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1 **A sedimentological approach for classifying sub-surface mine wastes: implications for shallow**
2 **mine geothermal energy.**

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9 **Abstract.** Following sub-surface coal extraction, workings become flooded and represent a potential aquifer for
10 shallow geothermal development projects. We investigate the internal structure of collapsed mine workings in
11 surface exposures of pillar and stall mine workings exposed through coastal erosion at Whitley Bay, NE England,
12 UK. These workings collapsed in stages, leaving a clay-rich anthropogenic sedimentary layer consisting of collapse
13 breccias and muds that gradually reduce the permeability of the system. Our data suggests workings do not collapse
14 as individual events and that sections near pillars may remain open to flow for years after the rest of the workings
15 have collapsed.

16 **1. Introduction**

17 The importance of coal during the industrial revolution and the large workforce required for its sub-surface
18 extraction led to the development of densely populated areas underlain by a labyrinth of mine workings.
19 Following the decline of sub-surface extraction, groundwater returns to pre-mining levels flooding the mine
20 workings (Younger, 2002). These workings provide potentially large aquifers (e.g. $5.1 \times 10^{12} L$ (Watzlaf and
21 Ackman, 2006)) that can be tapped to extract inexpensive low-enthalpy geothermal heat using ground source
22 heat pumps (Dochartaigh, 2009; Malolepszy et al., 2005; Monaghan et al., 2017). Additionally aquifers can be
23 'charged' with waste heat created through industry (e.g., refrigeration) and later extracted when required (i.e.
24 the winter) (Hamm and Sabet, 2010; Patsa et al., 2015; Sanner, 2001). Geothermal energy, in particular ground
25 source heat pumps tapping flooded mine waters, have significant potential in the decarbonisation and
26 regeneration of densely populated ex-coal mining areas (Malolepszy et al., 2003; 2005; Hamm and Sabet, 2010).

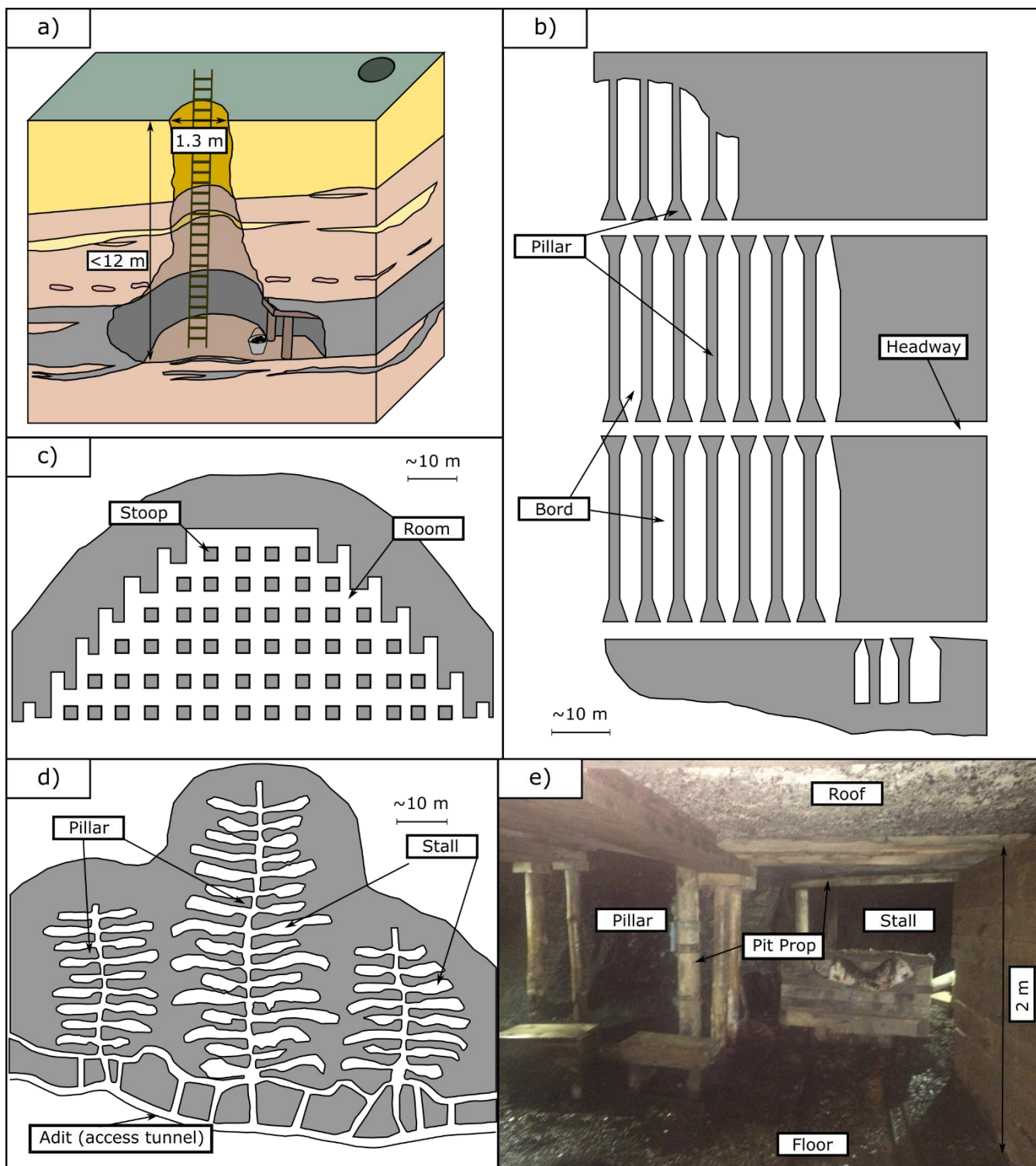
27 Open loop systems are typically employed for minewater geothermal systems, with coupled extraction and
28 injection wells (Banks et al., 2019). For production to be sustained, groundwater flow between the injection and
29 extraction boreholes is required, ideally with void space or permeable collapse material intersected by both
30 boreholes, while the water capacity of the mine should be high (Loredo et al., 2016; Lund, 2001). The water
31 capacity, defined here as the volume of water which can be extracted from the mine or mine reservoir (Loredo
32 et al., 2017; Menéndez et al., 2019) can reduce the effective volume and permeability of this void. While the
33 methods of coal extraction varied through time (e.g. bell pits), the pillar and stall method was widely used (Fig. 1)
34 (Bell and Bryn, 1999). Using this method coal was extracted from 'stalls', or 'rooms', supported by pit-props
35 (Daunton, 1981) and pillars wherein, 30 to 70% of the coal remained unworked to support the roof (Fig. 1)
36 (Garrard and Taylor, 1988; Wardell and Wood, 1965). For mine geothermal prospects, the majority of flow will
37 occur through open stalls, which will have a near infinite permeability (Loredo et al., 2017).

