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The rocks of Spireslack surface coal mine and its subsurface data: an introduction

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The rocks of Spireslack surface coal mine and its subsurface data: an introduction

R. Ellen, E. Callaghan, A. G. Leslie and M. A. E. Browne

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Front cover

Fault zone cutting the Top Hosie Limestone and seatearth in the Spireslack SCM void.

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Foreword

Spireslack surface coal mine (SCM), East Ayrshire, Scotland, contains exposures of coal-bearing Carboniferous strata of Visean to Namurian age. The entirety of the Limestone Coal Formation is exposed in a one kilometre long, over 130 m thick section within the high wall of the main void at Spireslack, whilst most of the Lawmuir, Lower Limestone and Upper Limestone formations are exposed throughout the remainder of the SCM. Natural, clean and continuous exposures of these economically important strata are rare, and therefore the exposures at Spireslack give an opportunity to better understand the geology of this part of the Carboniferous within central Scotland.

Legacy mining data from Spireslack includes georeferenced, XYZ data from late 19th to early 20th century underground coal mining, and late 20th to early 21st century surface coal mining. These data provide an understanding of the subsurface structure of the strata exposed within Spireslack, allowing a local scale geological framework to be constructed.

This report provides a description of the geology exposed at Spireslack, which can be used as a foundation for further research at the site, and contribute to a wider understanding of similar coal-bearing strata elsewhere in Scotland. This report also provides a description of a 3D model of the bedrock site, constructed from legacy mining data and from field survey.

Acknowledgements

The authors wish to express their thanks to SMRT, Robin Caldow and Kenny Ewart for access to Spireslack. Maps and diagrams have been prepared by the authors, except where stated. Chris Thomas is also thanked for constructive feedback on the text.

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Summary

Surface coal mining at Spireslack, East Ayrshire, has exposed a one kilometre long, vertical section of over 130 m of Carboniferous strata. This includes a variably exposed complete sequence through the Limestone Coal Formation, one of the main coal producing units in Central Scotland, and also the underlying Lower Limestone Formation. Parts of the Lawmuir and Upper Limestone formations are also exposed. Such laterally continuous exposures of these Carboniferous strata are rarely exposed in nature, and therefore Spireslack allows the opportunity to study their features in detail. These include laterally extensive fluvial sandstone sequences; palaeosol horizons with in situ tree casts; regionally correlateable limestones; fold and fault-related structures and their relation to differing mechanical rock properties; and regionally important marine bands and other fossils within the Carboniferous.

Data obtained from abandonment plans of earlier underground coal mining, and from more recent surface coal mining, have been used in combination with 1:10 250 geological fieldslips, to reconstruct the position and structure of seven mined coal seams from Spireslack in a 3D geological model. The model reveals geological folds previously photographed but not mapped before and allows the structure and position of the Muirkirk Syncline to be mapped accurately in this area.

This report firstly presents an account of the geology exposed at Spireslack, and secondly the results of the 3D geological model. The 3D model will underpin future geological investigations of Spireslack and act as a foundation for subsequent sub-surface geological modelling (e.g. seismic modelling, fluid flow modelling, etc).

1 Introduction

Spireslack is an abandoned surface coal mine (SCM) at Glenbuck, East Ayrshire, Scotland. The Carboniferous Limestone Coal Formation was mined here for its extensive and thick coal seams: indeed, it is one of the main coal producing units in the Midland Valley of Scotland. The Glenbuck area has a long history of mining beginning with bell pits sunk for ironstone in the late 18th century. Underground coal extraction was active in the late 19th/early 20th century followed by later 20th to 21st century surface coal mine operations. Underground coal mining within the Spireslack area was accessed via the Grasshill Pit, which closed in 1931 and presaged the final decline of Glenbuck village – of which there is little trace today. Surface coal mining began around 2000, ending in 2008 due to the decline of the Scottish coal industry.

As a result of the surface coal mining, the main void at Spireslack has created a spectacular worked face 1 km long and 130 m high, which exposes almost the entirety of the Limestone Coal Formation. Worked faces elsewhere across the site expose sequences from the Lawmuir, Lower Limestone and Upper Limestone formations (Figure 2). The geological structures and strata exposed here are not typically seen on anything approaching the same scale or completeness/continuity within natural sections across Scotland, or farther afield in the UK. Spireslack also preserves evidence of the earlier generation of mining, where 20th/21st century surface mine operations are superimposed on underground workings from the 19th/20th century.

Though the coal mines throughout the Glenbuck region were abandoned with no resources available for ground restoration, the current owners, SMRT (Scottish Mines Restoration Trust) are currently investigating solutions for the orphaned sites. BGS are assisting in this task: a geodiversity audit of the Spireslack surface coal mine was completed by BGS in 2015 (Ellen and Callaghan, 2015), with a follow up audit of the neighbouring Ponesk and Grasshill SCMs in 2016 (Ellen and Callaghan, 2016). BGS have also invited a number of UK universities to Spireslack, and a number of research projects focussed on the site are gathering momentum.

This report firstly provides an account of the geology exposed at Spireslack, based on a number of field visits made over the course of 2014/2015 plus past visits by BGS dating back to 2002. This report is therefore intended as an overview of the geology at the site, and as an foundation document for future research and education on the site. Secondly, the report presents results of a 3D geological model of the Spireslack area, constructed using legacy mining data collected over the last two centuries. This model is intended to underpin future geological investigations at Spireslack and to aid in a broader understanding of the region’s geology.

2 Geological Setting

In the following review of the bedrock and superficial (Quaternary) geology of Spireslack, information was derived from the published geological maps of the area; BGS 1: 50 000 scale map sheets 23W (Hamilton), and the geological memoir for Hamilton (Patterson et al., 1998).

2.1 GEOLOGICAL OVERVIEW

Spireslack lies in the Midland Valley of Scotland, bounded by the Highland Boundary Fault to the north, and the Southern Upland Fault to the south (Figure 1). The down-faulted region of the Midland Valley (essentially occupying the same area as the Central Belt of Scotland) between these two major faults consists mainly of Devonian and Carboniferous rocks (Figure 1) overlying Lower Palaeozoic rocks. Carboniferous sedimentary rocks in the Midland Valley of Scotland have been central in industrial development of Scotland, providing key resources such as coal, ironstone, oil shale, fireclay, sandstone and limestone.

The Carboniferous rocks exposed at the Spireslack surface coal mine are Viséan to Namurian in age (around 330 to 325 million years old). The strata (Figure 2) are assigned to the Lawmuir Formation of the Strathclyde Group and the Lower Limestone, Limestone Coal, and Upper Limestone formations of the Clackmannan Group (Browne et al., 1999). The strata at Spireslack are of typical Carboniferous rocks of this age: marine limestones and mudstones, shallow deltaic to fluvial sandstones and mudstones, and coals and related palaeosols (seatearths). These strata were deposited as upward coarsening, and sometimes upward fining cyclic packages, partly recording a fluctuating sea level.

The strata in the main void at Spireslack lie in the north-western limb of the broad upright north-east trending Muirkirk Syncline (Figure 3), and dip at 30° to 40° towards the south-east. The rocks are also displaced by mostly left-lateral (sinistral) oblique-slip faults. Narrow, up to 1 m thick, Palaeogene basaltic dykes intruded the Carboniferous strata around 60 million years ago.

Late Devensian grey-brown till (approximately 2 – 3 m thick) and dark brown-black Holocene peat (< 2 m thick), overlie bedrock. The till was deposited by ice sheets during the last Ice Age, the last main phase of which ended approximately over 13 thousand years ago. The colour of the till commonly reflects underlying bedrock.

Man-made deposits overlie both the bedrock and superficial deposits. Bell-pits dating from the 18th century are visible on the surface at the south of Spireslack by the site of Glenbuck village, whilst large rock-spoil heaps associated with the late 20th to early 21st century surface mine operations cover the pre-existing ground surface.

