Durham sub-basin samples were obtained from Marsden Bay, Claxheugh Rock, and Crime Rigg Quarry. In the Yorkshire sub-basin outcrop material was obtained from Kimberley, and from Little Scar beach at Seaton Carew. Outcrops of both the Durham and Yorkshire Sub-Basins are from Cycle 1, as well as Cycle 2 – Marsden Bay and Levitt Hagg Hole. In some cases, samples have been donated to this research project from personal collections e.g. Little Scar beach and Crime Rigg Quarry.

**Durham Sub-Basin**

Between South Shields and Sunderland there is a 10 km long continuous exposure of the Raisby Formation, Ford Formation and the Roker Formation, formerly ‘Magnesian Limestone’ (Smith, 1995; Stone et al., 2010).

**Claxheugh Rock [NZ 360571]**

The exposure at Claxheugh Rock lies within a fault-bounded trough near the core of the NNW-SSE Boldon Syncline, and is well known for being an almost complete section through the late Permian shelf-edge reef and its passage into equivalent backreef strata to the west. Furthermore, it is particularly important for displaying evidence of penecontemporanous submarine sliding and slumping on a large scale. At the exposure a sequence of Permian strata rests unconformably on the Upper Coal Measures (Westphalian C). It consists of an up to 18m thick (up to 58 m) sequence of Basal Permian (Yellow) Sands (Pryor, 1971), of which the north-eastern end of the face slopes steeply south-south-eastwards (Trechmann, 1954), upon which lies 0.77-0.90 m of Marl Slate, a finely laminated, buff and grey, slightly carbonaceous, dolomitic shale with laminae, lenses and thin beds of brown, carbonaceous, plastic clay, which is in turn overlain by 0-8 m of Raisby Formation formerly ‘Lower Magnesian Limestone’, a flaggy- to medium-bedded (0.05-0.30 m) very finely crystalline dolomite. The Raisby Formation is overlain by over 55m of very finely crystalline dolomite in even beds 0.1-0.25 m thick of the Ford Formation, formerly ‘Middle Magnesian Limestone’, reef and backreef facies, which are overlain unconformably by up to 6m of drift deposits and boulder clay. Two samples were obtained from thin yellow shale bands from inside the Marl Slate.

**Crime Rigg Quarry [NZ 344416]**

Crime Rigg Quarry is an important site for the Lower Permian Yellow Sands and the overlying Marl Slate and Lower Magnesian Limestone. The Marl Slate Formation is exposed at the top of a great thickness of Yellow Sands Formation. The basal and middle units of Raisby Formation are well exposed in the north of quarry, formerly the ‘Lower Magnesian Limestone’. Large faces in the quarry show the complex, interdigitating cross-bedding typical of the Yellow Sand Formation (Lawrence, 2009). A sample of the Marl Slate from Crime Rigg Quarry was donated by P. Gibson (North East Geological Society) for palynological analysis.

**Marsden Bay [NZ 398651]**

The sea cliffs at Marsden Bay are formed of 16-20m of cream and buff fine-grained dolostone of the Concretionary Limestone Formation, of the upper part of the Roker Formation (EZ2), formerly Upper Magnesian Limestone. All strata have foundered by the same amount (60-100 m). Some areas have been let down gently whereas others have had a more complex history of subsidence and are intensely fractured, known as ‘breccia-gashes’. After 135 m the cliff face exhibits a mixture of finely laminated and unlaminated rock consisting mostly of fine-grained buff dolostone but also some unlamented oolite. Some of the unlaminated beds including the oolite contain moulds of *Lieba*, *Permophorus* and *Schizodus*, and are graded and some have tight folds and shear-planes caused by downslope slumping and sliding. The six samples collected come from low lying thin bands of yellow shale at the base of the cliff face.

**Little Scar Seaton Carew [NZ 525300]**

11 samples were donated by B. Spencer dating to the uppermost Permian from an exposure of sea cliffs at Little Scar beach in Seaton Carew. This section spans the Permian-Triassic Boundary in East Yorkshire, to the south of Hartlepool. The exposure is a thicker, more proximal series of reduced beds, representing the erosion and deposition of terrestrial, extinction-derived soil carbon (B. Spencer pers. comm.).