38 Rock pillars and temporary supports (e.g. pit props, colliery arches) are designed to sustain the weight of the
39 overburden, however, following mining operations local stresses, rotting timbers, and the spalling of the pillars,
40 can cause the roof to fail and eventually collapse (Bruyn and Bell, 1999; Helm et al., 2013; Lokhande et al., 2005).
41 The failure of a single pillar will cause other pillars, particularly those in an up-dip direction, to become
42 increasingly stressed and risk collapse causing a knock-on effect until the support of the overburden is significantly

43 reduced (Bruyn and Bell, 1999). As roof material falls, the stalls become clogged and deformation migrates
44 upwards in a predictable manner (e.g. Garrard & Taylor 1988; Madden and Hardmam, 1992), eventually forming
45 crown holes at the surface. Pillar collapse and roof spalling, which can occur many years after mining operations
46 have ceased (Carter *et al.* 1981; Salmi *et al.* 2019a, b) can lead to widespread subsidence (Gee et al., 2017) often
47 occurring as individual events over relatively short time scales (days to weeks) (Carter et al., 1981; Marino and
48 Gamble, 1986).

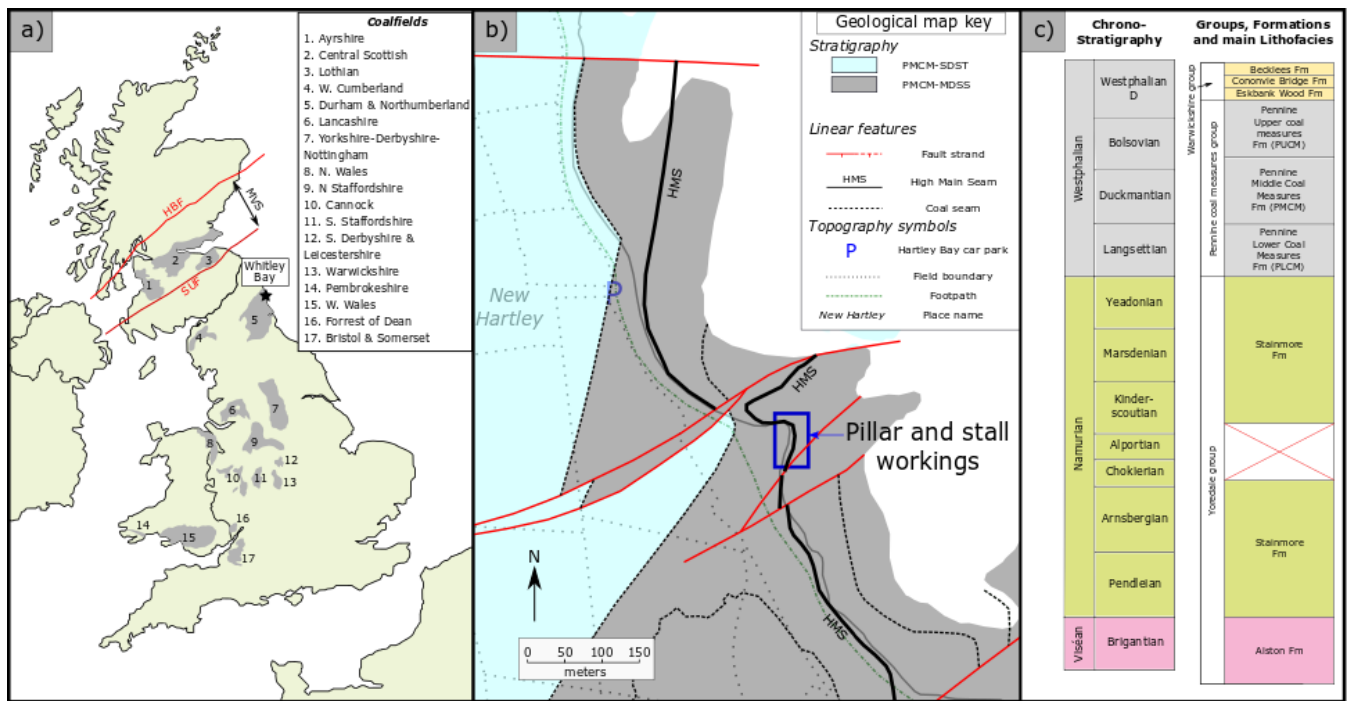
49 While the structure above the collapsed workings has been studied by many authors (e.g. Garrard and Taylor,
50 1988; Helm et al., 2013), the lithologies which make up the collapsed section and the processes by which they are
51 deposited has received little attention. With the emergence of shallow mine geothermal projects it is now
52 important to understand the characteristics of these 'mine wastes', and the processes involved if we are to
53 improve our estimations of the water capacity of pillar and stall workings for geothermal energy. To address this
54 we investigate exposures of workings at Whitley Bay exhumed by costal erosion using a detailed sedimentological
55 approach and highlight the implications of our findings for shallow mine geothermal projects targeting pillar and
56 stall workings. We find that the net water capacity and permeability of a potential mine geothermal site degrades
57 progressively after abandonment as the roof spalls, and finally collapses.

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59

60 Figure 1: Typical UK shallow mining methods. (b) to (d) show variations on the pillar and stall mining methods with regional variations
 61 in terminology and layout. (b, c and d redrawn from Bruyn and Bell (1999) a) bell pit, b) Bord-and-pillar workings, Newcastle upon Tyne
 62 (17th Century), c) Stoop and room workings, Scotland (17th Century), d) Pillar and stall workings, South Wales (17th Century), e)
 63 Photograph of pillar and stall workings, Beamish open air museum.

64 **2. Geological history**

65

66 **Figure 2: Geological setting. a) location of field site and UK coal fields (after (Donnelly et al., 2008), b) geology surrounding the workings**
 67 **at Whitley Bay, Northumberland (The map is modified from Geological Map Data BGS@UKRI (2018)) PMCM-SDST, c) Chrono-**
 68 **stratigraphy, formations and lithofacies of the Northumberland Trough (Chadwick et al., 1995). SDST = stand stone dominant sequence,**
 69 **MDSS = mudstone dominant sequence.**

70 UK Coal mines are found within numerous late-Devonian to early Carboniferous, east-west trending basins (Fig.
 71 2a) that formed in response to back-arc extension (Cope et al., 1992; Leeder, 1988, 1982; Soper et al., 1987).
 72 Coastal erosion has exposed a series of abandoned underground workings on the headland (national grid square
 73 NX34 76) just north of St Mary's Lighthouse, Whitley Bay (England) (Fig. 2b). Whitley Bay is located in the
 74 Northumberland Trough, a 50 km wide, ENE-WSW trending, half graben which formed in response to the
 75 extensional reactivation of the Iapetus Suture during the mid to late Carboniferous (Chadwick et al., 1995;
 76 Chadwick and Holliday, 1991; Johnson, 1984). The thickest coal seams (>2 m), many of which are workable;
 77 (Fielding, 1982; Smalls, 1935), are almost exclusively confined to the Pennine Middle Coal Measures which reach
 78 450 m thick in places (C.R. Fielding, 1984; Leeder, 1974; Smalls, 1935) (Fig. 2c).