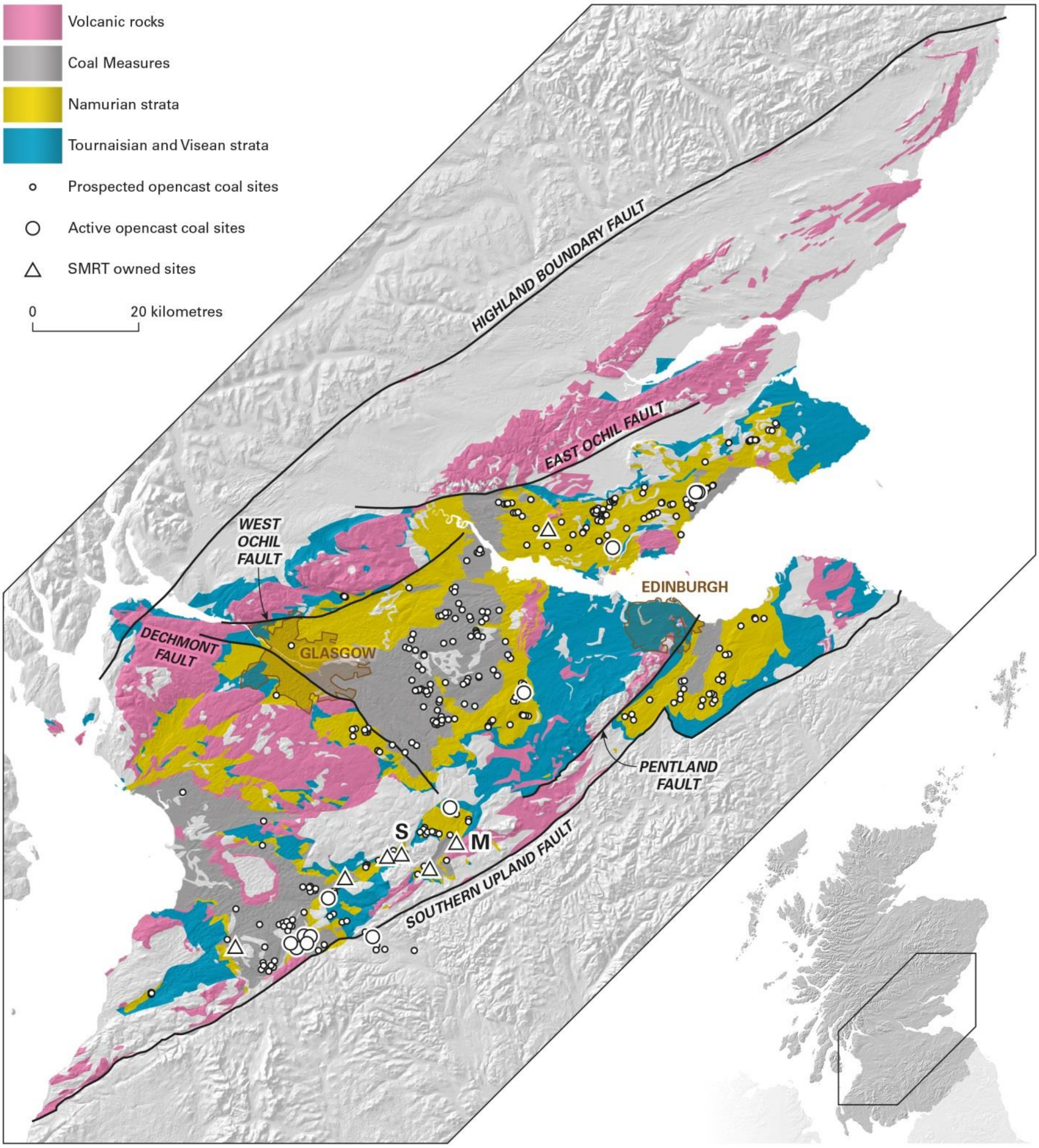

Figure 1: Generalised Carboniferous geology of the Midland Valley of Scotland, with major bounding faults – the Highland Boundary Fault to the north, and the Southern Upland Fault to the south. The map shows the locations of prospected and active surface coal mines in Carboniferous strata. Sites owned by the Scottish Mines Restoration Trust (SMRT) are indicated, including Spireslack (S) and Mainshill Wood (M).

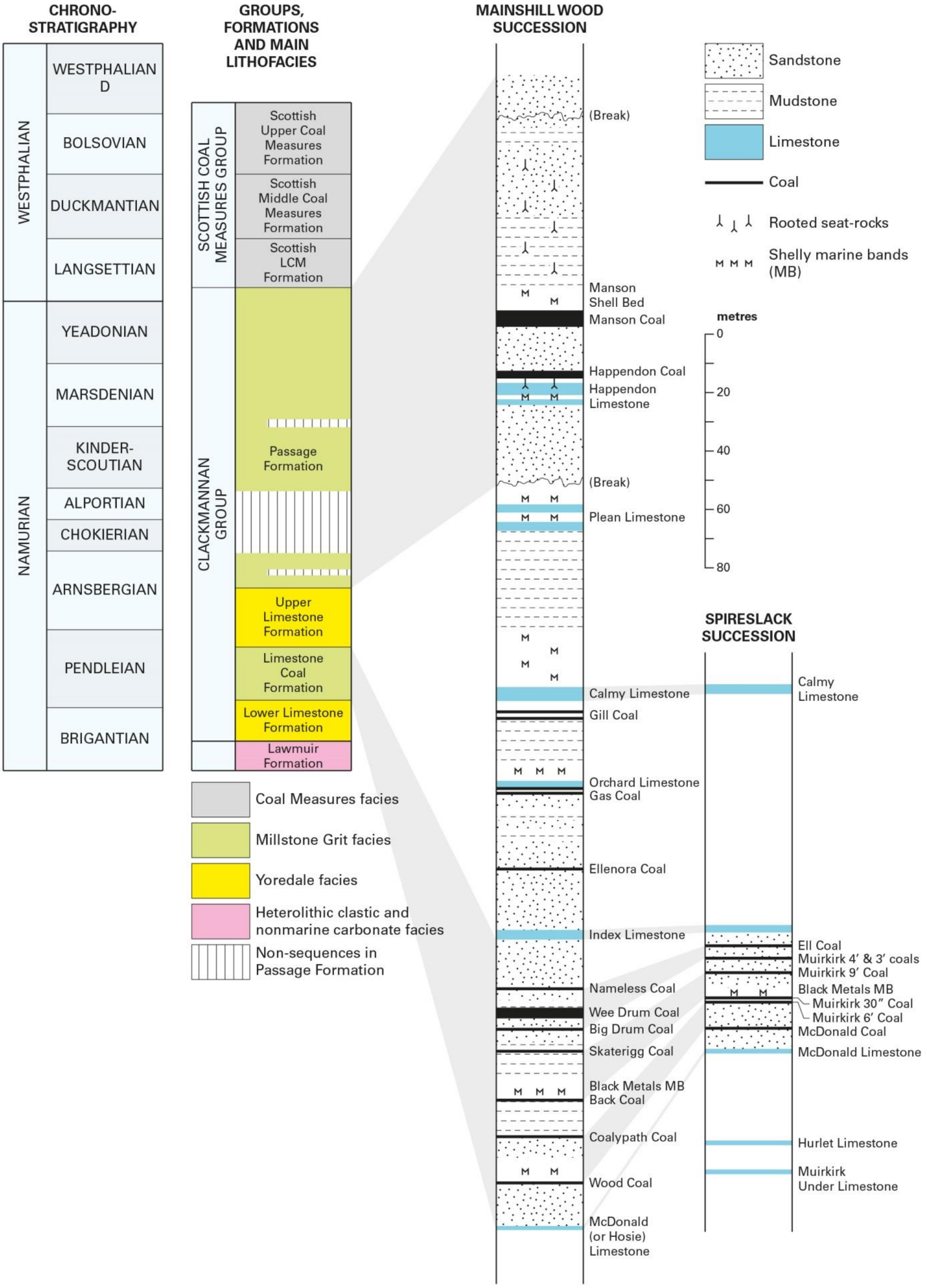

Figure 2: Stratigraphical framework for coal-bearing strata across the Muirkirk and Douglas area, based on exposures at Spireslack and Mainshill Wood SCMs. The key coal-bearing units and lithostratigraphical markers referred to in this report are highlighted in the more detailed columns.