**Yorkshire Sub-Basin**

**Kimberley Railway Cutting, Nottinghamshire [NZ 503452]**

Samples were collected from an upper Permian sequence at a railway cutting in Kimberley, Nottinghamshire, UK. This exposure has been long known (Wilson, 1876; Howard et al., 2009) and its palynology well-documented (Clarke, 1965) as well as its palaeobotany (Stoneley, 1958; Cleal & Thomas, 1995). At the exposure a 10 m sequence of the Cadeby Formation rests unconformably upon Upper Carboniferous Coal Measures. It consists of a 1.5 m thick basal layer of Permian Breccia, overlain by 7 m of “Lower Marl”, which is in turn overlain by several meters of ‘Lower Magnesian Limestone’ (Howard et al., 2009). At Kimberley the “Lower Marl” consists of red and yellow, medium-grained, calcareous sandstone containing thin bands of pale grey shale. It is from these shale bands that palynomorphs in this study were recovered, corresponding to samples K5 and K6 of Clarke (1965). Strata here represent marginal shallow marine deposits of the first major transgressive phase of the first depositional cycle of the Zechstein Sea. The precise age of the Magnesian Limestone is uncertain, but is generally considered to be late Permian (Lopingian).

**Pot Riding (between SE 527003 and SE 530007)**

This exposure is located along the disused South Yorkshire Junction Railway in the area known as Pot Riding in the Don Gorge area near Doncaster, within the type area for the Cadeby Formation proposed by Smith et al. (1974). The cutting exposes the Hampole Beds, a thin sequence located at the junction between the lower and upper subdivisions of the Cadeby Formation known as the Wetherby and Sprotbrough Members respectively.

At the site, 5 m of the topmost Wetherby Member is exposed. A transition from cross-bedded to parallel laminated oolitic dolomite and an overall decrease in bed thickness can be observed. 30-100 cm below the top of the Wetherby Member there is a minor erosion surface which is overlain by 20 cm of green silts and coarse-grained dolomites, in turn overlain by a metre of thinly-bedded oolitic dolomite and locally replaced by irregular masses of algal boundstone.

The top of the Wetherby Member is eroded, with the erosion surface undulating by a magnitude of 2.5 m – this is known as the Hampole Discontinuity. Elsewhere the discontinuity undulates as little as 30 cm indicating that the erosion at Pot Riding was more severe, producing the large undulations and small cliffs.

Pot Riding was originally described and logged by Moss (1986), and his interpretation of the environment was a marine-derived carbonate component and a combined estuarine and aeolian component derived of clastics. Overall, a continuous spectrum of environments is depicted.

Three samples, two of green siltstone and one of red mudstone, were taken from the middle Upper Dolomite of the Cadeby Formation Whetherby Member (Cycle EZ1) were taken from the Pot Riding exposure, corresponding to between locations 7 and 8 in Moss (1986). Permission to sample was acquired from Natural England and the Yorkshire Wildlife Trust to sample this site.

**Levitt Hagg Hole (SE 538011)**

A sample of red mudstone was taken at the base of the Edlington Formation, approximately 5 m below the top of the cliff. Levitt Hagg Hole is on the edge of an abandoned quarry in Sprotbrough Gorge, originally quarried for the fine-grained dolomite of the ‘Middle Limestone’/Edlington Formation.

**Sandal House, Laughton-en-le-Morthen (SK 519870)**

Permission to access this site was acquired from landowners. The Sandal House locality is an infilled quarry, now the site of Sandal Farm. One sample was acquired from this old railway cutting from underneath the base of the Cadeby Formation (EZ1), approximately 0.8 m above the infilled quarry floor. The small cliff exposes the dolomitic limestone of the Cadeby Formation Sprotbrough Member. The cliff is located at the southern end of a small limestone capped island surrounded by an apron of weathered sandstone. The slopes blend into the gentle scarp and dip topography of the underlying Pennine Upper Coal Measures Formation.

**Ashfield Brick Pit (SE 515983)**

Ashfield Brick-Clay Pit, Conisborough, is a partly-filled and partly re-excavated site. Its vertical range covers 20m of strata from the Carboniferous coal measured dormed in an equatorial coastal setting, the exhumed desert land surface formed by erosion of approximately 500 m of Carboniferous strata, a succession of water-laid desert litter of the Rotliegend, and sand trapped in hollows in the deserts surface, and the main part of the face represents the strata of the Zechstein Sea where lagoonal muds, open-sea shallow-water oolites, and scattered small reefs formed.