79 Carboniferous lithologies at Whitley Bay consist of fossiliferous and barren mudstones (50 to 55%), siltstones and
 80 sandstones (40 to 48%) and bituminous coals (<5%), which nearly always occur above seat-earths (Christopher R.
 81 Fielding, 1984; Fielding, 1985, 1982; Jackson et al., 1985; Lawrence and Jackson, 1986). These are interpreted as
 82 being deposited on a broad, flat deltaic plain with numerous distributary channels (Christopher R. Fielding, 1984;

83 Fielding, 1985; Jackson et al., 1985). Exceptional exposures of the Pennine Middle Coal Measures, including the
 84 High Main Seam (HMS), are observed along the 1.2 km long studied section (British National Grid NZ 364 756;
 85 Figure 2b).

86 The High Main Seam is highly variable in thickness (average 2 m, Fielding, 1982) and quality (Christopher R.
 87 Fielding, 1984; Jackson et al., 1985; Lawrence and Jackson, 1986; Murchison and Pearson, 2000) with centimetre
 88 to meter scale shale partings commonly present (Fielding, 1982). Immediately below the HMS thin ‘stringers’ of
 89 coal (centimetre scale) are often found, which are locally workable (Fielding, 1982). Based on the history of the
 90 coalfield (Table 1), and because the workings are above the water table, we suggest the coal at Whitley Bay was
 91 extracted somewhere between 1550 and 1710 AD.

Date	UK wide	Northumberland and Durham Coalfields
Pre-1200	Extracted by shallow pits or adits (shallowly dipping tunnels) ^{1,2} .	Workings of the high Main Seam date from Roman times ⁸ .
1200s	Widespread coal mining began increasing up to, including and following the Industrial revolution.	Early shallow workings (<7 to 10 m) primarily using adits from the coast/valley side, with bell pits also used ⁹
1300s	Bell-pits (Fig. 1a) became widespread ^{2,3} .	
1500s	Most shallow reserves accessible by surface access methods extracted and the Pillar and Stall method began ^{2,3} (Fig. 1d).	1550’s saw the increased extraction of the HMS, with coal becoming a significant commercial interest ^{3,10,11,12} . Pillar and stall workings began in the late 16 th Century ² .
1600s		The majority of coal close to sea-ports and above the water table extracted by the late 17 th Century ¹³ .
1700s		Technological advances in 1710 enabled coal to be mined below the water table ¹³ .
1800’s	Mining methods became standardised ^{1,2} (Fig. 1b, c & e). In 1850 detailed coal mine surveys began, with abandonment plans becoming mandatory from 1872 ^{1,4} .	1800 map of sea-sale collieries does not include Whitley Bay workings ³ . 1830’s to 1870s saw many large collieries opened up working the High Main Seam (e.g. Fenwick).
1900’s		1993: Easington colliery closes marking the end of underground coal extraction in the Durham and Northumberland Coalfields.

92 **Table 1: Summary of the mining history of the UK and Durham and Northumberland Coalfields. References; 1) Bell (1986), 2) Bruyn &**
 93 **Bell (1999), 3) Smalls (1935), 4) Healy & Head (1984), 8) Fielding (1982), 9) Dearman et al. (2000), 10) Page (1907), 11) Smalles (1938),**
 94 **12) Nef (1965), 13) Galloway (1898).**

95 **3 Methods**

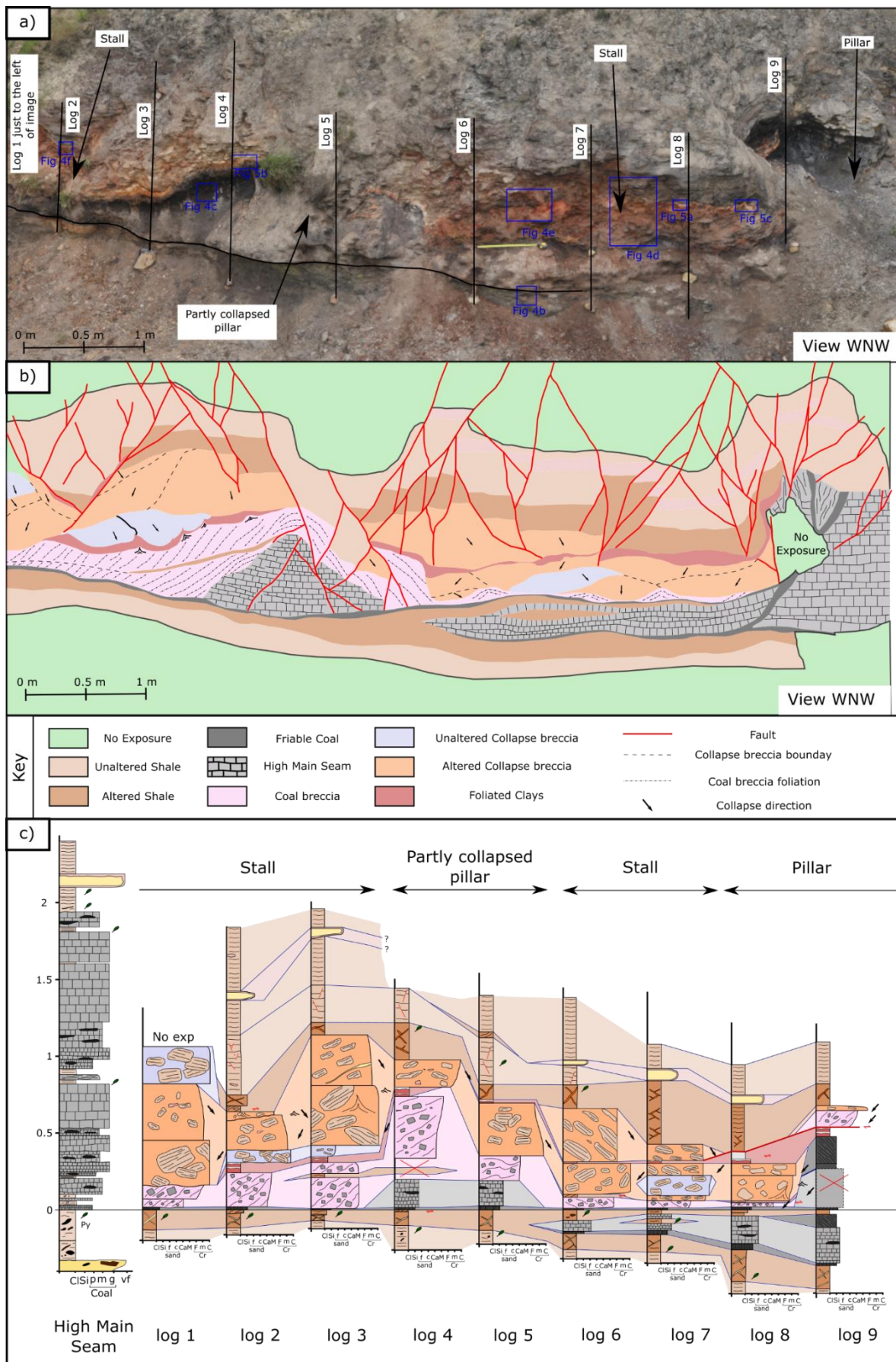
96 High-resolution sedimentary logs of 9 vertical sections, spaced every meter, were taken along the workings (see
97 Figure 3). Lithological boundaries, both structural and depositional, were defined as either based on a distinct
98 change in grain-size, or matrix type. A sedimentary log through the unworked High Main Seam at the base of
99 Hartley Steps (British National Grid: NZ 34469 75668) was taken as the comparative baseline for the collapse
100 lithologies. Facies were defined based on distinct changes in texture, grain size, stacking relationships and
101 sedimentary structures. Collapse breccias were described using the terminology of Woodcock & Mort (2008),
102 whereby chaotic-, mosaic- and crackle- breccias are defined based on clast size and ratio of clast to matrix. The
103 clast type, orientation (taken as the dip of preserved bedding) and aspect ratio were recorded, along with the
104 matrix composition. Muds in the sequence, which were not lithified, were described using the BS5930 (2015)
105 standard for clay-rich soils.