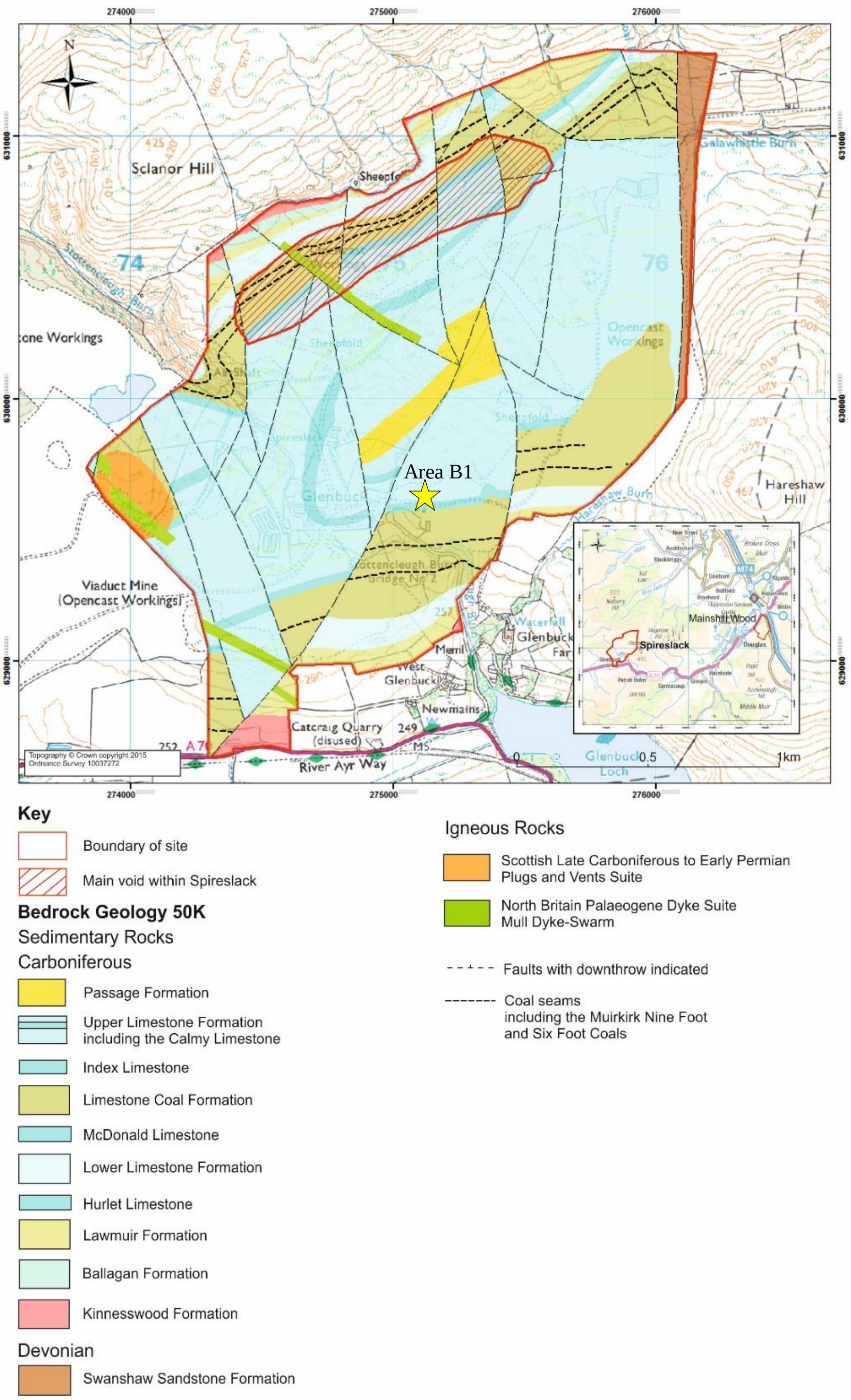

Figure 3: 1:50 000-scale geological map of the Spireslack site. The oldest rocks are exposed at the far eastern side of the site. They include sandstones belonging to the Lower Devonian Swanshaw Sandstone Formation. These are separated from Carboniferous rocks by a major north-south aligned fault. The Carboniferous strata have been folded into a broad south-westerly plunging syncline. Within the syncline, strata are offset by many minor faults with a dominant north to north-north-easterly alignment. The main void and Area B1 are indicated.

3 Geology of Spireslack – an overview

An overview of the key geological features within Spireslack is presented in the following sections. Most of the exposures are found within the Spireslack main void with the remainder in other worked faces e.g. within Area B1 (see Figure 3). All of the descriptions in this report are based on preliminary field investigations, and are intended as an overview and guide of the strata exposed. The geological features exposed at Spireslack would benefit from a detailed study in the future to include stratigraphical and sedimentary logging, and structural analysis. Local names (from the Muirkirk area) of the limestones are used throughout this report: their regional names and correlation are provided in Table 1.

Table 1: Correlation of the limestone beds in the Spireslack coal mine.

Formation	Central Coalfield Name	Local Name
Upper Limestone Formation	Calmy Limestone	Blue Tour Limestone
	Orchard Limestone	Orchard Limestone
	Lyoncross Limestone	Tibbie Pagan's Limestone
	Huntershill Cement Limestone	Birchlaw Limestone
	Index Limestone	Index Limestone
Lower Limestone Formation	Hosie Limestones	McDonald Limestones
	Blackhall Limestone	Muirkirk Wee Limestone
	Hurlet Limestone	Hawthorn Limestone
Lawmuir Formation	Blackbyre Limestone	Muirkirk Under Limestone

3.1 LAWMUIR FORMATION (BRIGANTIAN)

The Lawmuir Formation exposures throughout Spireslack consist of a variable sequence of sandstone, siltstone, mudstone, ironstone and limestone. One of the main marine limestones within the Lawmuir Formation, the Muirkirk Under Limestone, is exposed along the south-eastern edge of Area B1. It is a c. 60 cm thick unit composed of at least three limestone layers, separated from one another by grey silty mudstone (Figure 4). The limestones are grey and bioclastic, with prominent compound coral bands (Figure 5). The remainder of the Lawmuir Formation sequence is exposed above the Muirkirk Under Limestone, comprising a sequence of heavily fractured and weathered purple-grey mudstone, siltstone and pale sandstone, deformed as a result of faulting.

The upper section of the Lawmuir Formation is well exposed at the south–western edge of the Spireslack main void. A 10 m thick succession of dark-grey fossiliferous mudstones (Figure 6) and red-brown ironstone ribs (Figure 7) dominate the sequence. Both the mudstones and ironstone horizons contain abundant crinoid and brachiopod fragments.

3.1.1 Future Research/Further work

1. Fossil Identification

There are an abundance of fossils preserved within the Lawmuir Formation. These fossils should be documented, and merged with the existing knowledge of previously identified fossils within the Lawmuir Formation.

2. Sedimentary log

Using the exposures available, build up a sedimentary log of the Lawmuir Formation. This will aid with understanding of the total thickness and relationship of rock units within it to one another, allowing a better understanding of the depositional environment.

Figure 4: Muirkirk Under Limestone, Lawmuir Formation. The Muirkirk Under Limestone is at least a 60 cm thick unit of fossiliferous limestones and grey siltstones.

Figure 5: The bioclastic Muirkirk Under Limestone contains well preserved bands of compound corals. Individual septa and growth lines can be identified in the corals.

Figure 6: Fossiliferous mudstone of the Lawmuir Formation, with prominent crinoid columnal. The mudstone contains abundant crinoid fragments, with columnals up to 10 cm long.

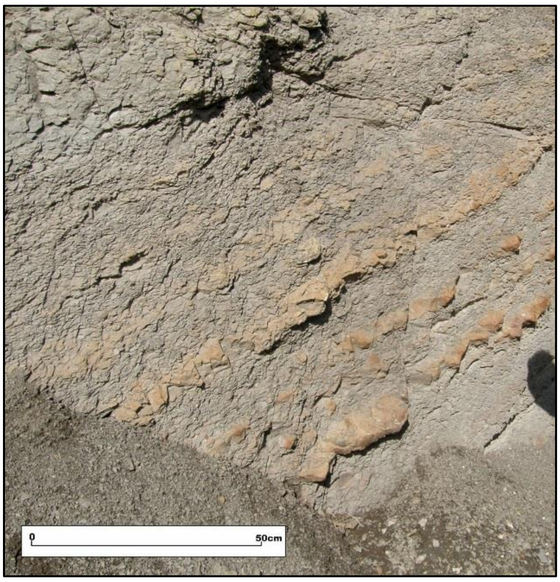

Figure 7: Ironstone bands within the uppermost Lawmuir Formation. The ironstone bands are interbedded with mudstones, and brachiopods are often found within them.

3.2 LOWER LIMESTONE FORMATION (BRIGANTIAN – PENDLEIAN)

The Lower Limestone Formation (LLF) in Spireslack consists predominantly of laterally extensive marine limestones, interbedded with mudstones. The base is taken at the bottom of the Hurlet (Hawthorn) Limestone, exposed at the south-eastern edge of Area B1 and at the south–western edge of the main void. It is seen in an at least 7 m thick section in the main void, with interbeds of siltstone and mudstone (Figure 8). It has a characteristic pale brown, nodular rubbly kaolinitic top with large productid brachiopods (*Gigantoproductus*) (Figure 9).

