

## **Review of paper submitted to Solid Earth**

**Title:** *The role of pre-existing jointing on damage zone evolution and faulting 1 style of thin 2 competent layers in mechanically stratified sequences: a case study from the Limestone Coal 3 Formation at Spireslack Surface Coal Mine.*

**Authors:** Billy J. Andrews, Zoe K. Shipton, Richard Lord, Lucy McKay

This paper provides a detailed description of a very interesting exposure in central Scotland. The locality is a disused surface coal mine and contains some fractures and faults related to the evolution of this part of Scotland. More importantly, the exposure allows a detailed analysis of the relationship between different types of fracture – faults, joints and veins, and how these vary in a mechanically layered sequence. The paper uses a range of geometrical and topographical analyses to provide a good analysis of the resulting fracture networks. The importance of the site is clear from the paper and as such **the paper provides a very valuable study that should be published.**

**There are, however, a number of revisions necessary before the manuscript is acceptable; these include the following:**

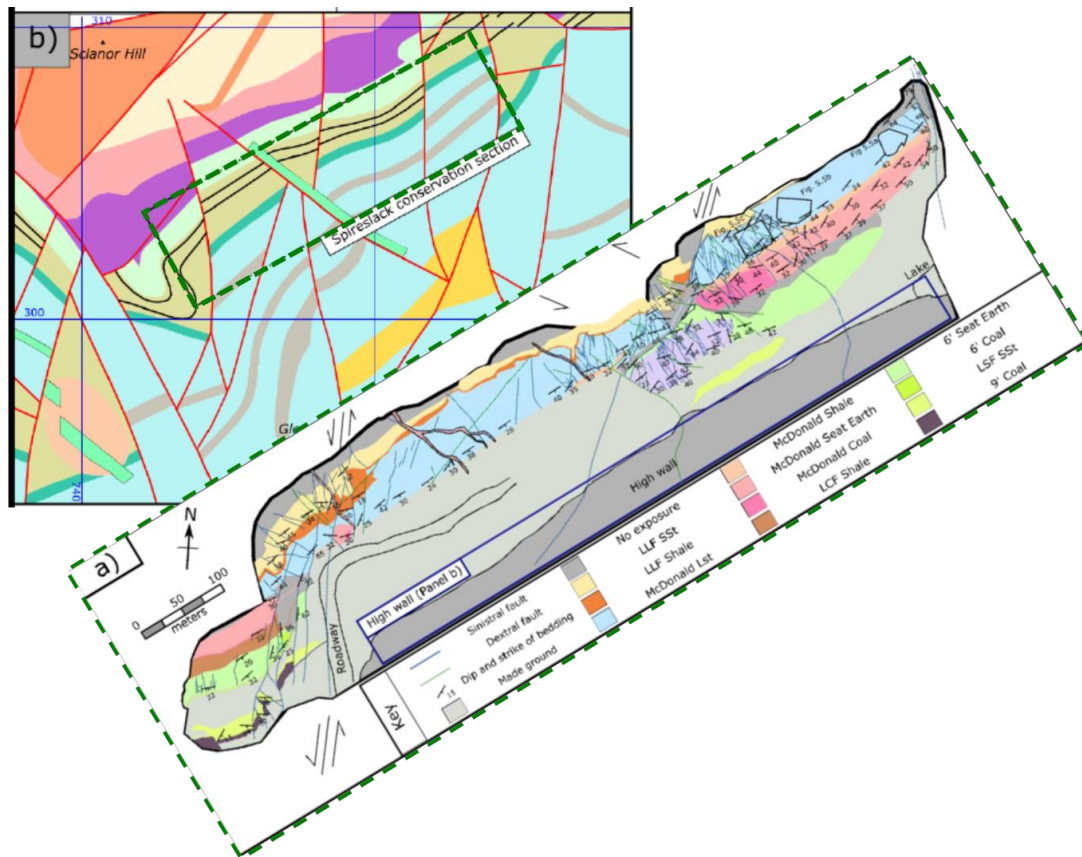
### **1. Tidy up the text by removal of inconsistencies and more precise definition of many of the terms used.**

I have added lots of specific comments and edits on the pdf. Most importantly many terms are used without clear definition, and their usage seems to vary from one section to another.

The use of 'self-juxtaposed fault' is particularly unclear. I think we need a clear definition of this term - the usage only becomes obvious as one reads the paper. In effect "self-juxtaposed" is really being used in place of "small". "Self-juxtaposed" describes the relationship between the wall-rock stratigraphy across a fault, and is thus a "topological" term describing the wall rocks NOT the fault, i.e. a small fault can produce a self-juxtaposition of the wall rock stratigraphy.

### **2. A better presentation of the maps and data.**

Although this aspect of the paper is generally good, the diagrams are rather detailed and "formal" in their approach. There are many opportunities to provide a more visual presentation of the relationships between the data. For example, the site could be more clearly described by combining the maps in Figs 1 and 3 as follows:



This allows comparison of the observed detail with the surrounding faults mapped by BGS.

### 3. The sequence of development of the structures.

This is presented at four main parts of the paper: (a) a discussion of the mineralisation (Section 4.1, especially lines 194-200); (b) discussion of faults (mainly section 4.2.1); (c) interactions between faults and fractures (section 4.2.2); (d) large offset faults (Section 4.2.3). The material in these sections contains a lot of detailed information and it is difficult to relate much of this to the evaluation of the fracture sequence. In part this is caused by a somewhat inconsistent terminology, with the definition and criteria for recognition of the different fracture types being unclear. I would recommend having a separate section that clearly discussed the fracture history.

In Section 4.1 the authors recognise 4 types of fracture: coal cleats, en-echelon arrays, mineralised shear fractures and barren shear fractures. These are not clearly defined and their illustration in Fig. 2 introduces a number of different terms (joint, vein, etc.).

In Section 4.2.2 there is also a lot of discussion of “lineations”, which appear to be mainly of low pitch, suggesting strike-slip. The authors also mention “reactivation” of the faults. I did not get a clear picture of how they view the faults. To me these could well be early normal faults (well described from elsewhere in central Scotland since the work of EM Anderson) that were later reactivated by strike-slip (again there are good example of strike-slip faulting elsewhere in the region). Is that the view of the authors? This should be discussed more clearly.

The authors use abutting and cross-cutting relationships to suggest relative ages of the different fractures. This generally works well for joints (especially where cross-cutting is rare) and veins, where cross-cutting can be used to determine relative age). The problem is that faults have displacement,

therefore abutting does not work so simply and needs to take account of this displacement. The fact that many of the fractures are mineralised, should allow greater use of cross-cutting.

In section 4.2.2, the interaction of faults and fractures is discussed, mainly in terms of the 'joints'. A number of key questions largely remain unanswered (or if they are they are buried in the text and not obvious to me). How are these 'joints' distinguished from 'barren shear fractures'? Do shear fractures and faults clearly displace the joints. Are there cross-cutting relationships between veins and joints? If so what are the relative ages?

This summary of joint/fault relationships shown in Fig 5 (lines 276-288 and Table 2) is interesting. The table has a lot of very long sentences and is difficult to read. The single sentences are really a collection of phrases that could easily be separated (and arranged more logically). There also appears to be a lot of missing words.

The analysis contains a number of rather surprising conclusions:

- 1) the "joints" predate the "faults", yet the faults are mineralized!
- 2) How do the faults and joints fit into the sequence of mineralization (lines 194-200)?
- 3) One set of "faults develops sub-parallel to the c.N110E joint set - can these be described as "faulted joints" (in sense of Zhao and Johnson (1992, JSG 14, 225-36).

These are important outputs for this paper and need to be clarified and highlighted, and discussed later in the paper.

The abutting relationships in Fig 5 appear to contain many contradictions (although I agree that the faults look late). The problem is that abutting and cross-cutting work well for joints (especially where cross-cutting is rare) and veins, where cross-cutting can be used to determine relative age. The problem is that faults have displacement, therefore abutting does not work so well.

The section on larger faults (4.2.3) contains a lot of detailed observation, but I would like to have seen some synthesis of these details. The discussion is not helped by the repeated use of 'offset' instead of 'separation'. Given that 'offset' can mean either a displacement component or a separation, it would be best to abandon the term altogether and talk about separation (where only relationships of layers is known) and displacements (where kinematics is supported by striations and/or piercing points).

#### **4. Fault and fracture topology**

The topology of the different fracture types contains some clear errors. Since the procedures are not explained clearly enough, I am left to speculate as to the causes.

I think the analysis using NetworkGT was carried out as follows:

1. The entire network was digitized.
2. The data were divided into sets based on orientation and fracture type (faults and joints)
3. The nodes and branches for entire network were then calculated (using the tool in NetworkGT)
4. This would then give the correct results for the entire network. This looks to plot correctly on Fig. 8, as the diamond symbol, although these are erroneously assigned to the "fault strands" in the key. The correct assignment would be: squares – faults; circles - open fractures and diamonds – all network, as indicated on the node triangle.. The resulting values for  $P_c$  in Table 3 also appear to be correct (i.e.  $0.96 \leq P_c \leq 1$ ).

To get the corresponding data for the faults and joints, the above steps should have been repeated for each fracture type. This is clearly not what was done, since the joints would have given very

similar results to the entire network, i.e. high Pc and Y-node dominated. There are certainly not as high a proportion of I and X nodes as plotted in Fig 8. The results for the branch plots may be more robust.

I think that the nodes for the entire network were somehow distributed into values for the joints and faults, probably by removal of the fault-related nodes and assigning those that remain to the joints. This does not work because the majority of the nodes are produced by intersection with joints. I think there may be similar problems with splitting the fracture types into sets, as individual sets of sub-parallel fractures contain few connected nodes and very few I-I branches (c.f. as plotted).

This means that the discussion of the implications of flow based on Fig 8 and Table 3 is flawed.

## **5. Network properties and flow/permeability**

There is also another major flaw in the discussion of flow and permeability in relation to the network characteristics. The reason this is flawed is that the network topology, essentially evaluates the connectivity of the fractures, whereas the permeability of the rock mass is a step-like function dependent on the percolation threshold, and, once this is reached, primarily on the conductance of the fractures on the connected component of the network. The correct topological analysis of each fracture type would allow discussion of this, but it would need to recognise the difference between the roles of: (a) a conductive joint network, (b) the palaeo-flow in an active fault network, and (c) the subsequent effect on mineralization of the fault network. For example, superposition of a connected network of sealing faults would counteract the conductivity of an earlier network of open fractures.

This whole section talks about “open fractures”. These are not clearly defined. How do they correspond to the ‘barren shear fractures’ and ‘joints’ discussed earlier.

## **6. Abstract and conclusions**

These do a very poor job in summarising the content of the paper. There is too much “discussion” and arm waving about role of lithology, strengthening by mineralization, and effects on permeability, with not enough on the key issues of the sequence of development and interaction of the different fracture elements.

## **7. Detailed comments are made on the annotated pdf**

David Sanderson

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# 1 The role of pre-existing jointing on damage zone evolution and faulting style of thin 2 competent layers in mechanically stratified sequences: a case study from the Limestone Coal 3 Formation at Spireslack Surface Coal Mine.



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9 **Abstract.** Fault and fracture networks play an important role in sub-surface fluid flow and can act to  
 10 enhance, retard or compartmentalise groundwater flow. In multi-layered sequences, the internal structure  
 11 and growth of faults is not only controlled by fault throw, but also the mechanical properties of lithologies  
 12 cut by the fault. This paper uses geological fieldwork, combined with fault and fracture mapping, to  
 13 investigate the internal structure and fault development of the mechanically stratified Limestone Coal  
 14 Formation and surrounding lithologies exposed at Spireslack Surface Coal Mine. We find that the  
 15 development of fault rock, and complexity of a fault zone is dependent on: a) whether a fault is self-  
 16 juxtaposed or cuts multiple lithologies; b) the presence and behaviour of shale, which can lead to  
 17 significant bed-rotation and the formation of fault-core lenses; and c) whether pre-existing weakness (e.g.  
 18 joints) are present at the time of faulting. Pre-existing joint networks in the McDonald Limestone, and  
 19 cleats in the McDonald Coal, influenced both fault growth and fluid flow within these lithologies.