106 In addition, photographs (320 images) were taken of the outcrop to create a high resolution, orthorectified,
107 photomontage (Fig. 3). Using the sedimentological information and location of logged sections, key boundaries
108 were mapped out and stacking relationships investigated. Within the collapse breccia, a number of sub-divisions
109 could be defined with subtle changes in clast orientation observed (e.g. 45 and 82 cm in Log 1). These areas were
110 used to help constrain the phases of collapse recorded in the sequence.

111 **4 Results**

112 **4.1 General description**

113 Through detailed field observations and sedimentary logging 8 facies were identified (Table 2). In this section,
114 'thickness' refers to the vertical thickness of a bed, pod, or lithology within the studied section. The relationship
115 between sedimentary facies within the workings can be split into two areas, pillars and stalls, depending on
116 whether unworked coal is present in the logged section (Fig. 3). Two stalls are present, which make up 69% of the
117 outcrop, with similar facies associations observed above the High Main Seam in the central pillar, and edge of the
118 northern pillar (Fig. 3).



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Figure 3: Workings of the High Main Seam at Whitley Bay: a) photomontage of the workings with the location of logs marked; b) section view and interpretation of mine wastes (collapse lithologies); and c) sedimentary logs through the undeformed High Main Seam at the

122 **base of Hartley Steps and through the workings at the locations marked in (a). For individual log descriptions please see Supplementary**
123 **1.**

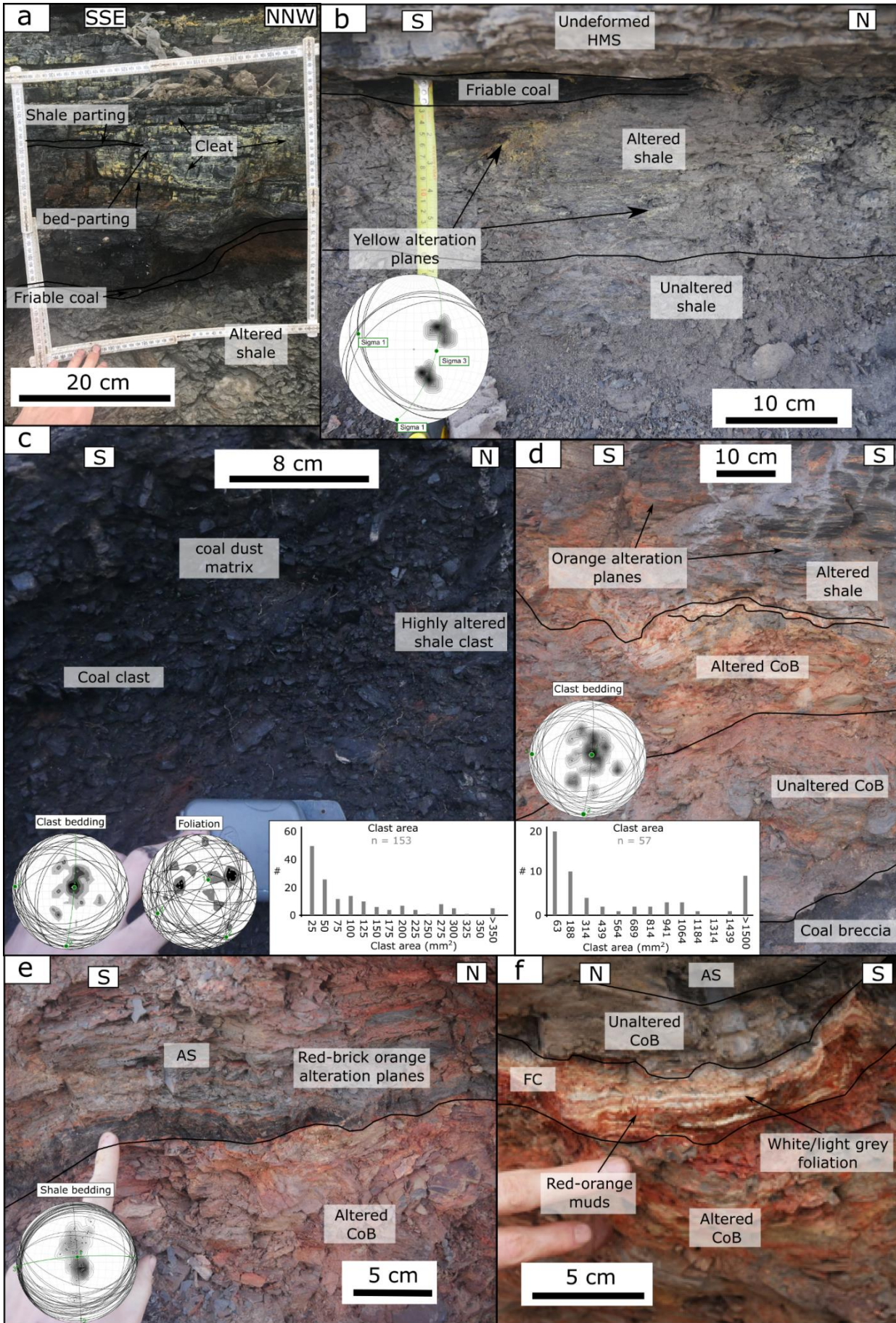
<i>Facies</i>	<i>Description</i>	<i>Depositional processes</i>
High Main Seam (HMS) Undeformed thickness = 2.01 m. Fig 4a	Interbedded unit containing 16 coal beds (2 to 43 cm thick) and 7 organic rich shale partings (1 to 4 cm thick). Euhedral pyrite crystals (<0.2 mm) occasionally visible along bedding planes. Locally Jarosite is developed along the cleat network, particularly towards the base of the High Main Seam.	The deposition of peat in a swampy, anoxic environment which was sporadically interrupted by clastic deposition in a delta plain environment ¹ .
Unaltered Shale (US) Beds 0.2 to 1 cm thick Fig 4b	A mudstone to silty-mudstone, which can be either organic rich or organic poor. Coalified plant fossils and euhedral pyrite (<0.2 mm, <5%) are often found along bedding surfaces, particularly below the HMS.	Low energy deposition in a variably oxic environment, related to the flooding of peat swamps ^{1,2} .
Altered Shale (AS) Beds 0.2 to 0.8 cm Figs 4a & b	Found within 20 cm of the HMS in both undeformed and worked sections. Similar to US, however, weathers more readily and contains shallowly dipping alteration planes (yellow below & brick orange above).	The development of acid mine water following mining operation causes the degradation of clay minerals and movement of the sulfur from the pyrite within the seam ³ .
Friable Coal (FC) <15 cm thick. Figure 4b & d	FC may be observed along the base, and within the workings, as well as along the edge of the right-hand pillar (Figure 3). FC is black, dominated by organic material (> 95%) and characterised by a very tight fracture network which cause the lithology to erode as a black powder. Fractures either occur perpendicular to layering, or at an angle forming a well-developed foliation.	Can either be formed by working related deformation of thin channel coals and stringers of the HMS or the development of tectonically deformed coals ⁴ along the edge of pillars during the collapse of workings.
Coal Breccia (CB) Thickness 2 to 55 cm Figure 4c	CB occurs along the base of the workings, and varies in thickness considerably. CB is a chaotic to mosaic breccia ⁵ consisting of angular clasts of coal (>90%) and highly altered shale. Coal clasts (median 60 mm ²) are bounded by bedding planes or cleats. Shale clasts are often altered to a red-orange, silt to clay grade dust. The matrix is dominated (<95%) by silt grade organic fragments with the remaining 5% consisting of quartz and occasional <0.5 mm pyrite crystals.	May be formed either a) through the spalling of the pillars, whereby talus-like deposits occur as pillars corrode through time ⁶ or b) through the down-dip flow of coal during flooding events being deposited in the lee side of pillar in a similar manner to bridge abutments ⁷ .
Collapse Breccia (CoB) Thickness 20 to 90 cm Figure 4d & e	The dominant lithology in the collapsed stalls CoB is found as altered or unaltered pods of clast dominated (85 to 90%) crackle breccia ⁵ . Clasts, are dominated by shale clasts (90 %), with clasts of ironstone, coal and bleach-white sandstone or seat earth also present. Clasts typically show high aspect ratios elongated parallel to bedding. The matrix is clay-rich containing brick-orange, silt grade clasts of altered shale and sand grains.	Rotation of clasts away from pillars as material collapses into the stalls ⁸ . Where the permeability of the workings is low, and mine water develops, clays in the collapse breccia degrade and develop the orange alteration colour.