The top of the LLF is taken at the top of the Hosie (McDonald) Limestones, best exposed within the south-west of the main void. The Hosie (McDonald) Limestones are a series of five limestones, each between 0.5 m to 0.7 m thick, interbedded with siltstones and mudstones up to 1.2 m thick, and are best exposed within the main void (Figure 10). It is possible that the lowest of these limestones is the Muirkirk Wee Limestone. The uppermost limestone (Top Hosie) forms the engineered north-west wall of the main Spireslack void, dipping at around 30 to 40 degrees toward the south–east (Figure 11). This limestone is abundant in fossils, displaying at least three types of trace fossil: dark grey, branching structures up to 10 cm long across the entirety of the pavement (?*Planolites*, also *Rhizocorallium*), and mm- sized dark grey narrow traces (?*Chondrites*), and fossils of trilobite (*Paladin* sp.), shark spine and brachiopods (Figure 12, Figure 13).

3.2.1 Future Research/Further work

1. Fossil identification/distribution

The Hosie (McDonald) Limestone pavement contains a range of fossils, which should be documented. The most notable feature is the bioturbated surface, which has at least three different trace fossils. What are these trace fossils? How extensive are they? Are they in any other limestone within the McDonald Limestone sequence? Are there any other shark spines or trilobites preserved, is this common for the Carboniferous of this age?

2. Hurlet (Hawthorn) Limestone

The Hurlet (Hawthorn) Limestone is widely recognised as having a rubbly, kaolinitic top. What is the cause for this? How extensive is the clay weathering? What is it composed of? What can this tell us about the environment of deposition?

3. Types of Limestone

Were the Hurlet (Hawthorn) and Hosie (McDonald) limestones deposited in the same environment, and do they have the same sedimentological character? i.e. are they both fossiliferous limestones with the same fossils, are they matrix-supported by mud or shells, etc.?

4. Sedimentary Log

Using the exposures available, build up a sedimentary log of the LLF. This will aid with understanding of the total thickness and relationship of rock units within it to one another, and allowing a further understanding of the depositional environment.

Figure 8: Hurlet (Hawthorn) Limestone, exposed in the western wall of the main void. The limestone consists of at least 7 m of limestone separated by beds of mudstone and siltstone. Photo looking to the south-west.

Figure 9: The top of the Hurlet (Hawthorn Limestone), exposed in Area B1, is distinctively nodular, and contains abundant gigantoproductids (brachiopods).

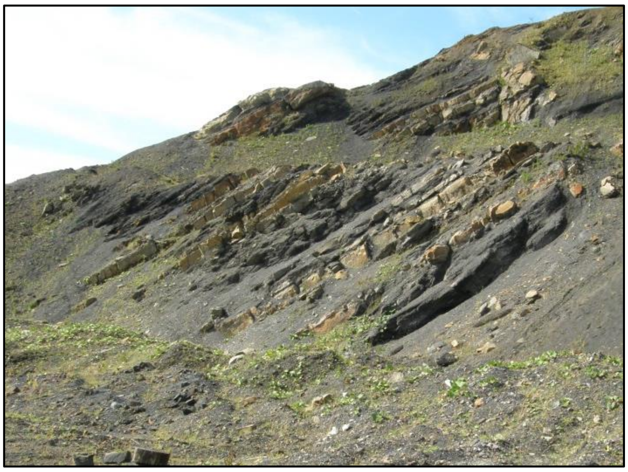

Figure 10: The Hosie (McDonald) Limestones, exposed at the south-western edge of main void at Spireslack. They consist of five limestones beds interbedded with mudstones and siltstones.

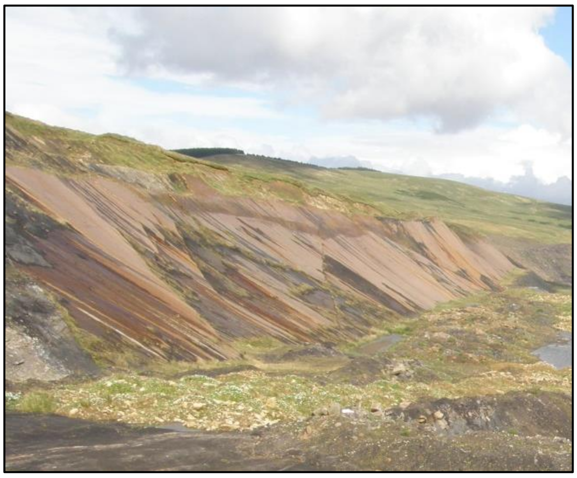

Figure 11: The Top Hosie (McDonald) Limestone engineered pavement. This limestone marks the north-west wall of the main void at Spireslack.

Figure 12: Fossilised shark spine preserved in the Top Hosie (McDonald) Limestone pavement in the north-west wall of Spireslack.

Figure 13: Trace fossils on the surface of the Top Hosie (McDonald) Limestone pavement.

3.3 LIMESTONE COAL FORMATION (PENDLELIAN)

The Limestone Coal Formation (LCF), almost the entirety of which is exposed at Spireslack, is a sequence of upward-coarsening and upward-fining cycles consisting of mudstone, siltstone, sandstone, seatearth and coal.

The LCF sequence at Spireslack is c. 95 m thick, and is exposed in a semi-continuous section in the high wall at the south–east side of the Spireslack main void (Figure 14). The base of the LCF is taken at the top of the Hosie (McDonald) Limestones, whilst its top is taken at the base of the Index Limestone, also exposed in the high wall.

A number of important Muirkirk sub-basin coal seams are exposed within the main void: in upwards stratigraphical order, the McDonald Coal, Muirkirk Six Foot Coal, Muirkirk Thirty Inch Coal, Muirkirk Nine Foot Coal, Muirkirk Three Foot Coal, Muirkirk Four Foot Coal and the Muirkirk Ell Coal. The coal exposed at Spireslack is mostly bituminous, with a 30 – 40 cm thick band of cannel coal present within the Nine Foot Coal seam (Figure 15).

Evidence of two regional marine incursions are also preserved, the Johnstone Shell Bed and the Black Metals Marine Band. The Black Metals Marine Band is not accessible, but is recognised in the high wall by its association with 3 distinctive ironstone horizons. The Johnstone Shell Bed (a dark-grey mudstone) contains a marine fauna and contains an abundance of calcareous brachiopods (Figure 16).

There are at least six significant units of sandstone (between 2 and 10 m in thickness) which display cross-bedding, stacked bars, point bars and chute channels and are channelized in places. Blocks of sandstone which have fallen from the high wall into the main floor of the canyon reveal abundant crinoidal fragments, bioturbation, cross-bedding, ripplemarks, organic fragments, and ironstone nodules (Figure 17, Figure 18). Seatearth within the LCF contain abundant fragments of organic material, consisting mostly of *stigmaria* root or *Lepidodendron* trunks (Figure 19).

There is evidence for underground workings in the Muirkirk Nine and Six Foot Coal seams, where the more recent surface mine operations have intersected older workings.

3.3.1 Future Research/Further work

1. Sandstone channels/distribution

There are at least six units of sandstone within the south-eastern face of the Spireslack void. Their thicknesses and extents should be mapped, and where possible, individual channels traced across the face. This would provide a good understanding of channel morphology and behaviour of sandstone units within Carboniferous strata. One sandstone unit thins toward a fault: is this true thinning of a sandstone package, or is it fault-related?

2. Provenance and source of the sandstone

Where the sandstone can be accessed, an assessment and study of the available palaeocurrent indicators should be carried out. This would provide an indication of the direction of the source (anticipated to be to the north-east). Are all six of the sandstone channels sourced from the same area? Use mineral provenance studies to determine this. Are they all well-sorted or is there a range of grain sizes?

3. Fossils (tree casts in seatearth and sandstones)

There are numerous tree casts and *stigmaria* roots preserved in seatearth, coal and sandstones. Are all of these fossils the same? Is there any variation in evolution within the Limestone Coal Formation sequence?

4. Sedimentary log

Using the exposures available, build up a sedimentary log of the Limestone Coal Formation. This will aid with understanding of the total thickness and relationship of rock units within it to one another, and allowing a further understanding of the depositional environment.

Figure 14: The south-eastern high wall of the Spireslack main void is cut largely in the Limestone Coal Formation, which comprises mostly of coal, mudstone, sandstone and seatearth.