## 20 1 Introduction

21 The mechanical properties, thickness, and interface properties of lithologies in a stratigraphic succession,  
 22 referred to as mechanical stratigraphy, combine to influence the deformation style of a rock mass (e.g.  
 23 Ferrill *et al.* (2017)). The effect of mechanical stratigraphy on faulting, in particular normal faulting, has  
 24 been studied for sand-shale sequences (e.g. van der Zee & Urai (2005); Schmatz *et al.* (2010)),  
 25 interbedded limestones and marls (e.g. Ferrill & Morris (2003), (2008); Long & Imber (2011); Ferrill *et*  
 26 *al.* (2012)), and ignimbrites (Soden and Shipton, 2013). The lithology being cut by the fault influences  
 27 fault dip: strands in competent layers have steeper dips than those in incompetent layers (Ferrill and  
 28 Morris, 2008). The ratio of competent to incompetent lithologies thus affects fault style and displacement  
 29 profiles (Ferrill *et al.*, 2017; Ferrill and Morris, 2008). When incompetent layers dominate the sequence,  
 30 folding is commonly observed with thin competent beds displaying fault-related folding (Ferrill and  
 31 Morris, 2008; Lăpădat *et al.*, 2017). The presence of incompetent lithologies also restricts fault growth  
 32 with strands terminating at incompetent beds. This leads to faults with high aspect ratios orientated





33 parallel to the strike of bedding (e.g. Nicol *et al.* (1996); Soliva & Benedicto (2005); Roche *et al.* (2013)).  
34 In addition to mechanical stratigraphy, pre-existing weaknesses play an important role in the nucleation  
35 and development of faulting (Crider and Peacock, 2004). The impact pre-existing weaknesses have on  
36 fault growth depends on the orientation of a weakness relative to the growing fault and the stress ratio  
37 (Lunn *et al.*, 2008; Peacock, 2001). The presence of pre-existing weaknesses can also influence the  
38 development of fault rock. For example, Soden & Shipton (2013) demonstrated that layer and joint  
39 spacing in ignimbrites affected the aspect ratio of clasts found within the fault core. Of course, mechanical  
40 stratigraphy itself influences the orientation of pre-existing weaknesses (Wilkins and Gross, 2002).

41 Fluvial-deltaic sequences are characterised by cyclical sequences of limestone, sandstone, siltstone, seat-  
42 earth, shale, and coal (Thomas, 2013). The competent lithologies in the sequence (limestone and  
43 sandstone) commonly contain joints. Coal has a unique, distinctive blocky texture due to the presence of  
44 two roughly perpendicular fracture sets called cleats (Laubach *et al.*, 1998). Cleats are ubiquitous in coals  
45 as diagenesis takes place, and thus represent pre-existing weaknesses which may affect the location,  
46 orientation and length of faults (e.g. Peacock (2001); Walsh *et al.* (2002)).

47 This study utilises exceptional exposures of the Limestone Coal Formation (LCF) exposed at Spireslack  
48 Surface Coal Mine (SCM), Scotland, to investigate the effect of lithology and pre-existing structures on  
49 the growth of strike-slip faults. Field photographs were used to map the key structures and kinematics at  
50 a 1:1,000 scale. High resolution photomontages were then used to map faults and fractures and investigate  
51 the interaction of faults and fractures with lithology and jointing. We find that faults cutting multiple  
52 lithologies are thin (<0.3 m), display a complex deformation pattern, and locally branch entraining lenses  
53 of sandstone. We also find that pre-existing joints and lithology strongly affect the growth and fluid flow  
54 history of small offset, self-juxtaposed, faults.

## 55 2. Geological setting

56 The Midland Valley of Scotland (MVS) is a 90 km wide, 150 km long, ENE-trending basin that opened  
57 during the late Devonian to Early Carboniferous in response to back-arc extension within the Laurussian  
58 Plate (Leeder, 1982, 1988). This was followed by a period of thermal subsidence which continued  
59 throughout Namurian and Westphalian times leading to the deposition and preservation of thick coal  
60 measures across much of the UK (Leeder, 1982; Figure 1a).

61 The MVS is bound by two major tectonic lineaments - the Southern Upland Fault (SUF) to the south and  
62 Highland Boundary Fault (HBF) to the north (Figure 1a) (Bluck, 1984). Carboniferous basins that have  
63 axes oblique to the main trend of the MVS (e.g. Central Scottish Coalfield; Francis (1991)). These basins  
64 can reach over 6 km in thickness (Dean *et al.*, 2011) and are often obscured by Quaternary deposits. Faults

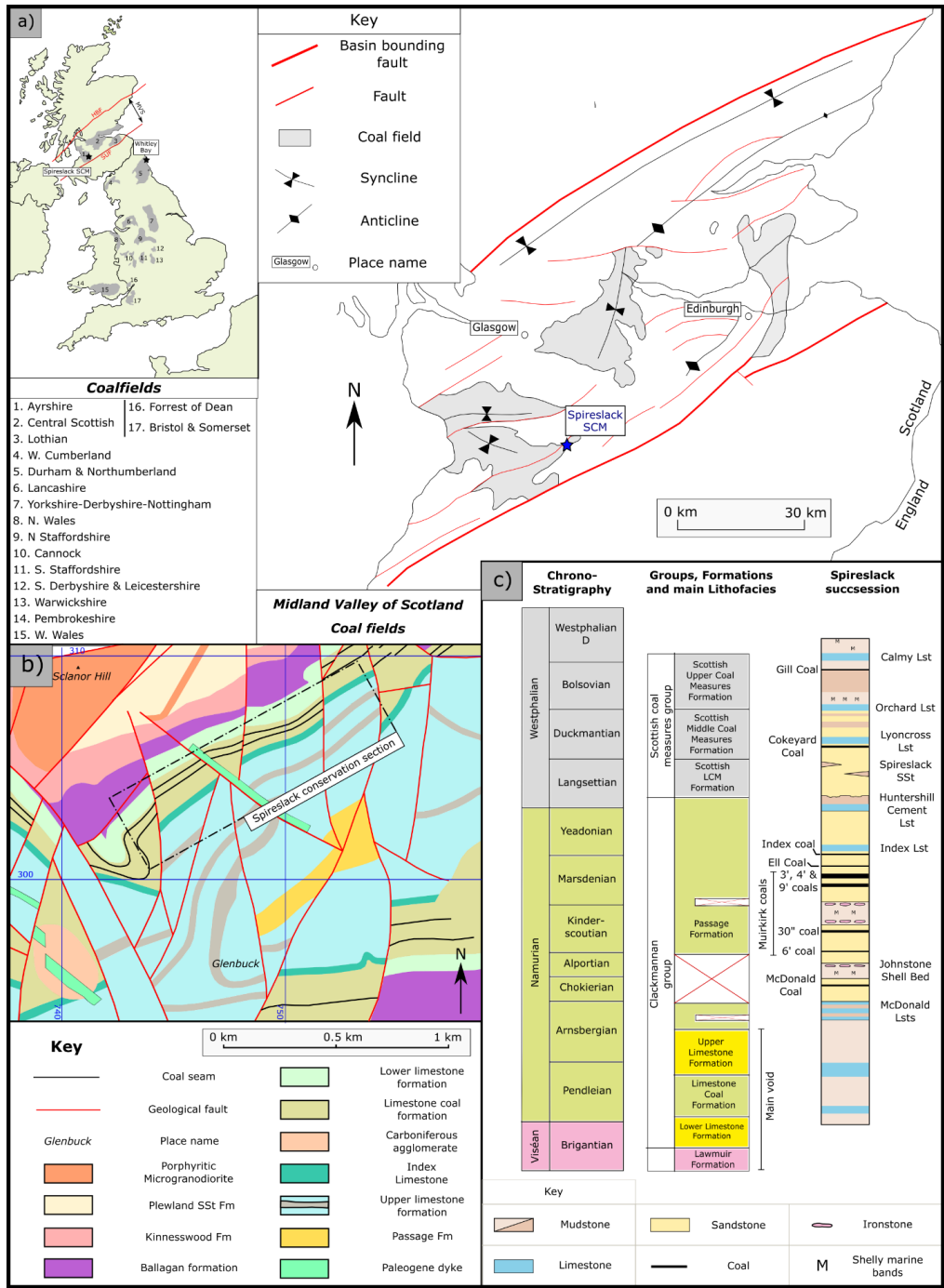


65 with associated, localised folding within the MVS have a complex history of reactivation caused by  
 66 sinistral strike-/oblique-slip during the Tournaisian and dextral strike-/oblique-slip during Viséan to  
 67 Westphalian times (Browne and Monro, 1987; Rippon et al., 1996; Ritchie et al., 2003; Underhill et al.,  
 68 2008).

## 69 2.1 Spireslack SCM

70 Spireslack SCM, next to the now **abandoned coal mining village of Glenbuck**, South Ayrshire, Scotland  
 71 (Figure 1a) provides an exceptional exposure of Carboniferous rocks in a 1 km long void (Figure 1b). A  
 72 20°- 40° southerly dipping ~~slope along~~ bedding planes ends in a <130 m high working face. The  
 73 stratigraphy, comprises a continuous succession of Viséan to Namurian strata including a complete  
 74 section through the Limestone Coal Formation (LCF) (Figure 1c) (Ellen et al., 2016, 2019). Bituminous  
 75 coal is found in cyclical fluvio-deltaic sequences that outcrop across much of the dip-slope and high wall,  
 76 bounded by the Upper and Lower Limestone Formations. The Lower Limestone Formation represents  
 77 more marine-influenced facies including extensive, fossil-rich limestone units (e.g. The McDonald  
 78 Limestone) (Davis, 1972). Above the LCF the Spireslack Sandstone comprises of one channelised, and  
 79 two tabular, sandstone beds (Ellen et al., 2019).

80 Offsetting this stratigraphy are several fault zones with shallow slip vectors and variably complex internal  
 81 structures. In addition to the faults, at least five Paleogene basaltic dykes are observed, which Leslie *et*  
 82 *al.* (2016) suggest intrude along pre-existing faults. The rocks exposed at Spireslack SCM are part of the  
 83 Southern Limb of the upright, WSW-ENE trending Muirkirk syncline that formed in response to mid- to  
 84 late- Carboniferous sinistral transpression (Davis, 1972; Leslie et al., 2016). Leslie *et al.* (2016) attribute  
 85 the faulting and folding observed at Spireslack SCM to this deformation, and have observed no evidence  
 86 of the later widespread dextral deformation (e.g. Underhill *et al.* (2008)).



87

88 **Figure 1: Location map: a) Map of UK coalfields (adapted from Donnelly (2006)) showing the**  
89 **location of Spireslack SCM and Structural features of the Midland Valley of Scotland; b) Regional**  
90 **geology of Spireslack open cast coal mine (after Ellen et al. (2019)); c) Regional stratigraphy of**  
91 **Spireslack SCM (after Ellen et al. (2019)).**





## 92 3. Methods

### 93 3.1. Field mapping

94 Geological mapping of the dip-slopes captured all units between the sandstones and shales below the  
 95 McDonald Limestones and the sandstone bed above the Muirkirk 6' Coal. Mapping was undertaken at a  
 96 1:1,000 scale onto printed aerial photography from Bing (2017). All faults with greater than 0.2 m offset  
 97 were recorded. Printed field photographs were used to collect more detailed observations at several key  
 98 sites.