<p style="text-align: center;"><i>Foliated Muds (FM)</i> Thickness 0.5 to 15 cm Figure 4f & 5</p>	<p>FM consists of mm to cm scale foliated muds which alternate between brick-red and off-white in coloration. Foliations typically stack from brick-red to white, with the top of the white foliations marking distinct depositional phases. Between 7 and 13 cycles can be identified, filling from the deepest point and occasionally showing soft-sediment deformation.</p>	<p>Cyclical flooding and evaporation of salt-rich fluids and mine water, causing a stacked sequence above the pre-existing CoB. The red foliations are likely caused by acid mine water reactions (see discussion for further details) forming Ochre deposits. Slumps develop either due to rapid deposition on the CoB top topography, or due to the further collapse along the workings.</p>
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Table 2: Facies description and interpretation of depositional environment. References: 1) Fielding (1984b); 2) Fielding (1982); 3) Younger et al. (2002); 4) Godyń (2016); 5) c.f. Woodcock & Mort (2008); 6) Martin & Maybee (2000); 7) Koken & Constantinescu (2008); 8) Lokhande et al. (2005).

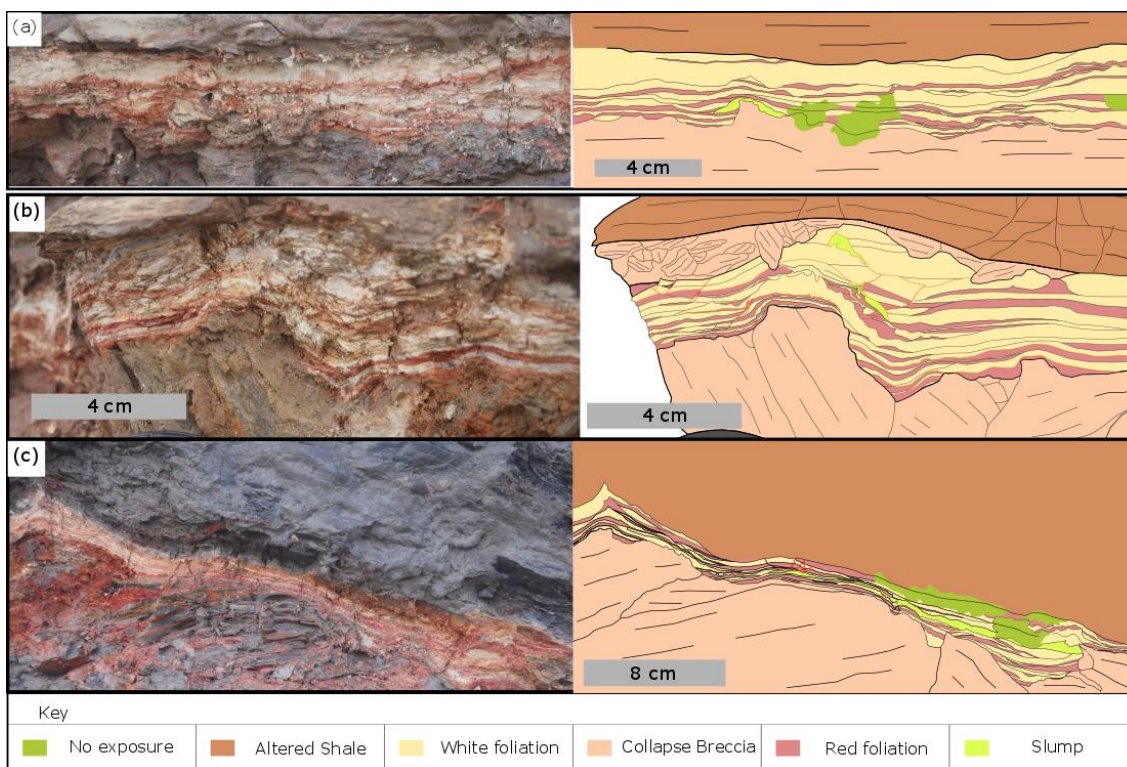
127 4.2 Stalls



128

129 **Figure 4: Facies photographs and associated clast and kinematic data.** The location of the photographs for (b) to (f) is indicated on Figure
 130 **3.** The photograph for (a) is taken at the base of Hartley Steps [British National Grid: NZ 34469 75668]. (a) undeformed High Main Seam
 131 with Jarosite developed along the cleats of the lowermost beds. (b) The succession underlying the High Main Seam, with the orientation
 132 of the yellow alteration planes shown in the inset stereographic projection. (c) Close up photograph of the coal breccia built up on the
 133 southern side of the central pillar. Inset stereographic projection display the orientation of clast bedding and the foliation picked out
 134 by fines. The inset histogram displays the equivalent circular area of all clasts measured in the field (n = 152). (d) The succession overlying
 135 the coal breccia. CoB = collapse breccia. The inset stereographic projection displays the orientation of bedding in the CoB clasts, with in
 136 inset histogram displaying the equivalent circular area of the clasts. (e) The contact between altered shale (AS) and Altered collapse
 137 breccia (CoB) at the top of the collapse lithologies. The insert stereographic projection displays the bedding of the altered and unaltered
 138 shale overlying the collapsed workings. (f) The development of the foliated muds above altered collapse breccia (CoB) towards the
 139 south of the outcrop.

140 The thickness of the collapsed stalls, defined as the distance between the laterally continuous friable coal, and
 141 the fractured unaltered shale at the top of the workings, ranges from 52 cm in log 7 to 114 cm in log 3 with the