Figure 15: 20 cm thick band of cannel coal within the Muirkirk Nine Foot Coal seam. The cannel coal formed in oxygen deficient shallow lakes. Photo facing south.

Figure 16: Johnstone Shell Bed, a current-rippled mudstone with abundant fossilised calcareous brachiopods; ripple crests are aligned top-right to bottom-left in the photo.

Figure 17: Fossilised *Lepidodendron* fragments preserved in a fallen block of sandstone.

Figure 18: Current-rippled sandstone of the Limestone Coal Formation, section view. Photo facing south.

Figure 19: *Lepidodendron* tree cast 3 m long, preserved in situ within the McDonald Coal seatearth. Photo facing west.

3.4 UPPER LIMESTONE FORMATION (PENDLEIAN TO ARNSBERGIAN)

The Upper Limestone Formation (ULF) exposures in Spireslack comprise cycles of predominantly sandstone with mudstone, siltstone and marine limestones. The base of the ULF is taken at the base of the Index Limestone, exposed in the main void. The Index Limestone is a 1.3 m thick grey, hard compact bioclastic limestone (Figure 20). Brachiopods and crinoid fragments are common. Overlying the Index Limestone is a 7 – 10 m thick black silty mudstone, overlain by a coarse-grained massive sandstone at least 10 m thick with cross-bedding throughout (Figure 21). This sequence of thick sandstones are also well exposed in Area B1, containing fluvial channels and overbank deposits. A 3 m thick mudstone rests above this sandstone unit, above which the sequence is eroded in the south–west end of the high wall. Faulting has thrown the uppermost part of the Upper Limestone Formation down at the eastern edge of the main void. Strata exposed near the pond level may include the Lyoncross Limestone, and the Orchard Limestone is exposed in the high wall above the pond. Surface mine workings have exposed the Calmy (Blue Tour) Limestone in the far north–east of the void. This limestone consists of a series of at least four massive, thick limestone beds alternating with siltstones and mudstones in a package of at least 10 m thick (Figure 22). The Gill Coal Seam sits beneath the lowermost exposed limestone. It is up to 1 m thick and contains significant pyrite mineralisation (Figure 23). Strata above this level in the Upper Limestone Formation are not preserved in the main void.

3.4.1 Future Research/Further work

1. Limestones

There are at least four different limestones exposed within the Spireslack SCM, two of which are definitely accessible: the Index and the Calmy (Blue Tour) limestone. Are both of these limestones the same, were they formed in the same environment? The Index is abundant in brachiopods yet the Calmy (Blue Tour) limestone is fine grained with sparse crinoid fossils. Is this due to depositional environment? How does that link to the surrounding rocks (coals and mudstones)?

2. Sedimentary log

Using the exposures available, build up a sedimentary log of the Upper Limestone Formation. This will aid with understanding of the total thickness and relationship of rock units within it to one another, allowing a further understanding of the depositional environment.

3. Pyrite mineralisation

There is abundant pyrite mineralisation within the Gill Coal, beneath the Calmy (Blue Tour) limestone. Is pyrite mineralisation seen elsewhere within the other coals exposed within Spireslack? If so, where does it occur, and why? Can this give us clues about its origin and environment of deposition?

4. Sandstone channels

There is at least one major unit of sandstone at least 10 m thick which is exposed at the top of the Spireslack main void, and also within Area B1. Its thickness, internal architecture and extent should be mapped, and where possible, individual channels traced across the face. Individual mud drapes taper out across coarser sandstone units, interpreted as overbank deposits. Mapping out the detail of the internal architecture of this sandstone would add to a good understanding of channel morphology and behaviour of sandstone units within Carboniferous strata.

Figure 20: The Index Limestone has a brownish-orange weathering rind, and contains abundant brachiopods.

Figure 21: Mudstone and sandstone overlying the Index Limestone in the western part of Spireslack.

Figure 22: Calmy (Blue Tour) Limestones exposed in a worked face at the north-east of the site.

Figure 23: Pyrite mineralisation is abundant in the Gill Coal seam, here seen in exposures in the north-east of the site.

3.5 IGNEOUS INTRUSIONS (?PALAEOGENE)

The Carboniferous strata at Spireslack have been intruded by at least five Palaeogene-aged basaltic dykes, each up to 1 m wide (Figure 24, Figure 25). The dykes intrude the strata vertically, and are exposed in both the high wall of the Spireslack main void, and in the Top Hosie (McDonald) Limestone Pavement. The dykes have a curvilinear form when traced from the high wall to the pavement, and in places, merge together to form one single dyke rather than two individual strands. Where the basalt intrudes a coal or carbonaceous mudstone layer, it is altered to white trap. The extent of the alteration appears to be related to bed thickness and dyke thickness. The strata are also apparently offset on a cm-scale on either side of the dyke.

3.5.1 Future Research/Further work

1. ‘White trap’ distribution

Where a basalt dyke cut carbonaceous layers, it and the immediately adjacent rock are altered to ‘white trap’. The extent and distribution of the white trap should be mapped, and samples taken for petrographical analyses. There is a literature gap regarding the distribution and limits of white trap, and their relation to, for example, dyke thickness, and sedimentary rocks intruded e.g. what level of carbon does a sedimentary rock have to contain before decarbonisation of the basalt will occur, and therefore form white trap?

2. Baked/chilled margins

The dykes exposed at Spireslack lack an obvious chilled or baked margin where they cut carbonaceous mudstones. It is possible the apparent white trap in the shales immediately adjacent to the dykes are weathered chilled/baked margins, but more work is required to determine this. Chilled margins are visible where the dyke intrudes the Top Hosie (McDonald) Limestone pavement but are not immediately obvious where it cuts the mixed succession in the high wall. Future work should map the extent of the chilled margins in the Top Hosie (McDonald) Limestone and their relationship to dyke thickness, and sample the baked limestone for petrographic analysis and comparison with unaffected limestone. This relationship should then be compared with where the dyke cuts other lithologies (e.g. sandstones/coal).

3. 3D geometry and linkage

The high wall exposure of the dykes gives the impression that the dykes are isolated vertical intrusions. However, it is clear from their exposure on the Top Hosie (McDonald) Limestone pavement that the dykes are spatially linked, as two of the dykes merge at the top of the limestone pavement. Dykes are often only exposed in a 1D or 2D sense, whilst Spireslack allows a 3D perspective of dyke intrusion to be studied. 3D modelling combined with field observations should be used to build a better 3D understanding of dyke geometry and linkage associated with Palaeogene rifting.

4. Petrology

What are the dykes composed of? Is this consistent with Palaeogene dykes elsewhere in the region? We assume that because of their orientation these are Palaeogene dykes. However, to confirm this, further petrological work is required.

5. Fracturing

Natural dykes are most commonly found in coastal exposures, where they have been smoothed and polished by coastal erosion, or in inaccessible high cliffs. Therefore measurements of fracture orientations and densities internal to the dyke are often difficult to measure. Fractures internal to the dykes are well exposed in Spireslack. These should be measured to allow us a better understanding of fracture frequency, spacing, orientation and intensity within dykes, as these will affect fluid flow within the subsurface. Comparisons should be made with dykes of different sizes in Spireslack to determine if fractures within vertical dykes are predictable, and can therefore be used in industry workflows to model fluid flow in a typical Carboniferous intruded sequence. Fractures in the wall rocks should also be measured to determine any mechanical change the dyke has induced during intrusion.

6. Country rock lenses

The south-eastern main face exposes a dyke which bifurcates around country rocks, leaving in-situ sedimentary rock lenses ‘floating’ in the dyke. What is the thermal alteration effect of these blocks? Do they differ depending on lithology, e.g. stronger thermal affect in mudstone vs sandstone due to mineralogy?

7. Mineralisation

Where the dyke intrudes the limestone pavement, the limestone is fractured and filled with calcite. Calcite mineralisation is also observed along fault planes. Are the two phases of mineralisation linked or are they unique? Where did the calcite form, dissolution of the limestone due to hot fluids associated with intrusion? Is there calcite mineralisation in the Limestone Coal Formation, which contains no limestone, or is it only locally found where limestones are present? How far does the mineralisation extend stratigraphically?