### 99 3.2 Analysis of fault and fracture networks

#### 100 3.2.1 Mapping procedure

101 Fault and fracture mapping was undertaken using two datasets: (i) a UAV derived photomontage of the  
 102 McDonald Limestone bedding plane collected by Dave Healy of Aberdeen University; and (ii) an auto  
 103 rectified photomontage of the high wall collected by the British Geological Survey. Interpretation areas  
 104 were selected from the dip-slope and high wall for analysis to understand the geometrical and topological  
 105 properties, and cross cutting relationships of fault strands and joint sets. Due to the instability of the  
 106 highwall, there was very little access to the foot of the highwall and the interpretations are made  
 107 principally on the photomontage. The interpretation areas were scaled in ArcGIS with mapping being  
 108 undertaken by the lead author at a scale of 1:30 for the dip-slope and 1:50 for the high wall. Lineament  
 109 mapping was undertaken by the same operator, at the same scale, to limit the effect of subjective bias on  
 110 the data collected (Andrews et al., 2019; Scheiber et al., 2015).

#### 111 3.2.2 Network analysis

112 Fracture topology describes a fault or fracture network as a series of branches and nodes (e.g. Manzocchi  
 113 (2002); Sanderson & Nixon (2015),(2018)). A branch is a fracture trace with a node at each end. Nodes  
 114 can occur where a fracture terminates into rock (i-node), abuts against another fracture (y-node) or crosses  
 115 another fracture (x-node). The proportion of different node types (i, y, and x) can then be plotted on a  
 116 triangular diagram for the purposes of characterising and quantifying the connectivity of the network  
 117 (Manzocchi, 2002; Sanderson and Nixon, 2015). In this work we interpret fault and fractures as  
 118 orientation sets and report fracture/branch trace length (tl), 2D fracture intensity (I), and the percentage  
 119 of connected branches (Pc).

120 Once the faults and fractures were interpreted (digitised as separate datasets), a visual assessment of the  
 121 network was undertaken followed by network analysis using the open source ArcGIS toolbox NetworkGT  
 122 (Nyberg et al., 2018) and the following workflow:



1. *Define sets*: Six ‘Interpretation boxes’ were added as shape files to the ArcGIS (three along the dip-slope and three along the high wall) and the orientation of faults and the fractures within them analysed. Length-weighted rose diagrams with 5° bin widths were used to interpret the ‘orientation sets’ in the network using NetworkGT (Nyberg et al., 2018). The digitised fault and fracture data sets were then combined using the merge function in ArcGIS, and all three investigated separately.
2. *Branch & Nodes*: The topology of the network was extracted using the ‘Branch and Node’ tool, which splits the fracture trace poly-line file into individual branches, and assigns nodes as a separate point-files (Nyberg et al., 2018). The resulting network was visually checked for errors (e.g. incorrectly assigned nodes) and manually adjusted in ArcGIS to remove spurious nodes and branches. Data were then exported to excel for further analysis.
3. *Network analysis*: For each network, the following data was extracted;
  - a. *Network connectivity*: For each dataset with the data not split into sets, the node and branch proportions were assessed using a triangular diagram (c.f. Sanderson & Nixon (2015)). The percentage of connected branches was then calculated using Equation 1.

$$P_c = \frac{(3N_y + 4N_x)}{(N_l + 3N_y + 4N_x)} \quad (\text{Equation 1})$$

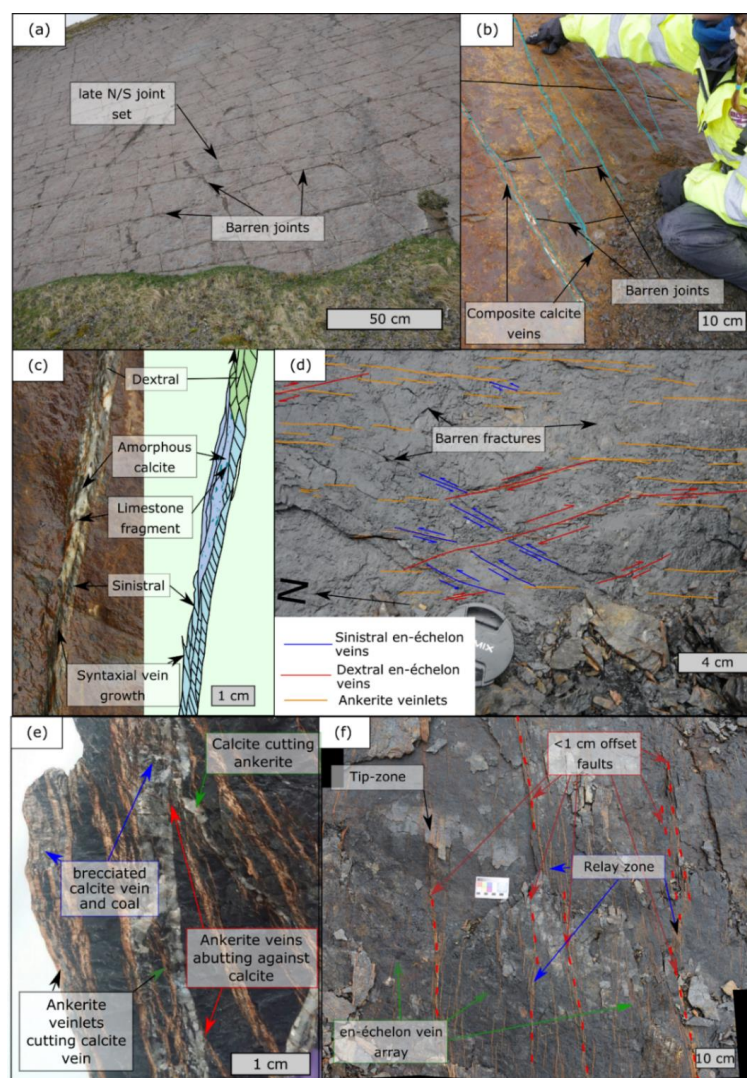
- b. *Trace length*: The trace length of digitised networks and sets within each sample area were assessed using trace length distributions (Andrews et al., 2019; Priest and Hudson, 1981), with the minimum, maximum, and median trace length values used to compare analysis.
- c. *2D fracture intensity*: We compare the intensity of the networks and sets within the network using 2D fracture intensity (Equation 2) ( $P_{21}$ ; Dershowitz & Einstein (1988); Rohrbaugh et al. (2002)).

$$P_{21} = \frac{\sum tl}{Area} \quad (\text{Equation 2})$$



## 147 4. Results

### 148 4.1 General fracture observations



149 **Figure 2: Typical fracture properties for McDonald Limestone & McDonald Coal:** a) barren joints  
 150 **observed away from faults across the southerly dipping (c. 40°) McDonald Limestone bedding**  
 151 **plane;** b) Mineralised N-S trending calcite veins, offsetting abutting E-W ladder joints on the  
 152 **bedding plane of the McDonald Limestone;** c) annotated field photograph and interpretation of a  
 153 **multi-phase composite calcite vein exposed in the vicinity to a small offset fault along the McDonald**  
 154 **Limestone Pavement;** d) bedding plane exposure of mineralised fractures present within the  
 155 **Muirkirk 6' coal;** e) annotated hand specimen displaying the vein relationships present during the  
 156 **faulting of the Muirkirk 6' coal;** and f) the larger-scale mineralisation pattern as you move towards  
 157 **small offset faults in the Muirkirk 6' coal.**



Fractures at Spireslack SCM typically occur in **two orthogonal** directions that vary throughout the site (NS and EW) and can be classified as either joints or shear fractures (often found in the proximity to faults). Away from faults, joints in the McDonald Limestone form two orthogonal barren sets trending roughly NE-SW and NNW-SSE. Orientation of these sets vary, with up to 20° of strike rotation observed throughout the site. Cross cutting relationships show that there are multiple ‘age sets’ (Figure 2a). NE-SW joints formed initially followed by sparsely spaced NE-SW joints then more NE-SW joints, which abut against the pre-existing NNW-SSE trending joints. Finally, a dense network of N-S joints abuts against both sets of E-W trending joints.

Calcite mineralisation is observed in the vicinity of, and along, primarily NW trending shear fractures (Figure 2b). Mineralisation occurs as two styles: 1) amorphous, where no growth structures are present and occasional fragments of limestone are observed within the mineralised zone, or 2) with syntaxial growth textures suggesting both sinistral and dextral motion during mineralisation. Along fault planes and within a few meters of faults, composite veins commonly occur, with multiple growth stages and evidence of reactivation (Figure 2c).

Fractures in the coal layers are commonly filled with a buff to orange coloured mineralisation, identified in the field as ankerite (iron rich carbonate) (Figure 2d-f). Fractures in coal occur as:

- *Coal cleats*: Ubiquitous in all coals. Spacing (typically <2 cm) is dependent on bed-thickness, coal quality and the presence of clastic material (e.g. shale partings) (Laubach et al., 1998).
- *Mineralised shear fractures*: Typically 2 to 15 cm in length, but increase to >1 m long as apparent shear offset increases. Fractures < 15 cm long abut against EW trending cleats, with trace length restricted by cleat spacing. The thickness of planar ankerite veins increases as the length of the fracture.
- *En-echelon arrays*: En-echelon ankerite veins display both sinistral and dextral motion (Figure 2d). Dextral arrays occur both simultaneously with, and later than, sinistral arrays.
- *Barren shear fractures*: In addition to the cleat network, fractures that abut against all other fractures and are often curved, have trace lengths typically between 5 to 15 cm. These may propagate from the tip of pre-existing mineralised shear fractures (Figure 2d).

A complex chronology of fractures is observed in the Muirkirk 6' coal. In Figure 2d dextral offset en-echelon vein arrays (red) cross cut earlier sinistral sets (blue), with the former abutting against mineralised shear fractures. Barren shear fractures then abut against both sets displaying a curvature indicative of a dextral stress state. Abutting relationships suggest the barren shear fractures likely formed at the same time as the dextral en-echelon vein array; however, they were not connected to a source of mineral rich



190 fluids. In Figure 2e, multiple phases of mineralisation and reactivation of veins can be observed. Veinlets  
 191 of ankerite both abut against, and cut through the calcite vein associated with a nearby small (<5 cm)  
 192 offset fault. Brecciation of coal and calcite is also observed, with undisrupted ankerite veinlets cutting  
 193 through the breccia. This requires a minimum of four stages of mineralisation/deformation:

- 194 1) Ankerite veinlets formed along the NS striking face-cleats.
- 195 2) Faulting leading to the development of coal breccia and calcite veining which either cut across  
 196 or abut against pre-existing structures.
- 197 3) Brecciation of the calcite vein and coal leading to the development of a chaotic fault breccia.  
 198 The breccia contains angular clasts of coal and calcite within an amorphous calcite matrix.
- 199 4) Finally, a return to ankerite mineralisation with dextral en-echelon arrays developed alongside  
 200 barren tip-damage zones.

201 These observations suggest that initial deformation and associated mineralisation occurred over a wide  
 202 zone of en-echelon arrays (Figure 2d), which was strongly influenced by the pre-existing cleat network  
 203 (Figure 2e). En-echelon arrays then began to interact leading to the development of localised mineralised  
 204 shear fractures (Figure 2f). As the trace length of the shear fracture increased, so did the thickness of the  
 205 zone leading to the formation of a dense array of small offset (<1 cm) strands which interacted through  
 206 the development of relay-zones. A later dextral **stress state**, demonstrated by reactivated features (Figure  
 207 2e), lead to another phase of en-echelon veins (Figure 2c), which also locally developed into mineralised  
 208 shear fractures.