 142 facies thicknesses and associations varying along the outcrop (Fig. 4c). The relationships of unaltered shale,
 143 altered shale and friable coal are the same as the undeformed section; however, the thickness of altered shale is
 144 greater beneath stalls. Coal breccia can be observed on-lapping onto the partially collapsed pillar (Fig. 4b), with
 145 the maximum thickness (c 40 cm) and larger clast sizes (median = 144 mm²) found closest to the boundary of the
 146 pillar. Coal breccia does not show clear grading; however, a weak foliation is picked out by fines that dip down-
 147 dip and away from the pillar (Fig. 4c). Towards the south of the outcrop coal breccia occurs as a discontinuous
 148 layer, with the foliation suggesting that soft-sediment deformation caused by later collapses caused the thinning
 149 and thickening of the unit.



151 **Figure 5: FC stacking patterns. The location of the detailed photographs are indicated on Figure 3. Please see text for a description of**
152 **key features.**

153 Foliated muds typically dip towards the SW and are observed in both stalls, overlying coal breccia in the south
154 and either coal breccia or collapse breccia in the north. Complex stacking patterns and sedimentary structures
155 are observed in the foliated muds, controlled by the underlying topography (Fig. 5). The alternating red- and
156 white- layers are cyclical in nature, with the number of cycles varying from 7 to 13. At the base of foliated muds,
157 the foliation can be seen on-lapping onto angular clasts of collapse breccia, with the thickest deposits occurring
158 in gaps between clasts of collapse breccia (Fig. 3). This shows that the collapse occurred after mining and was
159 followed by the deposition of the foliated muds, filling pods on the pre-existing topography on the top of collapse
160 breccia. Stacking patterns in Fig. 5a suggest that rotation of this topography occurred throughout the deposition
161 of the muds, leading to changes in depocenters probably caused by further collapse of workings disrupting the
162 collapse breccia.

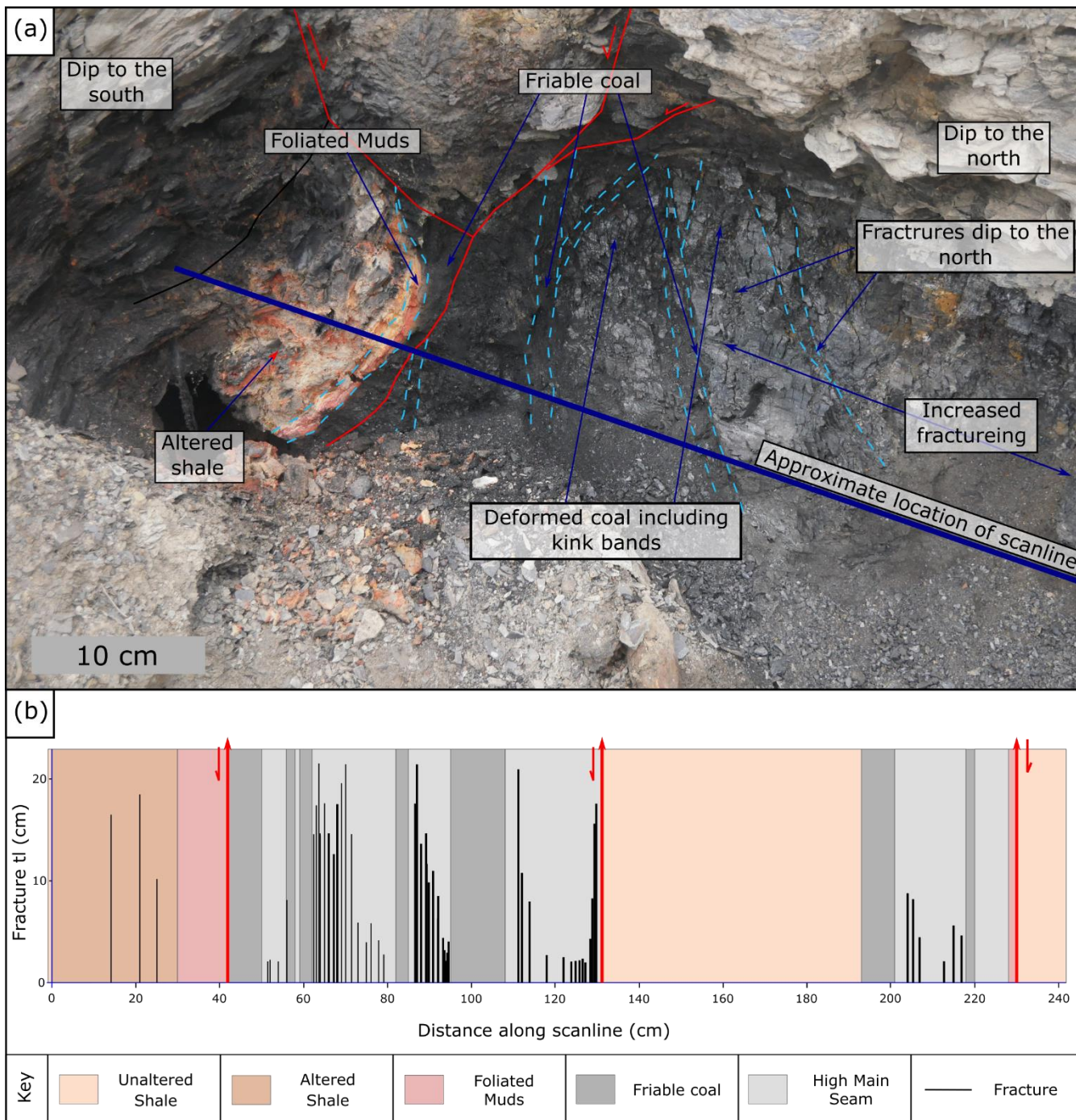
163 The bottom of the foliated muds is generally undisturbed, however, in the mid- to upper- sections of the deposit
164 slumps, minor faulting and soft sediment deformation can be observed. Slumps occur where a paleoslope occurs
165 either within the foliated muds or from the top of the collapse breccia. For example, in Fig. 5c a laterally extensive
166 slump deposit is observed, with normal faults developed at its head, and compressional features at its foot. This
167 can be observed along the shallowly dipping (c. 8° to 10°) upper surface of the collapse breccia. In Fig. 5b, the top
168 of foliated muds has been deformed by a later collapse, which causes the soft-sediment deformation of a thick
169 white layer, and small-scale faults and foliation rotation to occur.