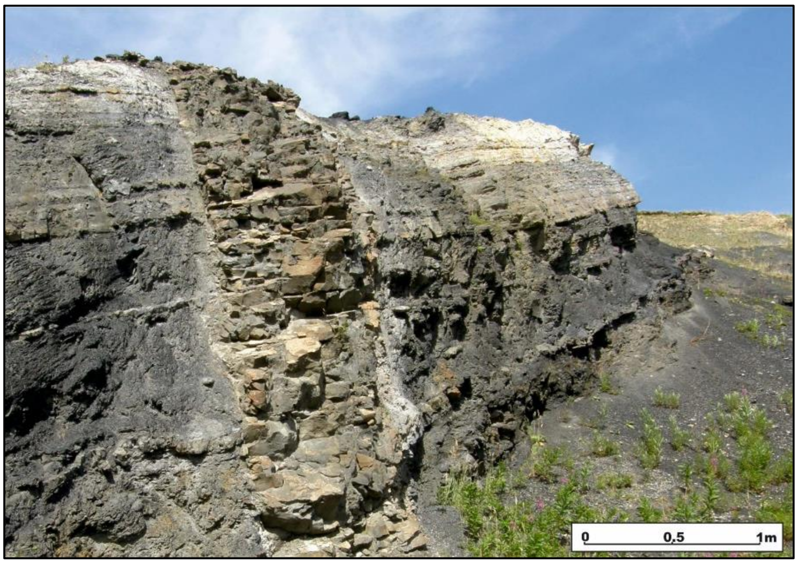

Figure 24: Palaeogene basalt dyke cutting the lowest part of the Limestone Coal Formation. The intrusion has baked mudstones along the contacts.

Figure 25: The same dyke as Figure 24, exposed in the high wall. The intrusion has been altered to ‘white trap’ where it has come into contact with the coal-bearing strata.

3.6 GEOLOGICAL STRUCTURE

The Top Hosie (McDonald) Limestone pavement and strata in the high wall are displaced by two sets of left-lateral, oblique-slip, curvilinear faults with a north – north-east and north – west orientation. When viewed in the high wall, the faults apparently indicate a normal sense of displacement: however, there is significant strike slip movement along these faults as indicated by the left-lateral sense of displacement within the Top Hosie (McDonald) Limestone. Each fault has a complex fault zone with individual fault segments either hard- or soft-linking depending on the scale of relay-ramp breaching (Figure 26, Figure 27, and Figure 28). Within the mechanically strong limestone pavement, fault planes are occasionally filled with calcite (multiple generations) though rarely fault rock. Where fault rock is present, it is a limestone-breccia. Abundant oblique-slip, polished and occasionally mineralised, gently plunging slickensides are present on the fault planes. When cutting the multi-layered high wall sequence, the fault zones are comprised of partial clay-smears, brecciated coal and fractured sandstone within the fault core. The faults appear to tip out within the thick mudstone unit overlying the Index Limestone. Mudstones and coals are intensely fractured surrounding the main fault zones and are highly polished on fracture planes. Small metre-scale thrusts are also visible in ironstone layers interbedded with mudstone within the basal Limestone Coal Formation (Figure 29) on the north-west wall.

The overall structure of the strata at Spireslack is that of the north-east trending Muirkirk Syncline, with the main void at Spireslack defining the northern limb of an upright, open, west-south-west – east-north-east trending syncline, generated in a mid- to late-Carboniferous sinistrally transpressive deformation. Previous BGS photography and 3D modelling (see section 4) from data provided from the 2004 surface mine operation has revealed the presence of decametre-scale, non-cylindrical tight folds to the north-east of the major fault displacing the strata at the east of the site. The plunging fold sequence is no longer visible at surface outcrop, as it is covered in back-filled made ground or inundated by deep water.

Combining the structural observations, these fault arrays are geometrically and kinematically consistent with an overall pattern of sinistral transpression at this time in the Carboniferous (Leslie et al., 2016).

There are natural regional joint sets formed within the Top Hosie (McDonald) Limestone, and cleat within the coal. The intensity of cleat within the coal increases with increasing proximity to fault zones. Ankerite mineralisation fills the cleat in coals adjacent to fault zones (Figure 30).

Historic underground working of the coal has resulted in subsidence and increased fracturing of the overlying strata.

3.6.1 Future Research/Further work

1. Displacement/length profiles

The Top Hosie (McDonald) Limestone pavement is cut by multiple small displacement faults. These small displacement faults vary in length and displacement value across the pavement, with fault tips (i.e. point along the fault at which zero displacement is observed) well preserved. Carrying out an analysis of fault displacement/length profiles along the pavement would allow us to build a database of fault properties in limestone, ultimately leading to predictive models of the behaviour of faults in limestone in the subsurface. Displacement/length profiles from the limestone can also be added into existing fault property databases from academics across the world in different lithologies (e.g. Kim and Sanderson, 2005) to increase our communities knowledge of fault zone behaviour.

2. Compare limestone with seatearth

The same faults cut multiple lithologies across the Spireslack void, allowing the chance to understand the role of lithology on fault structure and content. For example, the Top Hosie (McDonald) Limestone and the McDonald Coal seatearth are faulted by the same fault, yet both respond differently in a mechanical sense. For example, the limestone contains multiple fractures within the fault damage zone, yet there are less fractures in the seatearth. A detailed survey and scanline analysis of the fault across these two differing lithologies would allow a better understanding of the effect changes in mechanical properties in a mixed stratigraphy have on fault style.

3. Mineralisation in faults (ankerite mineralisation)

Ankerite mineralisation is only found within Spireslack along fault zones. This provides an indication of where the fault acted as a conduit to flow historically, and an understanding of how local that fluid was within the system. For example, is there evidence of fluid flow across other parts of the fault (and across lithologies other than coal)? Or only where the fault is in contact with the coal? How far does the ankerite mineralisation extend away from the coal?

4. Coal cleat

By taking measurements on cleat within the coal, and by comparing them with the local fault pattern, an understanding can be made regarding whether coal cleat is related to the local stress field surrounding Spireslack, or if there is a regional control: or more likely, a component of both.

5. Document fault/fold trend and orientations

A full structural analysis of the faults and folds at Spireslack should be collected to understand the kinematics of the area. Namely fault orientations, dip, slickenline readings, sense of displacement, amount of displacement, fault zone content (e.g. breccia/shale smear/mineralisation), cross cutting relationships. This analysis combined with a regional understanding of the tectonics of the area will allow a better understanding of the timing of the faults, and also how they relate to the folding observed across Spireslack.

6. What is the faulting associated with mine workings like?

Downward flexuring of the strata overlying the collapsed mines has resulted following underground workings. How far into the overlying strata is this effect observed? What has happened to the rock mass to accommodate this?

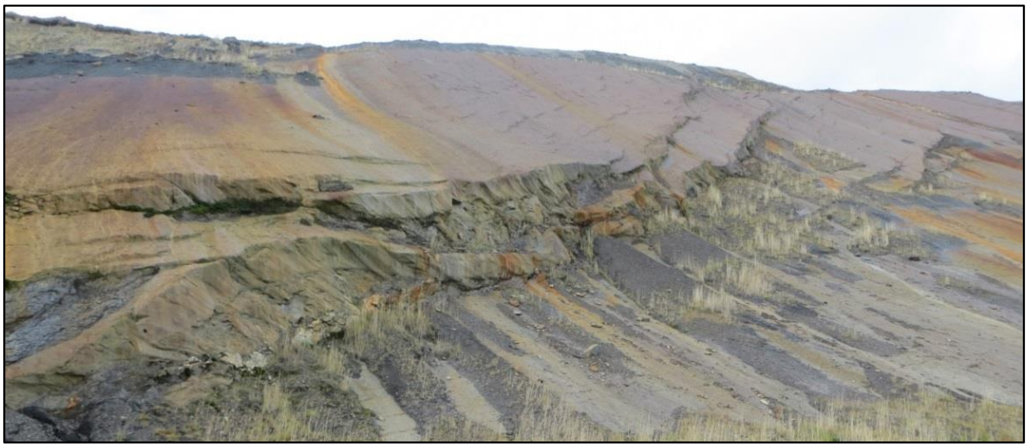

Figure 26: Faults within the Top Hosie (McDonald) Limestone pavement. The fault zone is dominated by hard- and soft-linked fault segments, with mineralised and slickensided fault planes.

Figure 27: Fault zones display differing deformation depending on the lithology they cut. In the north–west wall deformation is more brittle in the limestones (orange weathered in photo), whereas seatearths (grey rocks in foreground) deform in a less rigid manner.