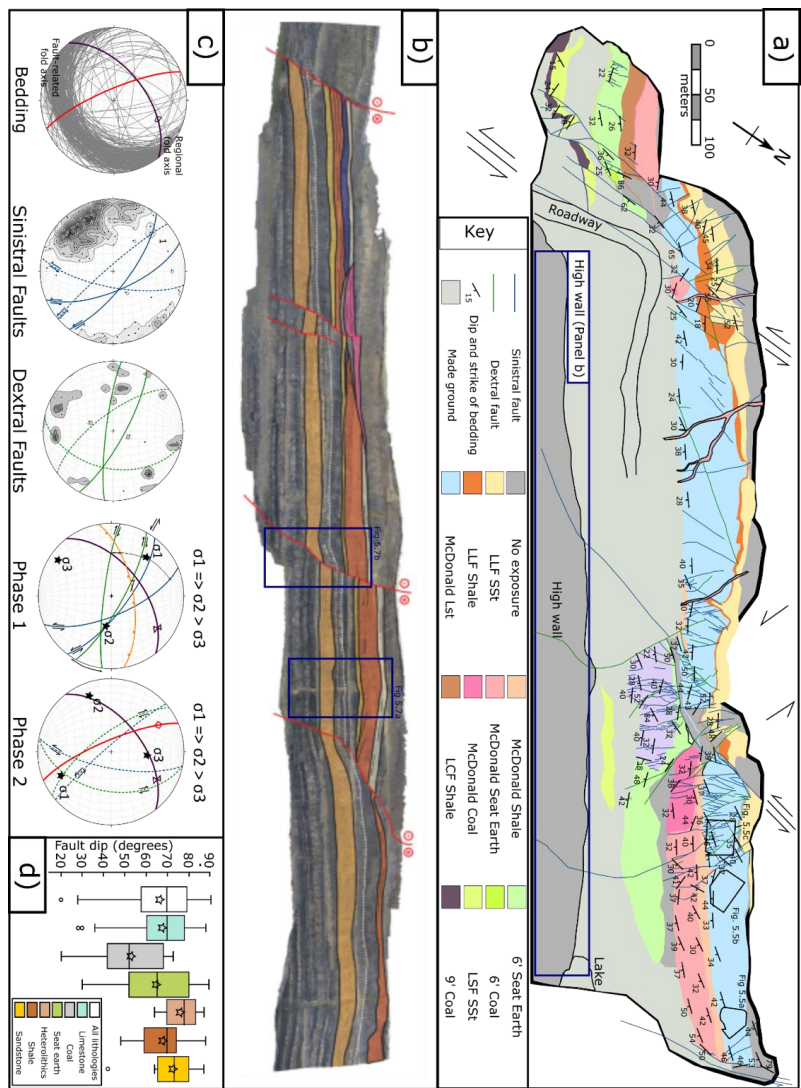
209 The other lithologies display a strongly developed fracture stratigraphy (c.f. Laubach *et al.* (2009)). The  
 210 McDonald Seat Earth exposed in the western panel (Figure 3a) lacks a well-developed joint pattern.  
 211 Instead, shear-fractures are observed in relation to small offset strike-slip faults which cut the dip-slope  
 212 (Figure 4a,b). Fractures are only found in close proximity to fault strands either forming sub-parallel to  
 213 fault strands in the hanging wall block, or oblique to the fault strands in relay zones and fault tips. These  
 214 fractures commonly display small sinistral and dextral offsets (mm to cm) and are typically barren,  
 215 although occasionally showing pyrite along the fracture plane. Sandstones displayed bed-bound joint-sets  
 216 in a similar manner to the McDonald Limestone. However, there was limited bed-parallel exposure to  
 217 explore the age and orientation of sets in sandstone lithologies. Seat-earth in the high wall, in contrast to  
 218 the dip-slope, displays a well-developed bed-bound fracture network. This suggests that mine-related  
 219 stresses have may have caused deformation of these lithologies and the natural network has been altered  
 220 by both subsurface and surface mining activities.



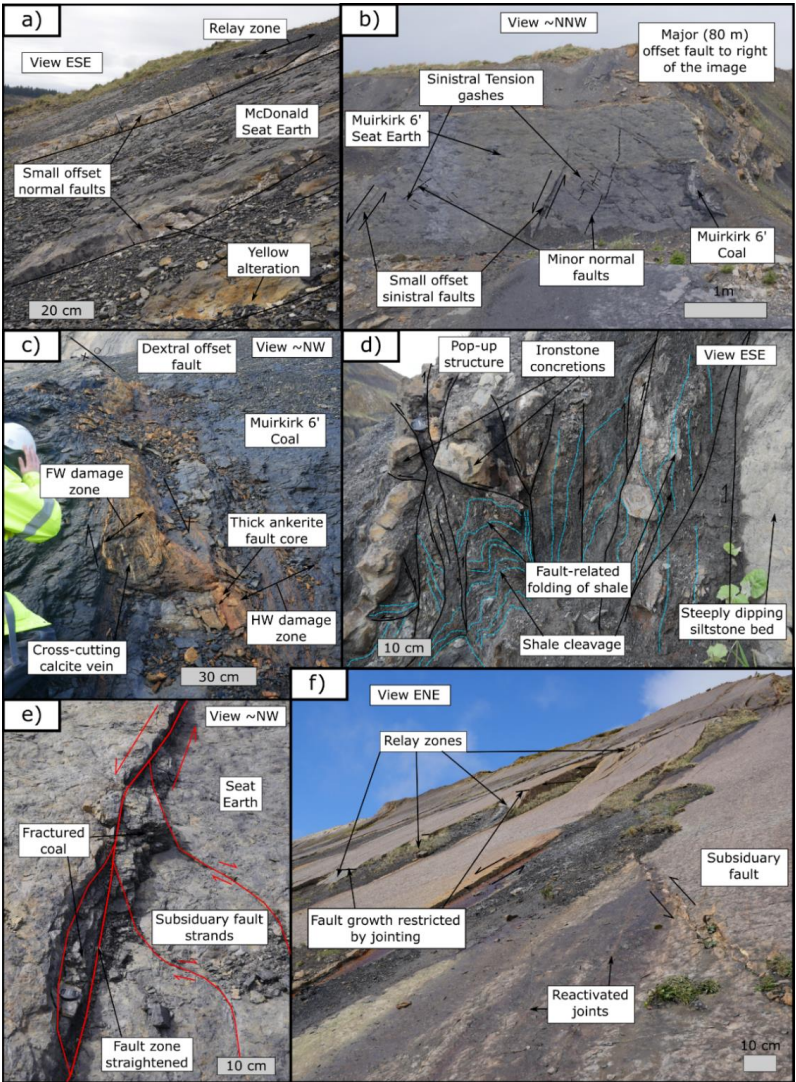




221 4.2 Fault observations  
222 4.2.1 Fault kinematics & Self-juxtaposed faults



224 Figure 3: Geological map of Spireslack SCM: a) Geological map undertaken as part of this study,  
225 displaying the locations of the detailed map-view fracture maps shown in Figure 5; b) Annotated  
226 photogrammetry of the high wall displaying the key stratigraphic horizons and faults (Ellen et al.,  
227 2019); c) Fault kinematics by lithology. Stereographic projections were created using Stereonet  
228 10.1 and contours represent 1% area; and d) box and whisker plots for fault dip by lithology.



229

230 **Figure 4: Characteristic observations of Self Juxtaposed Faults (SJFs): a) Small-offset (c. 15 cm) fault**  
231 **strands and relay structures, and b) tension gashes and small offset normal faults exposed within the**  
232 **McDonald Seat Earth in seat-earth exposed to the far west of Spireslack SCM; c) symmetric damage**  
233 **zone and thick zone of ankerite mineralisation along a c. 40 cm offset dextral offset fault cutting the**  
234 **Muirkirk 6' Coal; d) bed-parallel thrusts and folding developed within the shale which underlies the**  
235 **McDonald Limestone to the NE of the site; e) the development of small pods of fractured McDonald**  
236 **Coal along a small offset sinistral fault exposed to the SW of the site; f) the interaction between faults**  
237 **and joints along the southerly dipping bedding plane of the McDonald Limestone.**

238 Several steeply dipping faults with low angle **lineations** (5° to 30°) were mapped at Spireslack SCM  
239 (Figure 3). Fault offset ranges from cm-scale, where displacement is limited to specific lithology (self-  
240 juxtaposed), up to the largest offset fault (c. 120 m true offset according to Ellen *et al.* (2016)) which cuts  
241 the east of the site. Most faults (75%) **belong to** a sinistral offset set, which formed simultaneously with



~NE trending dextral faults. Additionally, a later set of sinistral faults with offsets of cm's to m's, and associated dextral faults, offset the earlier faults. Fault strike varies across the main void (Figure 3c), with a N-S trend in the east and west of the site and a NW-SE trend in the centre. Fault dip depends on the lithology cut by the fault. Dips in the McDonald Limestone range from 45° to 88° (mean = 69.1°, n = 47), however, in coal seams fault dips range from 20° to 73° (mean = 49°, n = 24). In the shale interbeds, layer bound bed-parallel thrusts (e.g. 040°/70° SE) with cm to m-scale offsets and associated folding can be picked out where they offset ironstone layers (Figure 4d). The McDonald Seat Earth in the west of the site displays dip-slip slickenfibers (50° to 60°), but only in faults with offset less than 1 m.

Self-Juxtaposed Faults, with offset less than 3 m, form either isolated strands (e.g. west of the void), or a network of sinistral and dextral strands (e.g. near the centre of the void) (Figure 3). The internal structure of self-juxtaposed faults depends on the lithology that the fault strand cuts (Figure 4, Table 1). Only large offset fault strands can be traced between beds (e.g. the 5 m offset fault cutting the western panel; Figure 3), apart from where large packages of sandstone are found (e.g. the Spireslack Sandstone). For lithologically restricted faults, trace length is typically low and well connected, with strands typically abutting against another fault strand in < 15 m.

The majority of faulting at Spireslack SCM fits a sinistral-offset strain-ellipse (Figure 3c). In this model the early dextral faults represent R' Riedel shears, with normal faulting of the McDonald Seat Earth, thrusting in the shale and Riedel shears of the major fault strands which bound the workings developing in the centre of the void. Bedding, which dips towards the south, matches a fold axis of 042°/80° N and is likely to have been developed under the same stress state as the regional Muirkirk syncline. Faulting that cuts the earlier structures (e.g. the oblique sinistral fault and minor dextral fault strands) does not fit within this strain ellipse, and likely formed under a later dextral strain (Figure 3c). In addition to the two phases of strike-slip tectonics, Paleogene dykes are observed exploiting pre-existing N-W trending fault strands. These locally display pods of edge brecciation similar to that developed along faults in limestone, and show dip-slip lineations suggesting there could have been a late stage of normal faulting.