170 Foliated muds may either be overlain by further collapses (collapse breccia), which often cause soft-sediment
171 deformation of the pre-existing units, or to the far north by altered shale. Altered shale makes up the top of the
172 collapse lithologies and is brought down onto underlying lithologies by a series of fault strands that lead to the
173 closing of open space (Fig. 5b) and the extrusion of foliated muds along the edge of the pillar (Fig. 6a).

174 **4.3 Pillars**

175 Two pillars, which make up 31% of the outcrop, are observed, one to the north and another near the centre of
176 the studied section. In the northern outcrop, the top 0.45 m of the undeformed High Main Seam succession is
177 observed and the base is visible in the foreshore up-dip of the studied section; suggesting that the full thickness

178 of the seam (c. 2 m) is present at this location. The base of the High Main Seam exposed in the centre of the
179 outcrop (logs 4 and 5) closely matches the log of the undeformed sequence (Fig. 3c). However, above the
180 undeformed coal in log 4 and 5, 14 to >40 cms of coal breccia are observed. This displays a subtle foliation, which
181 dips away from the pillar and contains semi-randomly orientated clasts (Fig. 4c). Above the coal breccia, the
182 central pillar shows facies associations more similar to that observed in the stalls (see above). The unaltered shale
183 at both locations display low-amplitude folding (Fig. 4e), with material subsiding from above the pillars into stalls
184 (See Fig. 3).



185

186 **Figure 6: Northern Pillar: a) annotated field photograph displaying key structural elements of the edge of the northern pillar; b) scanline**
 187 **through the edge of the pillar displaying the trace length of fractures. The location of the scanline is highlighted in a.**

188 The High Main Seam in both pillars displays increased fracturing compared to the undeformed section, along with
 189 local development of friable coal (Fig. 6). The scanline taken through the northern outcrop (Fig. 6b), highlights
 190 that within 5 cm of the friable coal the trace length and intensity of fractures increases. Fractures are often
 191 observed to form parallel to, and utilising the pre-existing cleat network. Locally, particularly between strands of
 192 friable coal, the rotation of coal, including cleats, fractures, and coal bedding is observed (Fig. 6a). This suggests

193 that fracturing occurred prior to the block rotation of the coal, and that only later deformation (e.g. development
194 of kink-bands) occurred during the development of friable coal.

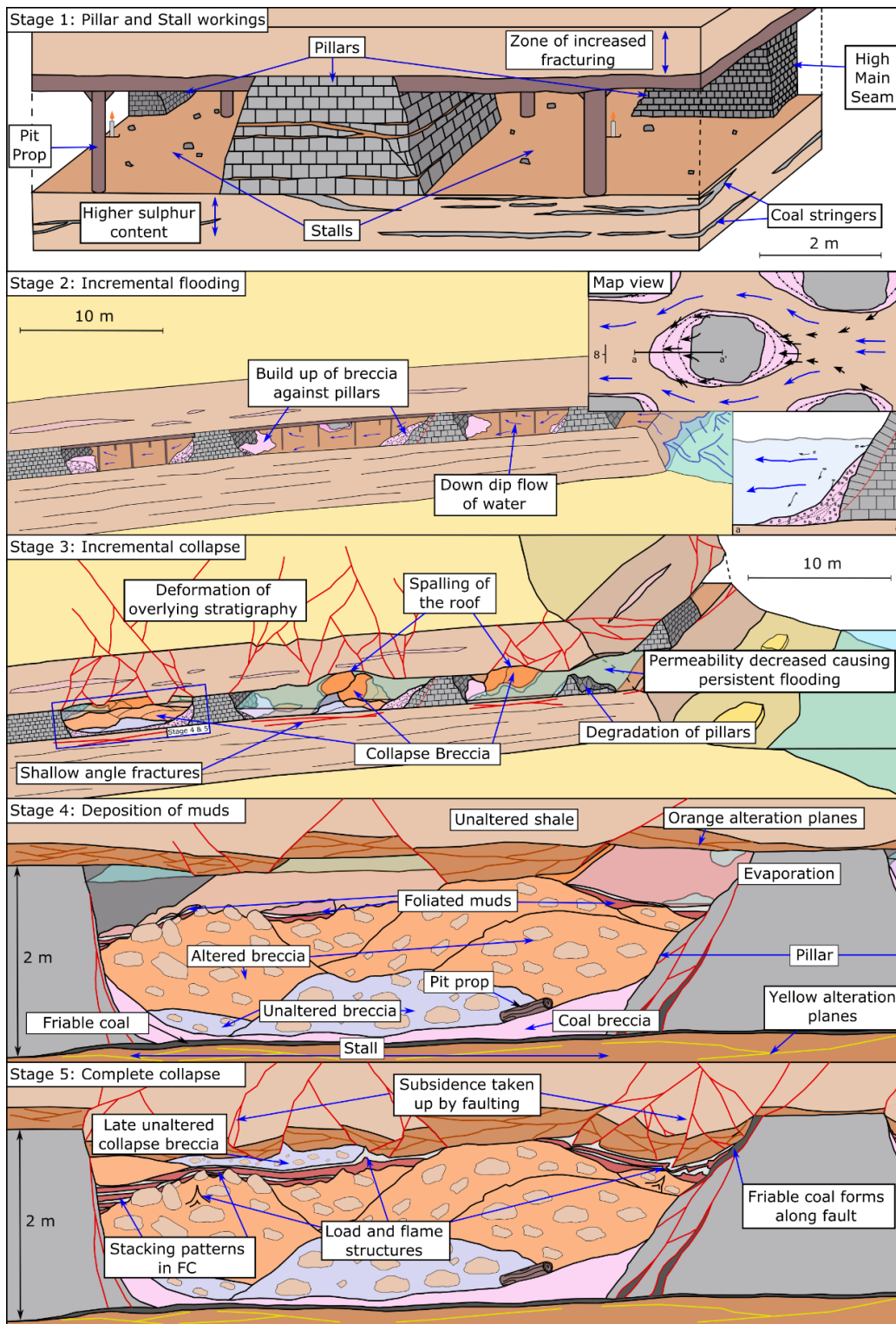
195 Bedding orientation below the High Main Seam is similar to the seam itself ($040^{\circ}/10^{\circ}$ W), however, bedding above
196 the seam maintains thickness and dips to the north and south with a mean fold axis of $105^{\circ}/80^{\circ}$ N (Insert Fig. 4a).