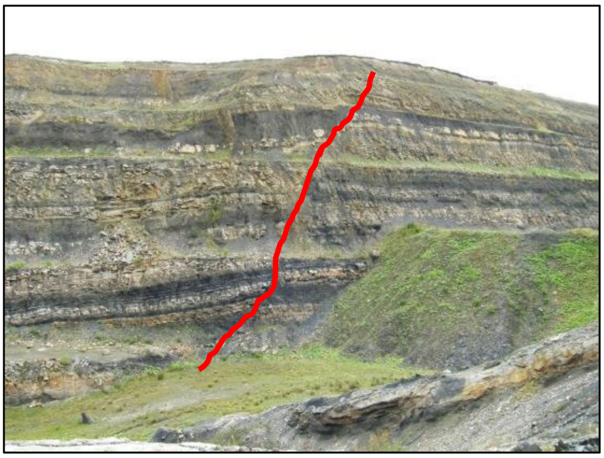

Figure 28: The fault shown in Figure 27 exposed here in the high wall face (highlighted in red). The damage associated with the hanging wall of the fault is not as obvious in the view of this section, and deformation appears to be localised along one strand.

Figure 29: Small thrust faults and localised folding are found in competent ironstone layers within weaker mudstones. Strain is more distributed within the incompetent mudstone, where it is accommodated by closely spaced polished fractures. The ironstone has shortened in response to the strain.

Figure 30: Where coal is cut by the fault zone, the intensity of the cleat increases approaching the fault. The more intense cleat is mineralised by weathered orange-brown (ankeritic iron carbonate).

3.7 QUATERNARY

Quaternary deposits consisting of grey-brown glacial till (approximately 2 – 3 m thick) and dark brown-black peat (< 2 m thick) cover the strata at and around the Spireslack SCM (Figure 31). In an exposure at the east of the Spireslack surface mine boundary, up to 2 m of dark brown peat overlies a sandy glacial till, with the boundary between marked by a conspicuous ~10 cm thick bleached zone. It is thought (Archer, N. pers. comm. 2015) this bleached zone represents the formation of a podzol (a soil) in the till. This usually forms in cool humid climates where peat develops on top of sandy tills. Where the peat comes into contact with the till, organic compounds in the peat have been washed out by rainfall and combined with aluminium and iron in the layer below. The till layer below has a bleached appearance because it becomes higher in silicon and lower in aluminium and iron – i.e. the main mineral left following podzolisation is quartz.

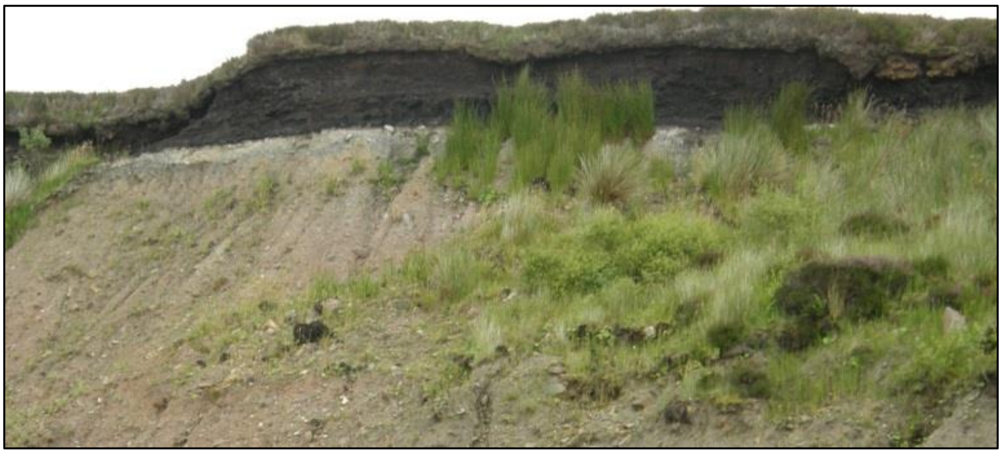

Figure 31: Thick peat deposits overlie till across the unworked parts of the site. Till is bleached at the base of the peat due to podsol formation.

3.8 MADE GROUND

There are at least two generations of made ground deposits (consisting of mine waste such as blocks of sandstone, limestone and mudstone) within the Spireslack surface mine. These form large, at least 70 m thick mounds, sitting above peat or till layers and are best seen at the eastern margin of the Spireslack surface mine boundary.

3.9 OLD UNDERGROUND MINEWORKINGS

Historical underground workings have left packed mine waste deposits within collapsed short wall workings, intersected during surface coal mine operations (Figure 32). These deposits consist mostly of brecciated and poorly sorted coal or other rock fragments within the collapsed void space. The earlier 19th/20th century underground mine workings extracted coal from at least the Muirkirk Nine Foot and Six Foot coals within the area of the surface mine void at Spireslack. At the eastern edge of this locality's extent, adjacent to a minor c. 1.2 m displacement fault, the Muirkirk Nine Foot coal maintains its original (unmined) thickness of c. 3 m. However, where evidence of mining commenced, the layer which originally contained the coal thins to a maximum of c. 1.5 m thick and the space that was originally occupied by coal is filled with packed mine waste (representing a collapsed room or short wall working). The sandstone overlying the mine waste is warped downward and fractured, representing collapse of the overlying strata into the mined void. An in situ, fallen pit prop is preserved within the base of mine waste – these wooden pit props would have held up the roof of the mines whilst coal was being extracted (Figure 33). Stoops (coal pillars) left in place during underground workings to stabilise the mine workings are also visible within the Nine Foot Coal seam in the west of the main void.

Bell-pits, associated with historic ironstone and limestone mining, are present at the southern edge of the Spireslack SCM in fields just south of the Glenbuck village site.

Figure 32: Old mine workings in the Muirkirk Nine Foot Coal seam seen in south wall of the main void. The thick pillars of coal (P) propped up the roof of the mine workings whilst the adjacent coal was extracted.

Figure 33: Wooden pit prop in situ within the Muirkirk Nine Foot coal workings. The wooden props were used to hold up the roof of the workings as the coal was extracted. The prop, sitting above packed mine waste in the photo, has since collapsed due to the overlying weight of rock above.

4 3D Model of Spireslack Surface Mine

To add to the BGS knowledge of the structure of the Glenbuck area, a 3D model has been constructed, based on mine data of the strata at Spireslack (Figure 34). Geospatial data collected during the underground and surface mining phases at Spireslack provide an accurate point cloud of XYZ data, allowing a 3D reconstruction of the Carboniferous strata at depth. The model was constructed using Move, the 3D geological modelling software (designed by Midland Valley Exploration). The 3D model of Spireslack described in this report is the result of an initial phase of work to pull together relevant geospatial data into a single space, in order to gain an understanding of the broad subsurface structure. Future refining of this model is anticipated following further analysis of the higher resolution data, such as photogrammetry and Lidar data. This section of the report describes the data used to build the model, the techniques used, and recommendations for future work.

4.1 MODEL DATASETS

The following datasets were imported into Move:

- DTM (trimmed to area of interest based on major bounding faults)
- 10k standard fieldslips: NS72NW, NS72NE, NS73SW, NS73SE.
    - Linework, faults and dip data digitised within Move
- Shapefile of the Spireslack main void (3D point cloud)
- Aerial photographs of site
- Traces of faults and dykes digitised in Geovisionary. Photogrammetry and Lidar scans were carried out on the south-eastern main face and north-western limestone pavement respectively. The data was loaded into Geovisionary allowing a fully georeferenced 3D view of the Spireslack main void to be visualised. The data is of such high resolution that individual faults and dykes can be digitised.
- Georeferenced scan of Scottish Coal Spireslack Geological Plan
    - Contours of Muirkirk Six Foot Coal, Muirkirk Nine Foot Coal, McDonald Coal and Gill Coal digitised within Move from scan
- Abandonment Plans from underground workings (contours and spot heights):
    - Muirkirk Six Foot Coal
    - Muirkirk Nine Foot Coal
- Excavation model - seam data for base of individual surface mined coal seams (contours and spot heights):
    - McDonald Coal
    - Muirkirk Six Foot Coal
    - Muirkirk 30 Inch Coal
    - Muirkirk Nine Foot Coal
    - Muirkirk Four Foot Coal
    - Muirkirk Three Foot Coal
    - Muirkirk Ell Coal
    - Faults

4.2 MODELLED SURFACES/VOLUMES/FAULTS

Name of Modelled Surface	Lexicon Code – RCS
McDonald Coal	MCDC-COAL
Muirkirk 6 Foot Coal	MSIX-COAL
Muirkirk 30 Inch Coal	MTIP-COAL
Muirkirk 9 Foot Coal	MNFC-COAL
Muirkirk 4 Foot Coal	MFFC-COAL
Muirkirk 3 Foot Coal	MTFC-COAL
Muirkirk Ell Coal	MKEC-COAL

4.3 MODEL WORKFLOW

The data for the abandonment plan and excavation model were provided in .dxf format. This was imported into Move, and manually sorted to keep only the geological information (‘coal lines’, ‘contour normal’, ‘contour prominent’ and ‘fault lines’) from the files within the .dbf file.