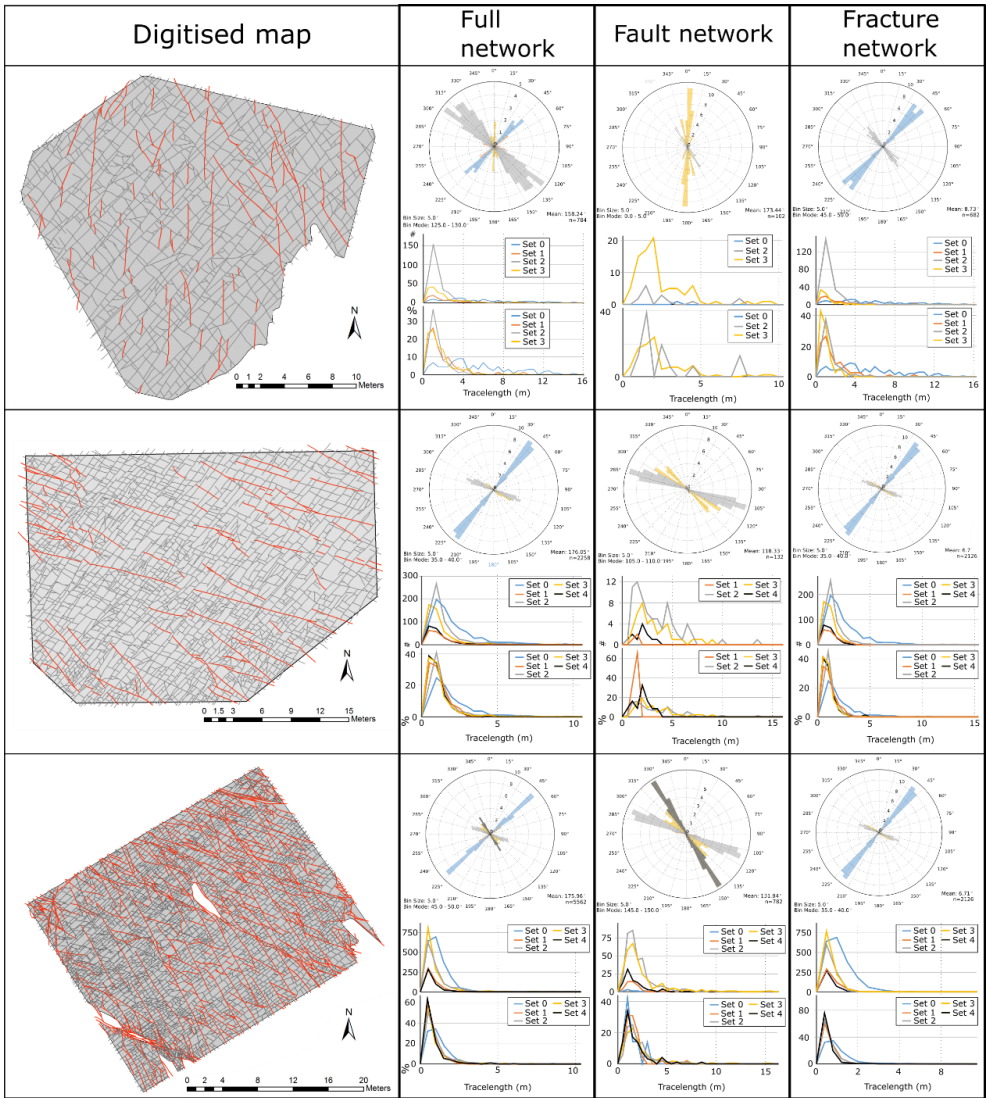


Lithology	Self-juxtaposed fault characteristics
McDonald Seat Earth	Segment linkage, folding, and increased fracturing between strands led to the development of a highly asymmetric damage zone (Figure 4a,f). Faults typically barren, only displaying yellow alteration and occasionally pyrite.
McDonald Limestone	Self-juxtaposed faults, associated relay zones, and nearby N-S trending joint sets, are mineralised (calcite), display high displacement to length ratios (2.4 to 2.8), and show extensive folding of the surrounding lithologies (Figure 5.4f). Strands often abut against favorably orientated pre-existing joints.
Coal	Fault strands are characterised by a fault core comprising of a 5 to 20 cm thick zone of ankerite, with occasional calcite mineralisation, brecciated coal and pyrite (Figure 4c). The fault core is discontinuous along strike, with displacement transferring to other strands after 1 to 5 meters (Figure 2c). The gentle folding of the bed between strands is taken up by a symmetric zone of damage consisting of increased fracturing, en-echelon veining and mineralised shear fractures. The structures represent a continuation of the processes discussed in Section 4.1.1.
Shale	Fault strands are rarely observed. High angle thrusts (40° to 60°) dominate, with bed parallel folding picked out by ironstone concretions (Figure 4d), which themselves can display internal deformation (tension gashes). Near self-juxtaposed faults a cleavage is developed sub-parallel to the fault plane, which combined with slickenfibers on competent bedding planes suggests bed-parallel slip.

267 **Table 1: Self Juxtaposed Fault characteristics.**

268 4.2.2 Interaction between faults and fractures within the McDonald Limestone

269



270 **Figure 5: Fracture maps with increasing intensity of faulting:** For each digitised map the exported  
271 **fault** (red lines) and **fracture** (dark grey lines) maps, along with the interpretation areas used for  
272 the analysis (light grey) are provided. The orientation data, colour coded by sets, is then provided  
273 using length weighted rose diagrams with 5° bin widths. Trace length is presented as trace-length  
274 histograms as well as normalised trace-length histograms with bin widths of 0.25 m. Histograms  
275 are colour coded to match the sets outlined in the orientation data.



276 The style of the fault and fracture network in the McDonald Limestone changes across the site (Figure 3)  
277 with the chronology and network properties of each sample area described in Table 2. Overall, the  
278 network is well-connected and dominated by x- and y- nodes, with i-nodes only observed where faults  
279 transfer displacement to another strand. As fault intensity increases, the complexity of age relationships  
280 in the fault-fracture network increases. Where fault intensity is low and not favourably orientated to  
281 reactivate joints (Figure 5), the age relationships match that described in Section 4.2.1. Across all sample  
282 areas faults abut against the larger trace-length NE trending set (Figure 5), which are interpreted as  
283 forming prior to faulting. When the interaction between faulting and jointing increases, either through an  
284 increase in fault intensity or joints being favourably orientated for reactivation, age relationships become  
285 complex with new fractures forming concurrently with faulting, probably during stress field rotation. The  
286 fact that age relationships vary across the site suggests a highly heterogeneous stress field, which was  
287 rotated relative to locally active fault strands. An increase in fault offset also affects the intensity, trace-  
288 length and connectivity of the network.



Sample area	Sets & age relations	Trace length & intensity characteristics	Network topology & connectivity
1 Fig. 5a	Joint sets occur as two roughly perpendicular sets, an older 045° trending set and later 145° trending set. Faults are present as a separate NS trending set, which displace both joint sets, typically abut against large trace length NE trending joints, are mineralised and display sinistral syntaxial growth textures (e.g. Figure 2c). In the vicinity, and locally abutting against faults is a final stage of jointing, either associated with initial fault slip or later dextral reactivation.	The NE trending set ranges in has a larger trace length ( $4.10 \pm 3.40$ m) compared to the SE trending set ( $1.30 \pm 1.10$ m), with the latter typically abutting against the NE trending set. Trace lengths in the NS trending set range from 0.20 to 9.30 m (Median = 1.60 m), and typically abut against the NE trending set. Fault intensity is low (0.4 f/m), with moderate joint density (2.6 f/m) split into 1.3 f/m for the NE set, 1.0 f/m for the SE trending set and 0.3 f/m for obliquely aligned features.	The connectivity of the full network is high ( $P_c = 0.99$ ) and is dominated by y nodes (76%), with X-nodes representing 23% of nodes. Field observations suggest the majority of x-nodes mapped on the drone map represent two y-nodes separated by <5 cm. The fault network is dominated by l nodes (90%) and is poorly connected ( $P_c = 24\%$ ). The joint network is dominated by y-nodes and has a connectivity of $P_c = 95\%$ .
2 Fig. 5b	Dominated by barren joints, with faults displaying a NW trend, which reactivate appropriately orientated joints and abut against NE trending joints. The age relationships are complex and show multiple generations of joints, typically orientated in a NE or NW trend, however, many joints are observed which do not fit these sets.	Faulting is slightly higher intensity than SA1 (0.5 f/m), with fault trace length varying between 0.20 and 13.20 m (median 1.20 m). Small trace length faults are found oblique to the main strand (e.g. northerly trending faults median trace length = 0.80 m). Joint intensity is 3.1 f/m with the majority of fractures belong to the NE (1.7 f/m) or NW (0.7 f/m) trending sets. Fractures off this trend typically have smaller tl (Median = 0.60 to 0.70 m) compared to the NE (median = 1.30 m) and NW (median = 1.00 m) sets.	The connectivity of the full network is high ( $P_c = 0.99$ ) and is dominated by y nodes (88%). The fault network is dominated by l nodes (89%) and is poorly connected ( $P_c = 28\%$ ). The joint network is dominated by y-nodes and has a connectivity of $P_c = 90\%$ .
3 Fig. 5c	The complexity of joints varies considerably throughout SA3. Some areas display a simple relationship with an early ENE trending set and later NNW trending set, however, other areas display fracture corridors, which are aligned at a similar orientation to faulting, and which display multiple generations of joint formation. Faulting occurs as two sets, trending NNW, and NW. Faults typically abut against ENE trending joints, and locally cause the formation of new joints and rotation of pre-existing features.	Faulting intensity increases considerably in SA3 (1.9 f/m), with fault trace length ranging from 0.10 to 15.30 m (median = 1.40 m). The majority of faults trend between 125° and 155° (0.16 f/m) and display a higher median trace length (1.40 m) compared to other faults (1.10 m). Joint trace length is smaller in SA3 (0.50 m) compared to other sample areas (Median tl = 1.00 m and 0.80 m). Although most joint trend is NE (2.4 f/m) the NW trending set displays a wide range in orientation (125° to 155°) and 17% of joints are off axis from these trends. NE joints display a larger trace length, ranging from 0.00 to 5.50 m (median = 0.70 m) compared to other orientations (median = 0.40 m).	The connectivity of the full network is high ( $P_c = 0.99$ ) and is dominated by y nodes (93%). The fault network is dominated by both l- (55%) and y-nodes (45%) and is moderately connected ( $P_c = 71\%$ ). The joint network is dominated by both i- and y-nodes and has a connectivity of $P_c = 77\%$ .

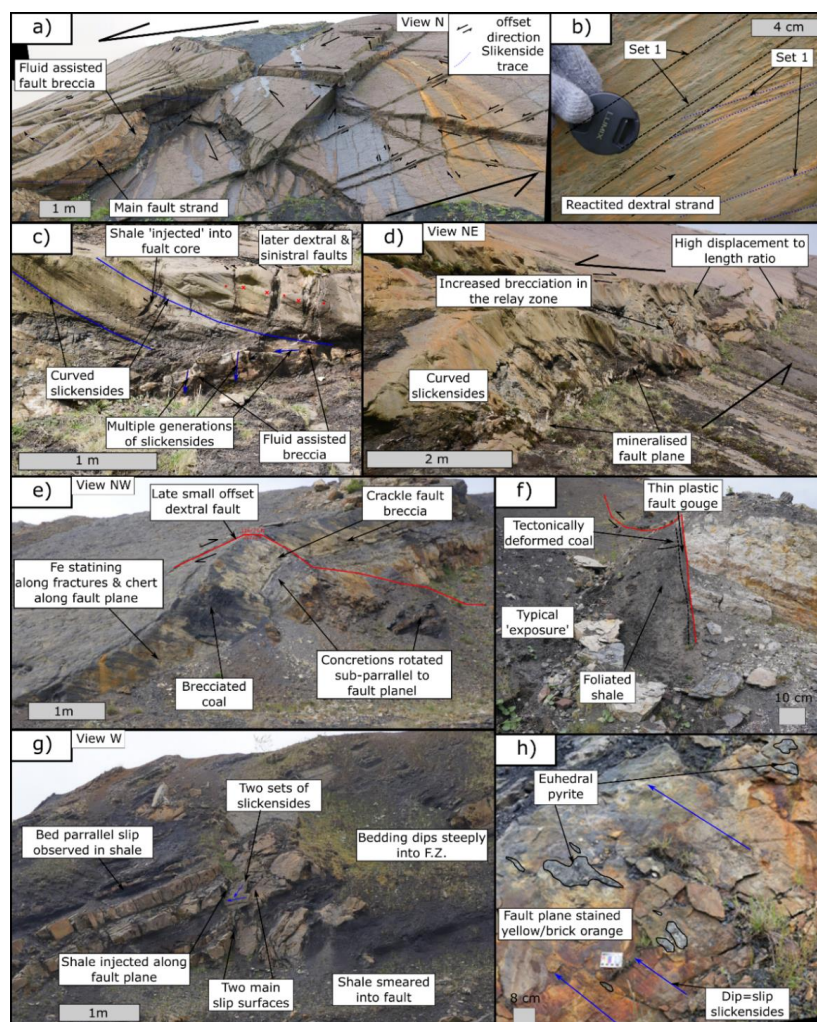


289

290 **Table 2: Network characteristics for the sample areas outlined in Figure 5**