The succession at Ashfield Brick Pit was first described by Gilligan (1918), and has more recently been described and studied by Mitchell et al. (1947), and Downie (1967).

The main face exposes the Cadeby Formation (Wetherby Member) and is composed of the 0.28 m bed of buff, saccharoidal, very fine-grained dolomite. This is overlain by a 0.18 m bed of thinly bedded and flaggy, very fine grained, cream coloured saccharoidal dolomite. Above this lies c. 0.55 m of cream-coloured, porous, soft, saccharoidal dolomite containing scattered U-shaped burrows 13-16 mm in diameter, which is covered by 0.40 m of grey-buff, saccharoidal dolomite arranged in uneven beds 0.15-0.2 m thick separated by an irregular layer of dense finely-mottled buff and purple-red dolomite, with both beds containing bivalve and bryozoan casts. Above the bivalve-bryozoan beds a 0.45 m thick section of unevenly flaggy beds of grey-buff, saccharoidal dolomite with two discontinuous brick-red clayey 0-0.15 m layers 0.03 m apart. There are some irregular red patched and a few poor clasts of the bivalve *Bakevellia*. Above this is a 0.90 m single bed of buff, ooidal dolomite grainstone containing very abundant *Bakevellia* casts and is called the ‘Bakevellia Bed’. This is overlain by 1.25 m of cream-buff saccharoidal fine grained dolomite arranged in four beds 0.12-0.55 m thick, containing abundant bivalves. Above this is 0.45 m of buff saccharoidal dolomite arranged in one to three beds with 0-0.06 m of grey and dark red mottled clayey mudstone filling hollows at the top and a 0.07-0.12 m basal group of thin wavy-bedded dolomites with several laminae of red dolomitic clay. Topping this is 0.6 m of cream and buff saccharoidal dolomite which is unevenly thin- and medium-bedded. The face ends with 4 m of cream and buff saccharoidal, porous, dolomite arranged in fairly even beds of 0.20-0.70 m. It passes sharply into a bryozoan boundstone patch-reef which is approximately 30m wide.

One sample of light grey clayey mudstone was taken from the 0.45 m thick layer of dolomite containing grey and dark red mottled clayey mudstones. This bedded dolomite now lies approximately 1 m above the quarry bench.

Currently located below the bench and inaccessible, but previously described, is the rest of the Wetherby Member including a 3.2 m succession of marls and mudstones overlying the 0.4-1.7 m breccio-conglomerate and cemented sand of the Basal Permian deposits, which in turn overlain by the Westphalian Upper Coal Measures of the Carboniferous.

This site differs from others exposing the Cadeby Formation Wetherby Member. Typically, the Carboniferous-Permian unconformity is flat to gently-rolling bearing a thin scattering of small subangular pebbles that were probably loosened from the land via extreme temperature variation s and chemical (salt) weathering. Pebbles concentrated in hollows are also expected to accumulate during flash floods and periods of high rates of run-off, especially in areas of steep local relief where the breccia components are of a more local origin. However, the breccia here differs from the typically well-cemented Basal Permian Breccias that are common across the Cleveland High and are composed of resistant multi-cyclic pebbles that likely accumulated as desert piedmont pavements.

The Lower Marl facies at this site are likely a local variant, disconnected from the main area of Lower Marl in Yorkshire. Instead it is one of a number of small patches of Cadeby Formation that are unevenly distributed at outcrop north of Sheffield. The Lower Marl is an argillaceous facies belonging to the Wetherby Member of the Cadeby Formation and is not the older Marl Slate strata, which does not crop out in Yorkshire. Instead of being deposited under deeper-water anoxic conditions like the Marl Slate, the Lower Marl of the Wetherby Member was deposited at a slow rate in a low-energy inshore shallow lagoonal setting lying landwards of an oolite shoal or barrier bar.

The exposed part of the face is typical of the Wetherby Member, however the amount of dark red argillaceous layers and patches of red staining is abnormal, potentially derived from the strongly reddened Carboniferous clay-rocks immediately beneath. The regionally extensive ‘Bakevellia Bed’ is likely the product of an unusually extensive single sheet of coquina, implying a shallow-water deposition environment and moderate energy conditions. However, the upper part of exposure is typical of the Wetherby Member, with its ooidal grainstones composed almost entirely of dolomite, and the patch-reef. A broad, shallow, clear, open marine shelf setting with moderate energy is inferred.

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