These XYZ files were loaded into Move creating a 3D framework of the worked seams. The contours (polylines) were resampled within Move at 1 m spacing (retaining original control points) and converted into a point cloud. These points combined with spot height data were collected into Move’s surface building algorithm and used to construct a 3D surface using the Delauney Triangulation method, in order to honour all of the data. Erroneous points and spikes were manually removed where they represented mispicked points within the data.

To identify faults from the XYZ data, the surfaces were colour mapped for curvature to identify discrete surface dip changes which may represent faults or changes in orientations across dykes. The outlines of faults or dykes picked in this method were drawn using the 3D line drawing tool to represent the location of faults to be later checked and cross-referenced with faults observed in the field.

Method:

1) Import .dxfs into Move, and separate by attribute
2) Extract observation points, contours and fault lines from data
3) Resample contour data to 1 m nodes
4) Convert resampled contour data to point cloud
5) Build surfaces (Delauney Triangulation) from the point cloud
6) Clean up erroneous points and triangles
7) Use curvature analysis to draw eye into bumps on the surface which are likely to represent faults/dykes
8) Using the 3D line drawing too, trace on faults surrounding differences in curvature or individually select triangles composing possible fault trace.

4.4 MODEL ASSUMPTIONS AND LIMITATIONS

The 10k geology sheet is based upon data from the older underground mine workings, and as such, has no record of the significant fold structure to the north-east of the fault. It was therefore assumed that for the purposes of building this model, the more recent 20th/21st century surface mine abandonment data contains the more accurate XYZ positions, as it was acquired using differential GPS on the bases of coal seams during extraction. When comparing the XYZ positions of the older mine working and surface mine abandonment plans, there is a 5 – 10 m difference in the Z value between the Muirkirk Six Foot Coal seam subsurface positions, whilst the dip and XY position are similar. In addition, a mismatch was noted between the mapped 10k geology sheet line work and the projected positions of the surface mine abandonment coal seam data to the DTM. For example, the difference in distance for the Top Hosie (McDonald) Limestone is around 35 m and for the Muirkirk Six Foot Coal seam, 18 m. Conversely, the older mine workings data has a better match, consistent with the original 10k geology linework being based on the older data.

4.5 FUTURE MODELLING

The model is currently a work in progress and requires further work to refine it. The steps necessary to improve the model are discussed below.

- Fault and dyke traces digitised from the Geovisionary Spireslack project should be incorporated with the interpreted faults and dykes digitised from the mine plan XYZ data – how do they compare, and how do the fault and dyke traces vary across the now empty void, using the mine plan XYZ data as a guide?
- Currently the model is composed of areas of surfaces where mining took place – it would be appropriate to extend these surfaces so as to have a more complete model which shows the broader synclinal structure of the area. This can be informed by the 10k geological line work.
- Some of the mine abandonment modelled surfaces overlap each other in areas where faults are presumed. This is geologically incorrect and will be fixed in future modelling.

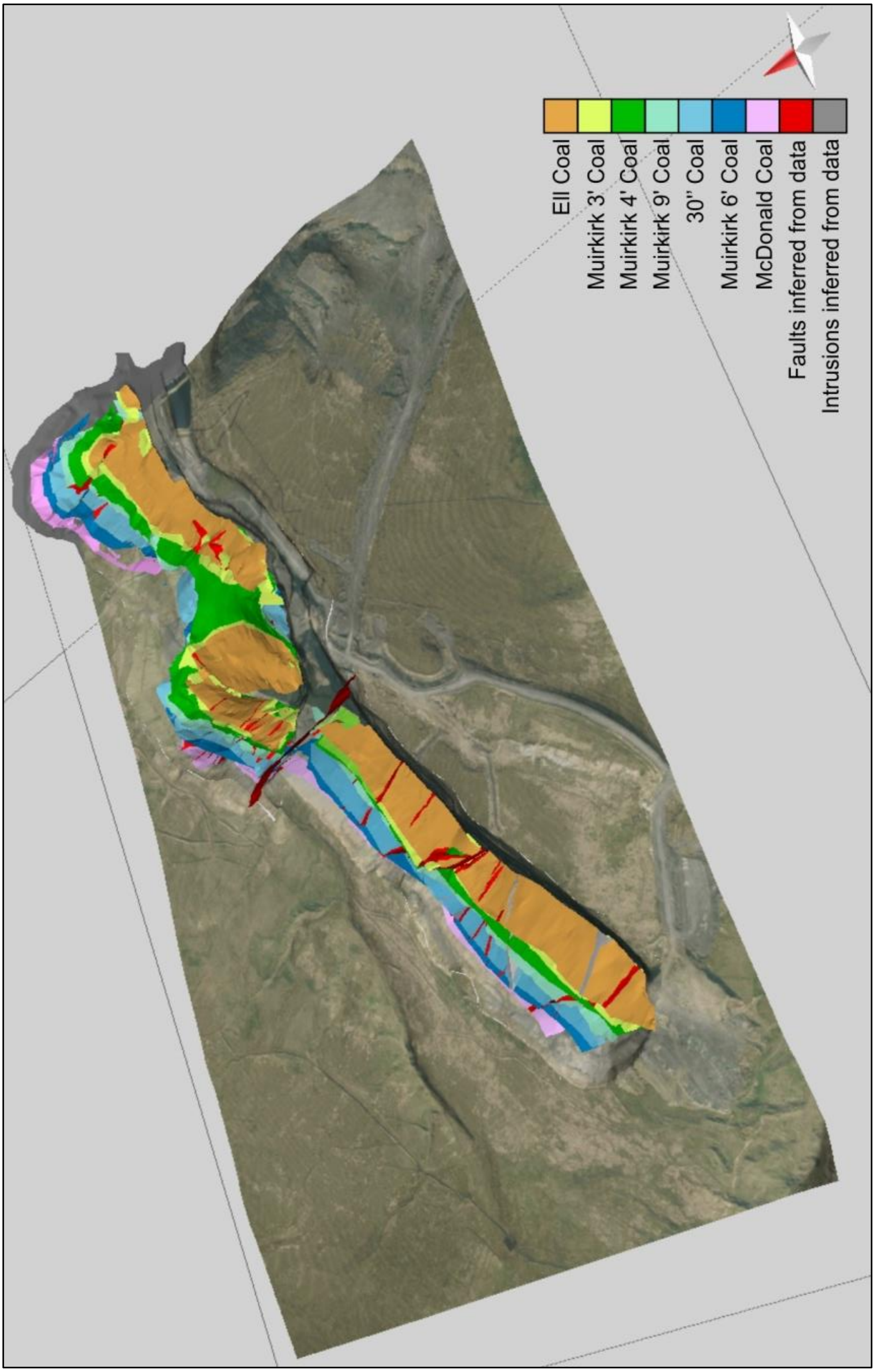

Figure 34: 3D model of strata mined from Spireslack main void. Each surface represents a coal seam, and was constructed from geospatial subsurface data. During the modelling, a more complex fold structure was revealed at the north-east of the site – this structure is not captured by present BGS 10k geological maps.

5 Recommendations and summary

The Spireslack surface coal mine exceptionally exposes Carboniferous strata belonging to the Lawmuir, Lower Limestone, Limestone Coal and Upper Limestone formations. The authors have carried out a preliminary survey of the geology exposed but further analysis and documentation of the features is required. As stewards of the site, BGS arguably should hold a comprehensive baseline of data regarding Spireslack to offer to universities, industry and other interested parties. We suggest a campaign of detailed sedimentary and stratigraphical logging be carried out to record the detail of this site for future generations. Structural analysis and recording of the fault zones should also be carried out as a baseline for future research.

The 3D model is still a work in progress. In order to finalise the model, it requires additional time to incorporate data from Geovisionary (to allow accurate geospatial mapping of faults and dykes) to aid in the construction of the fault network at Spireslack. Field work should then be incorporated for ground truthing the fault data from the model. The surfaces are currently patchy in their extent and have not been extended beyond the sub surface data constraints – therefore in a future phase of modelling the currently generated surfaces will be extended beyond their limits so as to fill the entire area of interest. This will be done taking the existing 10k geological sheet into consideration but using mine data as the preferred surface location of seams.

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