## 291 4.2.3 Large offset faults



292

293 **Figure 6: Large offset fault characteristics:** a) complex fault mesh consisting of multiple strands of  
 294 sinistral and dextral strike slip fault planes (offset marked with arrows) picked out by shallow  
 295 striations and the offset of the McDonald Limestone bedding plane; b) field photograph of a ~3 m  
 296 offset fault strand within the complex mesh which displays multiple generations of fault striations,  
 297 with local dextral reactivation separating striations belonging to set 2; c) fault architecture and d)  
 298 view along strike of a 3 to 5 m offset fault strand exposed along the southerly dipping bedding dip-  
 299 slope; fault architecture of the same 5 m offset fault cutting e) lithologies surrounding the McDonald  
 300 Seat Earth, and g) interbedded sandstones, siltstones and shales of the Lower Limestone Coal  
 301 Formation; f) primary slip plane of the ~80 m offset fault which cuts the west of the site; and h)  
 302 shallowly dipping, sinistral dip-slip fault plane within a ~2 m thick sandstone bed of the Limestone  
 303 Coal Formation.





304 Faults that offset multiple lithologies (i.e. non self-juxtaposed) have a complex deformation style (Figure  
305 6). Fault dips still vary depending on lithology, with steeper dips observed in competent lithologies for  
306 the same fault. For example, a 4 m offset fault changes orientation from 135°/85° NE in the McDonald  
307 Limestone to 110°/72° N in the McDonald Seat Earth. This change in orientation causes bed rotation and  
308 the development of lenses, particularly in sandstones and seat-earths. Examples of larger-offset faults are  
309 provided below, with the complexity of faulting depending on the lithologies cut by the fault (Figure 6)  
310 and the plane of observation (i.e. map (Figure 3) vs high wall (Figure 7)).

311 Example 1: Fault meshes in the McDonald Limestone and surrounding lithologies

312 Faults cutting the McDonald Limestone with less than 3 m offset lead to the development of fault meshes  
313 (Figure 6a). Rotation of bedding is accommodated along several fault-strands accompanied by the  
314 development of tension gashes. The thickness of individual fault cores is low (<5 cm, Figure 6a,b), and  
315 does not increase with displacement. Fault cores are mineralised, with local development of matrix-  
316 supported breccias containing angular limestone clasts and clasts of re-worked calcite. These textures,  
317 along with the development of **Mode 1 fractures that offset previous slickenfibers** (Figure 6c),  
318 demonstrate fault reactivation. Multiple generations of slickenfibers are developed whose dip shallows  
319 from the top to the base of the bed (Figure 6c, insert), providing further evidence of block rotation within  
320 the fault zone. Folding and bed parallel deformation of the under- and over-lying shale helped  
321 accommodate this rotation.

322 Example 2: Dip-slip faulting of sandstones and seat earths

323 3D exposures of faults cutting sandstone are rarely observed, however, in the center of the void there a 3  
324 to 5 m offset fault cuts decimetre thick seat-earth and sandstones of the Limestone Coal Formation (Figure  
325 3). The fault-plane is low-angled (100°/40° S) and displays dip-slip (40° to 55°) lineations. The fault plane  
326 is altered to a brick-orange colour (Figure 6). Pyrite is locally preserved within corrugations along the  
327 fault plane and consists of <4 cm euhedral crystals (usually <0.5 cm). The alteration and pyrite  
328 preservation suggests sulphur-rich fluids migrated along the fault zone, and pods of crystal growth  
329 developing elongated to the slip-vector suggesting this was syn-kinematic. Where coal is observed above  
330 seat-earth (Figure 4e), brecciation of coal, thin zones of friable coal develop and cleats are rotated relative  
331 to the orientation of the fault plane.



332 Example 3: ~5 m offset fault cutting interbedded lithologies from the Lower Limestone Formation and  
 333 Limestone Coal Formation

334 A ~5 m offset, sinistral fault is observed cutting limestones and sandstones of the Lower Limestone  
 335 Formation and the McDonald Seat-Earth to the west of the void (Figure 3). In the McDonald Seat Earth  
 336 (Figure 6b) fault dip changes from ~60° near the base of the outcrop to 007°/79° NE near the top and low  
 337 angle lineations (e.g. 20°/107°) and offset markers indicate a sinistral offset. The main fault plane is cut  
 338 by several later barren fractures (e.g. 116°/74° N and 292°/71° NE), which occasionally show cm-scale  
 339 sinistral offset (18°/019°). Brecciated McDonald coal is found within undulations on the fault plane. In  
 340 the underlying shale, several iron concretions (<10 cm) have been locally rotated and sheared in response to motion along the  
 341 fault. An asymmetric damage zone is developed, with minimal deformation of the footwall and a 20 to 30  
 342 cm wide zone of higher fracture intensity developing in the hanging wall. Bedding in the seat earth away  
 343 from the the fault displays gentle (2-5m wavelength), low amplitude (~50 cm) folding with wavelength  
 344 decreasing towards the fault.

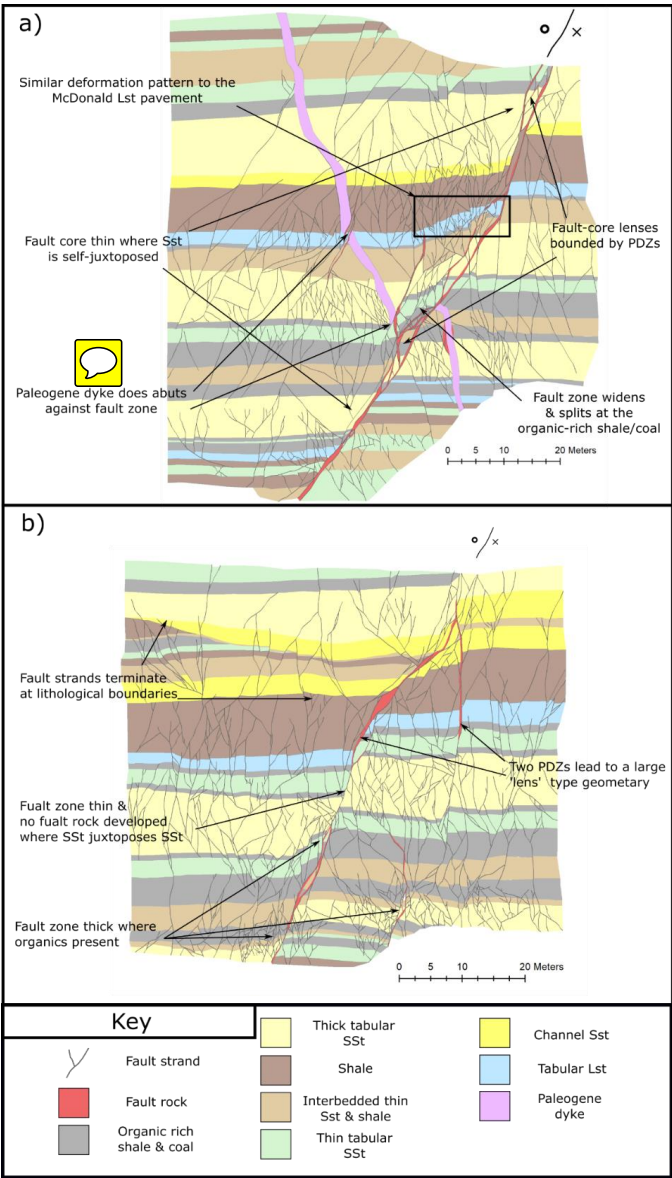
345 In the underlying Lower Limestone Formation, the same fault develops a complex, 2 to 3 m thick,  
 346 mineralised fault zone (Figure 6c). The fault core is characterised by two mineralised slip surfaces  
 347 (216°/60° W & 261°/68° NW), each with shallow (10°/080°), moderate (25°/050°) and steeply (68°/083°)  
 348 dipping sets of slickenfibers developed. It is unclear which order these developed, and all apparently  
 349 display sinistral offset markers. Along the fault surface (015°/88° E), a ~5 cm thick pod of matrix  
 350 supported brecciated limestone is present in the hanging wall. Shale appears to have been locally injected  
 351 into fractures that had already been mineralised with calcite. To the north of the fault, the interbedded  
 352 sandstones, limestones, and shale dip steeply into the fault zone, reaching dips which match that of the  
 353 fault plane (60° to 70°). In contrast, bedding to the south displays only low amplitude folding (015°/56°  
 354 N; 043°/56° N).

355 Example 4: 80 to 100 m offset fault cutting the full sequence

356 The internal structure of the 80 to 100 m offset fault that cuts the west of the main void is only observed  
 357 at a single location (Figure 6e). The footwall comprises 6' Seat Earth that has been highly fractured,  
 358 juxtaposed against highly altered coal and folded shale with a steeply dipping cleavage. The fault core is  
 359 comprised of a thin (<5 cm), clay rich zone of plastic fault gouge containing <2 mm clasts of sandstone  
 360 and organic fragments. The altered coal has lost its cleat network and is noticeably harder than its  
 361 unaltered equivalent, creating a spark when struck with a geological hammer. This increase in coal rank  
 362 is potentially due to shear-heating (c.f. Fowler and Gayer, 1999; Li, 2001). Shear fractures in the  
 363 surrounding seat earth are often stratabound and increase in intensity towards minor-slip zones and the  
 364 fault core.



365 **Example 6:** *Fault strands cutting the high wall*



366

367 **Figure 7: Digitised fault strands of sinistral faults cutting the Limestone Coal Formation exposed**  
368 **along the high wall: a) sinistral fault which displays between 2 and 5 m of throw and has been cut**  
369 **by a later Paleogene dyke which is not observed with the main PDZ; b) sinistral fault with displays**  
370 **between 2 and 8 m throw along two PDZs.**





371 Fault strands cutting the high wall (Figure 7) appear to show a simpler geometry to those observed on the  
 372 dip slope (Figure 6). It should be noted that because of the predominant strike-slip kinematics significant  
 373 out of plane displacement exists, so visible offsets represent an underestimate of true displacement. The  
 374 majority of throw is taken up by a small number of fault strands, particularly when faults cut channelised  
 375 sandstones and limestones. Individual fault strands are thin and form an interconnected network of self-  
 376 juxtaposed faults. Fault core thickness is typically below the width of a pixel on the orthorectified  
 377 photographs (~5 cm), however, on the major faults the fault-rock thickness can be measured, although  
 378 the rock type not quantified. The thickness varies considerably down-dip (<1.4 m), and while a continuous  
 379 strand is observed in Figure 7a, in Figure 7b no fault rock is observed where the thick sandstone bed is  
 380 self-juxtaposed.

381 The deformation style in the high wall varies depending on the lithological juxtaposition, with the  
 382 proportion of sandstone in the faulted section controlling whether fault-core lenses are developed. For  
 383 example, in both panels of Figure 7 fault-bounded lenses are seen in the lower third of the high wall.  
 384 Faults are steep (apparent dip ~70° to 80°) with displacement taken up along a single fault strand, and  
 385 damage zone evolution is low in areas where thick sandstone units are juxtaposed. However, where  
 386 interbedded units are juxtaposed against each other the fault zone widens to 4 m in Figure 7a and 4.5 to  
 387 6 m in Figure 7b. Within these zones beds of competent lithology are rotated away from the main fault  
 388 zone and subsidiary antithetic fault strands develop which abut against the main strand. Small offset faults  
 389 are more abundant in the thick tabular sandstone, interbedded and shale units, with fault stands abutting  
 390 and branching at lithologically controlled mechanical boundaries.



## 391 5. Discussion

### 392 5.1 The role of lithology on faulting style: self-juxtaposed vs non self-juxtaposed faulting

393 The observations at Spireslack SCM suggest that faults initiated both in the competent lithologies  
 394 (sandstone, seat-earth and limestones) and the coals (Figures 3, 4). The properties of the faults (trace  
 395 length, connectivity, D-L ratio and fault-rock development) depend on the lithology being cut, and the  
 396 degree of non-self-juxtaposition. This is similar to observations of the growth of normal faults in  
 397 interbedded limestones and marls (Ferrill et al., 2017), basalts (Ellen 2011), as well as 2D and 3D  
 398 numerical modelling (Schöpfer et al., 2007, 2016). Self-juxtaposed faults developed in all the competent  
 399 layers at the same time and initially grew as isolated strands, before interacting with other strands from  
 400 the same unit. This behaviour matches established models for fault growth (Fossen and Rotevatn, 2016;  
 401 Walsh et al., 2002; Wibberley et al., 2008).



402 However, large offset faults which breach more than a single lithology are strongly affected by the  
 403 presence and behaviour of shale interbeds. Shale in the sequence behaves in a ductile manner with folds  
 404 and cleavage developing (Figure 4d), and enables bed-parallel slip. In Figure 6g, shale is squeezed into  
 405 pre-existing mineralised fractures, indicating the highly ductile nature of shale during faulting. The  
 406 ductility of shale can be affected by many factors including lithology, mineral composition, organic  
 407 carbon content, diagenesis, and thermal maturity (Wang and Gale, 2009). Burial depth is a major  
 408 controlling factor for many of these properties and it is important to consider both the current and past  
 409 burial depth (Yuan et al., 2017). As shale is buried and compressive stresses increases, the ratio of pre-  
 410 consolidation stress and compaction-related stresses control the behaviour of shales and mud rocks (Yuan  
 411 et al., 2017; Nygård et al., 2006). **As a general rule, shales are ductile during burial, and brittle during**  
 412 **exhumation where they experience stresses below the maximum stress they have encountered.** While  
 413 estimates vary across the Midland Valley, it is suggested the Limestone Coal Formation has a maximum  
 414 burial depth of <3,000 m at around c. 60 Ma (Monaghan, 2014). Ductile behaviour of the shales at the  
 415 time of faulting suggests that faulting was active during burial, rather than uplift. This will have enabled  
 416 faults to initiate as isolated strands in competent lithologies. When faults accumulated enough  
 417 displacement to cut multiple lithologies, shales accommodated the rotation of bedding, leading to rotated  
 418 blocks and multiple generations of curved slickensides.

419 **Self-juxtaposed faults coal** remained relatively undeformed, or developed a thin zone of ankerite  
 420 mineralisation. This differs from published examples ~~in, where~~ tectonically deformed ~~coals in the form~~  
 421 ~~of~~ soft-coal bands are ~~often~~ associated with normal faults (Godyn, 2016; Ju et al., 2012; Li et al., 2018),  
 422 or bed-parallel slip in compressive environments (Frodsham and Gayer, 1999; Li, 2001). Soft coal bands  
 423 often display a range of brittle and ductile features, for example S-C type cleavages, minor thrusts and  
 424 folding (Li, 2001), all of which act to degrade the quality of the coal. Archival photographs of the far  
 425 east of the site show that soft-coal bands were also not developed where coal was extracted from an area  
 426 where bedding steepened to ~70° (Ellen et al., 2016; Leslie et al., 2016).

427 The fault core of the large offset faults often contain pods of coal present as un-mineralised chaotic fault  
 428 breccia (Figure 6e). These deposits form in asperities along the fault zone, which get cut as the fault  
 429 straightens. Asperities, formed by corrugations along the fault zone, have previously been identified both  
 430 in the field (Sagy et al., 2007; Wright and Turner, 2006) and from seismic data (e.g. Lohr *et al.* (2008)).  
 431 Asperities typically form aligned parallel to fault slip (Hancock and Barka, 1987), which is also observed  
 432 in fault zones at Spireslack SCM. The behaviour of coal in the larger faults (Figure 6) differs from small  
 433 offset faults (Figure 4) in that no mineralisation is observed. Where coal was observed overlying seat-  
 434 earth (Figure 4e), coal was rotated, brecciated and thin zones of friable coal developed, suggesting that  
 435 coal becomes entrained into the fault core as a rotated block, similar to a fault-core lenses (Gabrielsen et



al., 2016). This suggests that while self-juxtaposed faults can be used to understand fault growth up to a certain point, once multiple lithologies are cut the processes change such that self-juxtaposed faults are not representative of large offset faults (c.f. Ellen, 2011).

## 5.2 Jointing and the effect of pre-existing weaknesses on the deformation style and fault growth

The mechanically stratified succession at Spireslack SCM has led to the development of a fracture stratigraphy (Laubach et al., 2009). Orthogonal joint sets are developed in the MacDonald Limestone (Figure 2a), as cleats in the MacDonald coal (Figure 2d) and bed-bound joints within the sandstone layers. While only two orientation sets are observed within the MacDonald limestone, abutting relationships show these formed as at least 4 ‘age sets’. Similar observations reported for other sites (Peacock et al., 2018; Sanderson, 2015) confirm that fractures in the same orientation, did in fact grow in response to separate deformation events. Another way in which multiple age sets can develop is where the intermediate ( $\sigma_2$ ) and minimum ( $\sigma_3$ ) principal stresses are nearly identical, and can therefore easily switch between each other (Caputo, 1995; Caputo and Hancock, 1998). The ratio of principal stresses changes the mechanical response of the layer (Healy et al., 2006; Moir, 2010; Moir et al., 2010)), with the dip and dilatancy of fractures varying depending on the difference between ( $\sigma_2$ ) and ( $\sigma_3$ ) (Chang and Haimson, 2000; Haimson and Chang, 2000).

The joints at Spireslack SCM formed both prior to and associated with faulting: the sparsely spaced joint set **likely** forming in response to far-field stress fields during burial, and later sets related to the early stages of faulting and folding associated with the Muirkirk Syncline. This folding, and later faulting is attributed to mid-to late Carboniferous sinistral transpression (Leslie et al., 2016). A late-stage dextral event locally reactivates these structures, reactivates cleats within the coal (Figure 2 d, e, f), and locally causes kink-bands to develop. This dextral strain was not identified in the work of Leslie *et al.* (2016). and could be correlative to Upper Carboniferous deformation to the east of the MVS (Underhill et al., 2008). Paleogene dykes, intruded along pre-existing NE to N trending faults, display a minor amount of reactivation, with brecciation and dip-slip lineations developing along the margins. This suggests that late stage extension, orientated to enable the reactivation of NE trending structures occurred since the Paleogene, possibly linked to isostatic rebound or the opening of the North Sea or Irish Sea.

The presence of joints in the McDonald Limestone, and cleats within the Muirkirk 6' Coal influence the internal structure and fault growth in these lithologies (Figure 4, 6). In both lithologies multiple sets of pre-existing weaknesses existed at the time of faulting, however, it was only those orientated roughly orthogonal to fault trend which caused fault strands to terminate (Figure 4). Coal cleats in the Muirkirk 6' Coal show evidence of reactivation (forming mineralised shear fractures and en-echelon arrays), and may act to restrict the growth of these features. Although small-offset fault strands display evidence of



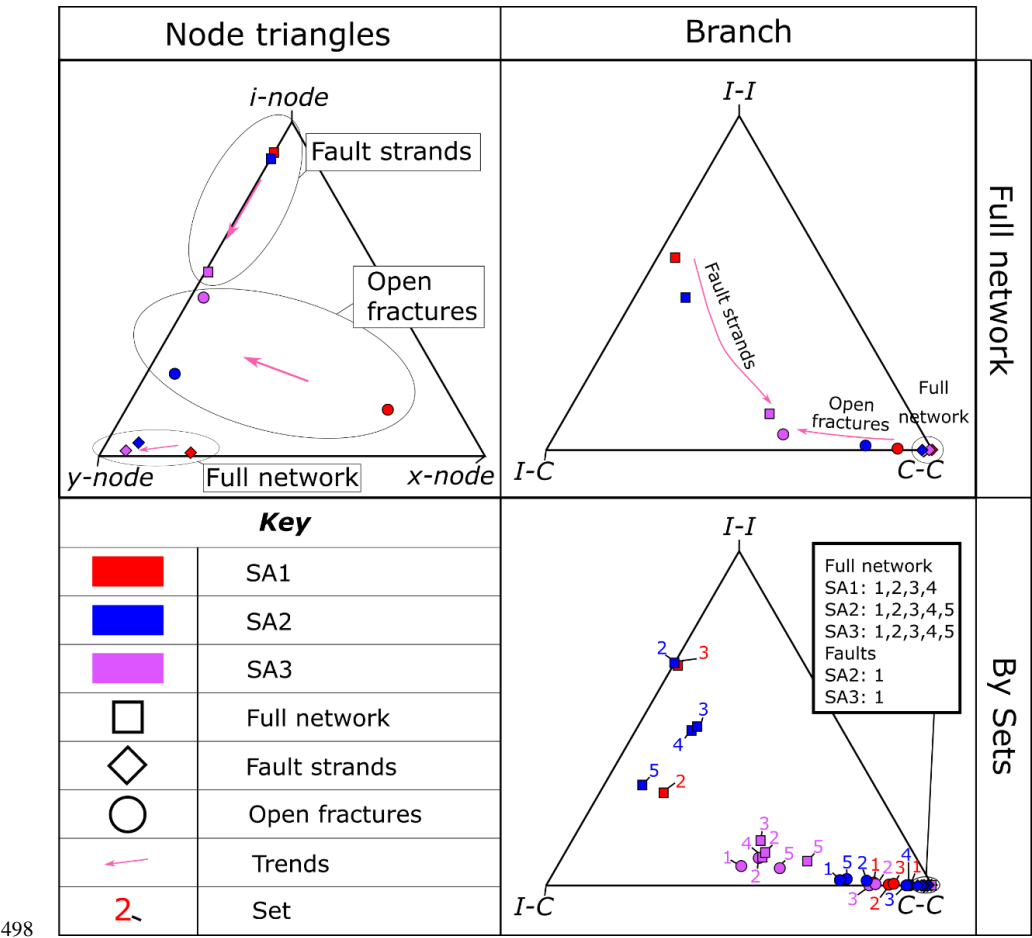
469 reactivation (e.g. brecciated coal, calcite and ankerite), further displacement is often taken up by the  
470 formation of new shear fractures. Mineralisation of the cleats causes the strain-hardening of the coal with  
471 pre-existing weaknesses (cleats) becoming mineralised strength inclusions. During the dextral  
472 deformation stage new mineralised fractures formed, and tip-damage zones developed from the end of  
473 shear fractures that had developed during the sinistral phase.

474 While joint sets in the McDonald Limestone may become rotated close to fault strands, no increase in  
475 fracture intensity is observed and a typical core-damage zone structure is not developed (e.g. Caine *et al.*  
476 (1996); Gudmundsson *et al.* (2010); Bense *et al.* (2013)). Mineralisation (primarily calcite) increases  
477 towards the fault core, with fault cores in the McDonald limestone comprising of multiple generation of  
478 slickensides, mineralisation and calcite matrix chaotic fault breccias (Figure 6a, c). While some rotation  
479 of individual joints occurs towards the east of the site, the majority of joints remain planar and instead  
480 acted as planes of weaknesses which became reactivated to accommodate fault slip. The rotation of joint  
481 strike is in part related to the bulk rotation of competent beds along shale inter-beds into fault zones which  
482 is observed both along the dip-slope and high wall. In Figure 5, the folding of the McDonald Limestone  
483 can lead to previously mis-oriented joints becoming more favourably orientated to reactivation

484 Displacement on large offset faults, such as those observed in the high wall, is typically localised onto a  
485 small number of principal displacement zones (Figure 7). This indicates that while jointing strongly  
486 impacts early fault parameters, once a fault reaches a certain displacement, small-scale features such as  
487 joints have only a minor effect on fault growth. The effect of joints on the early growth characteristics of  
488 faults is discussed by Wilkins *et al.* (2001), who found faulted joints to develop little fault rock, and to  
489 have considerably smaller displacement/length ratios that would be expected for faults which do not cut  
490 jointed lithologies. Pre-existing joint-sets restrict fault-growth for self-juxtaposed faults through the  
491 formation of faulted joints (Peacock, 2001; Soden *et al.*, 2014; Wilkins *et al.*, 2001), with lithology  
492 becoming the major control once faults breach multiple layers (Nicol *et al.*, 1996; Soliva and Benedicto,  
493 2005; Wilkins and Gross, 2002). This behaviour is not observed in the McDonald Seat Earth, where  
494 jointing is not present. Instead fault strands grow as single strands, which interact with other strands to  
495 form tip-damage zones and relay zones where displacement transfers between fault strands (Fossen and  
496 Rotevatn, 2016).



497 **5.3 Effect on flow pathways**



499 **Figure 8: Network topology data.** Node and branch triangle (after Sanderson & Nixon (2015)) are  
 500 presented for the full-network, mineralised fault strands, and open joints, for each of the three  
 501 sample areas shown in Figure 5. Branch data is then presented by sets, as outlined in figure 5, to  
 502 investigate the directionality of network connectivity.



		Network parameter	Sample area		
			SA1	SA2	SA3
a) Combined network	#lines		784	2258	5562
	D (F/m2)		3.1	3.5	5.9
	Pc		1.00	0.99	0.96
	TI (m)	Min	0.09	0.02	0.04
		Max	14.71	13.16	15.33
Median		1.12	0.90	0.51	
b) Fault network	#lines		102	132	782
	D (F/m2)		0.4	0.5	1.9
	Pc		0.24	0.28	0.71
	TI (m)	Min	0.22	0.21	0.10
		Max	9.33	13.16	15.33
Median		1.62	2.34	1.36	
c) Joint network	#lines		682	2126	4778
	D (F/m2)		2.6	3.1	3.9
	Pc		0.96	0.90	0.77
	TI (m)	Min	0.09	0.02	0.04
		Max	14.71	10.33	5.49
Median		1.53	0.86	0.46	

**Table 3: Overview of network properties for: a) the combined fault and fracture network; b) the mineralised fault network; and c) the joint network which does not display mineralisation or reactivation during faulting.**

Mineralisation along fault planes within coal (Figure 4), limestone (Figure 4 & 6), sandstone (Figure 6), and to a lesser extent seat-earth (Figure 4 & 6), locally provides evidence of flow within the structures. Fault-related veins display one or more crack-seal events (Figure 2c) indicating along-fault flow was related to fault assisted opening of dilatational zones leading to the connection of pre-existing fractures (Ferrill and Morris, 2003; Laubach et al., 2009; Ferrill et al., 2014). The multiple events suggest pathways only remained open for a small amount of time and probably closed following fault slip (c.f. Sibson 1990, 1992). Faults in the McDonald Limestone behave in a similar way to other faults in carbonates with primary slip surfaces becoming sealed following slip (e.g. Billi *et al.* (2003)).

Fault-related mineralisation in both limestones and coals would act to reduce connectivity, and hence permeability, of the network (Figure 8). At the time of faulting, the majority of the network had been formed, however, only joints/cleats orientated favourably for reactivation became mineralised. Following mineralisation, these fractures became sealed and closed to future fluid flow. During faulting, the connectivity of the network on the McDonald Limestone bedding plane varies depending on the intensity of faulting (Table 3). Fault-assisted fluid flow in areas of low fault intensity (0.4 f/m<sup>2</sup>; Figure 5) was primarily confined to a sparse network of partially connected NS trending, poorly connected (Pc = 0.24) fault strands. Where faulting of a similar intensity (0.5 f/m<sup>2</sup>) is orientated favourably to reactivate joints



(SA2), the connectivity remains low ( $P_c = 0.28$ ), however, fault trace length is greater due to the orientation and spacing of pre-existing joints. When faulting intensity is high (1.9 f/m), the connectivity of faults is high ( $P_c = 0.71$ ), and both sets of joints become reactivated. Because multiple sets of joints may restrict the growth of faults, trace length of individual fault strands is low and strain is taken up by many small offset faults.

Faulting caused the development of several new joints, with joint intensity increasing from 2.6 in SA1 where limited shear fractures are observed, 3.9 f/m where fault intensity is high. The joint network initially remains well connected ( $P_c = 0.96$ ), however, as joints become reactivated connectivity drops to  $P_c = 0.90$ . In SA3, where fault intensity has increased to 1.9 f/m, the connectivity of the joint network drops to  $P_c 0.77$ . It is also important to consider the orientation of the feature when considering fluid-flow properties of the network. For example, while faults typically have a low to medium number of connections per branch, those orientated between  $060^\circ$  and  $100^\circ$  plot close to the C-C vertex of the branch triangle (Figure 8). This is also observed for joint sets, with those trending to the NW being the most connected.

The evidence of transient fluid flow in both the McDonald Limestone and Muirkirk 6' Coal highlights the importance of understanding the evolution of a fault and fracture network when assessing the geological and fluid-flow history of a particular site. If fracture data were collected using the high-resolution imagery alone, and not combined with field evidence, all fractures might be assumed to have been open to flow. This would lead to a significant over-estimation of the permeability of the network. For example, in SA3 the connectivity of all lineaments is  $P_c = 0.96$ , however, when only joints which have not been reactivated by faulting are considered, this drops to  $P_c = 0.77$ . In this case the trace length, which represents one of the most important parameters in fracture modelling (Lei et al., 2017; Min et al., 2004) would also be overestimated, with mineralised fault strands displaying a larger median trace length of 1.36 m. The presence of mineralisation only within particularly orientated joint or cleat sets also highlights the importance of stress state on hydraulic properties of fractures (Cherubini et al., 2014). While no data exist to quantify the magnitude of modern day stresses in Scotland (Comerford et al., 2018), the stress orientations have been suggest as roughly EW extension (Baptie, 2010), and a northerly trending maximum compressive stress (Heidbach et al., 2008). This stress orientation would tend to reduce the aperture of large trace length ENE to NE trending joint sets, further reducing the modern-day connectivity of the network.



#### 552 5.4 Implications for growth of strike slip faults

553 While the role of mechanical stratigraphy on normal faults has received considerable attention, relatively  
 554 few studies have focused on the effect on the development strike-slip faults (Gross et al., 1997; Nemser  
 555 and Cowan, 2009; Sylvester, 1988). With the abundance of small-offset strike-slip faults in transtensional  
 556 basins, it is of increasing importance to be able to predict the behaviour of such structures for hydrocarbon  
 557 extraction (e.g. Gamson *et al.* (1993); Shuichang *et al.* (2009)), shallow geothermal projects (e.g.  
 558 Malolepszy (2003)), carbon capture and storage (Solomon, 2007), and geotechnical engineering  
 559 (Donnelly, 2006).

560 The amount of strike-slip on these faults is not quantified: the irregularity in the slip vectors makes  
 561 calculations of total slip based on dip slip and slickenlines unreliable. However, the total slip is likely to  
 562 be substantially greater than the observed dip-slip with slickenlines between 5 and 30 degrees rake, the  
 563 total slip will be 2 to 11.5 times the dip-slip distance. The total thickness of all fault strands is low, with  
 564 a maximum thickness of fault rock of 1.4 m (including fault-core lenses), and typically <30 cm. This  
 565 value is low even for scaling of dip-slip displacement and thickness. This implies that the fault zone  
 566 thickness has not grown as a function of the total slip.

567 The orientation of the pre-existing weaknesses and bedding with respect to the fault growth geometry is  
 568 different for strike slip faults than normal faults. We find the growth of mineralised shear fractures and  
 569 self-juxtaposed faults in coal to be retarded by the pre-existing joint network (Figure 2 & 4). Similarly,  
 570 in Figure 5 favourably orientated joints either retarded the growth of self-juxtaposed faults, or are  
 571 reactivated as shear fractures in the McDonald Limestone. The orientation of features that are orthogonal  
 572 to propagation direction (e.g. NE joints cutting the McDonald Limestone), will cause a mechanical  
 573 barrier. However, joints that are favourably orientated will be re-activated. Similar differences in  
 574 mechanical response relative to an applied stress has been observed in rock deformation experiments for  
 575 planar weaknesses (e.g. mud laminations (Whittles et al., 2002)) and cleats (Li et al., 2016). Unlike normal  
 576 faults, where fault strands will step between joints in different beds (Wilkins et al., 2001; Wilkins and  
 577 Gross, 2002), in strike slip faults self-juxtaposed faults will step in bedding-parallel view. The local  
 578 orientation of joint sets, which is altered by the folding of competent layers (Figure 3) leads to the complex  
 579 interaction of faults and joints observed at Spireslack SCM (Figure 5). In non-self-juxtaposed faults  
 580 (Figures 6 & 7), it is instead primarily bedding which cause the termination of fault strands. Although  
 581 this is similar to normal faults in mechanically layered sequences (Ferrill et al., 2017), the effect is less  
 582 than would be expected and single through-going footwall strands are often observed. This suggests that  
 583 the orientation of bedding and bed-perpendicular will have a significantly significant impact in the growth  
 584 of strike slip faults than dip-slip faults.





## 585 6. Conclusions

586 The exceptional exposures of the Limestone Coal Formation exposed at Spireslack SCM enabled the  
587 effect of lithology and pre-existing structures on the internal structure, fluid flow properties, and growth  
588 faults to be investigated. We find that the internal structure of fault strands is strongly affected by: a) the  
589 lithology that was faulted; b) whether multiple lithologies are cut by the fault or not; c) the presence and  
590 behaviour of shale interbeds, and; d) the presence and orientation of pre-existing fractures. The geological  
591 evolution of Spireslack SCM displays a complex relationship of folding, brittle deformation and stages  
592 of mineralisation.

593 Faults in the McDonald Limestone and Muirkirk 6' Coal are strongly affected by the presence of the pre-  
594 existing joint and cleat network. In both cases, this causes the restriction of fault growth, with individual  
595 strands abutting against favourably orientated structures. The mineralisation of the cleat network in the  
596 Muirkirk 6' Coal led to an increase in the strength of the coal seam, with later reactivation concentrated  
597 at the tips of mineralised cleats. This is not observed in the McDonald Limestone, but the strength  
598 difference between the vein fill and the host rock is less. In both units, because fault planes become  
599 mineralised the permeability of the rock mass decreases as fault intensity increases. Our work  
600 demonstrates the importance of considering not just the lithologies being faulted, but also whether pre-  
601 existing weaknesses are present. Where pre-existing weaknesses are present, fault-growth will be  
602 restricted and the connectivity of a network can drastically change through time following mineralisation  
603 and/or changes in stress directions/folding.

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