197 Folding is subtle above stalls, however, above pillars it is clearly visible. At this location the folding and rotation
198 of bedding along antithetic faults occurs such that two anticlines and three synclines with wavelengths of 0.5 m
199 to 2 m are observed. We suggest folding is due to the rotation of the overburden following roof collapse.

200 **5 Discussion**

201 5.1. Processes involved in the formation of collapsed pillar and stall workings

202 We investigated the processes which occur during the collapse of abandoned pillar and stall mine workings. This
203 has allowed for the first time the development of a conceptual evolutionary model for the temporal evolution of
204 the internal structure be proposed. We find that the collapse at Whitley Bay occurred through five distinct phases,
205 as evidenced by sedimentary facies and associations, deformation style and sedimentary structures. The stages
206 are outlined below and summarised in Fig. 7.



207

208 **Figure 7: Conceptual evolutionary model of the collapse of pillar and stall mine workings based on Whitley Bay, Northumberland. See**
 209 **text for description of each stage.**

210 **Stage 1 & 2: Extraction of coal and build-up of CB:**

211 Estimated between 1550 and 1710 AD (see Table 1), the High Main Seam was worked using pillar and
 212 stall mining methods. The shallow depth of the seam at this location suggests that access was most likely
 213 from an adit cut from the sea. Coastal erosion rates in the area range between 0.15 to 0.30 cm per year

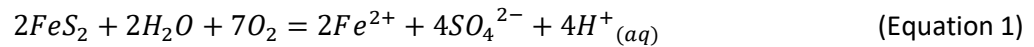
214 (Tingay and Ellis, 2016), suggesting that a minimum of between 46.5 m and 93 m of rock has been eroded
215 since the mine was developed. Assuming no disruption due to faulting in the eroded section and
216 disregarding isostatic uplift and recent seal level rise, the seam would have been 8 to 10 m above the
217 mean high-water mark. Lying above the water table, workings would not need to be pumped but
218 designed to drain under gravity via adits, so flooding would only have occurred following periods of heavy
219 rain or winter storms. During the extraction of coal, small fragments of low-value coal and coal dust would
220 be left behind. These would have been transported down-stream (towards the SW) during flood events
221 and deposited against pillars, leading to the development of the coal breccia. The on-lapping of coal
222 breccia onto the degraded pillar (Fig. 3b), orientation of the faint foliation (Fig. 4c), and clast-bedding
223 orientation (Fig. 4c) matches the deposition pattern you would expect in a shallow channel flowing
224 around an obstacle (e.g. scouring around vertical dikes (Koken and Constantinescu, 2008)). separation of
225 coal by density to form a coal “lag” is typical in streams and beaches. Following the end of mining
226 operations upkeep was no longer required, and pillars began to spall and collapse (Ebrahim F Salmi et al.,
227 2019). Larger, high value, clasts of coal would then be added to the breccia (**Stage 2**).

228 **Stage 3: Incremental collapse and steady reduction in permeability:**

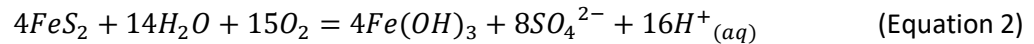
229 As time passed, episodic flooding degraded pillars and pit-props and the roof of the workings began to
230 sag and spall (e.g. Bruyn & Bell 1999). In agreement with the work of Helm *et al.* (2013), we find collapse
231 initiated near the centre of stalls, which were only held up by pit-props, followed by several small
232 collapses propagating towards the pillars. Initially collapses did little to reduce the overall permeability
233 of the workings, and episodic flood waters would flow around the collapsed sections. As the percentage
234 of collapsed material increased, clays sourced from shales would clog pore-space between clasts. The
235 breccia, which was poorly sorted and already had a low permeability, would have become saturated.

236 Mine water is typically acidic and can represent a significant environmental risk if it leaks into surface
237 and/or groundwater resources (Younger, 2004, 1995). The acidity of mine-waters is a product of both
238 ‘vestigial acidity’ caused by the past oxidation of pyrite, and ‘juvenile acidity’ caused by the products of
239 seasonal pyrite oxidation above a fluctuating water table (Younger, 1998). A complex cycle of chemical

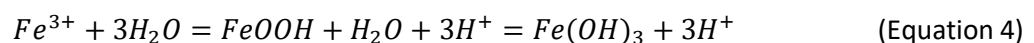
240 reactions takes place as pyrite oxidises (See Stumm and Morgan, (1981) for full description). However,
241 the simplified net products can be described through Equation 1, with the overall sequence being acid-
242 producing (Equation 2) (Banks et al., 1997):



244 *Pyrite + water + oxygen = ferrous iron + sulphate + acid*



246 While little pyrite oxidation will take place below the water level, oxidation will be abundant in the
247 unsaturated zone with the reaction products mobilised as ground water rises (Younger, 1993; Younger
248 and Sherwood, 1993). The high acidity and oxidising environment represents the ideal situation for the
249 development of Ochre (Younger et al., 2002). Ferrous iron released by the oxidation of pyrite will remain
250 in solution while acidity is particularly high (pH < 2.5) or where oxygen levels are reduced (e.g. fully
251 saturated workings) (Banks et al., 1997; Younger et al., 2002). However, when the ferrous iron is exposed
252 to the atmosphere partial oxidation will occur leading to the precipitation of iron oxyhydroxide (Ochre)
253 (equation 3 and 4) (Banks et al., 1997).

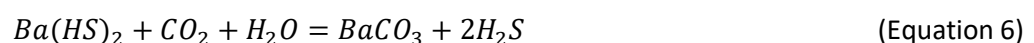
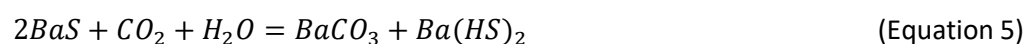


256 The pyrite within the saturated collapse breccia, would have been oxidised to form weakly acidic mine
257 waters (Turner and Richardson, 2004; Younger, 1995, 1994), that altered clays in the matrix and clasts of
258 the collapse breccia and mobilised iron from the ironstone nodules/beds. This oxidation and leaching
259 caused the red-orange coloration and bleaching respectively. The presence of breccia pods that do not
260 show alteration suggests that some earlier and later collapses did not become saturated, potentially due
261 to being above the water level or lacking hydrogeological connections with mine water. Onlapping
262 relationships suggest the collapse at Whitley Bay occurred through a total of 19 events (Fig. 3b).

263 **Stage 4: Formation of the foliated muds.**

264 The fluid which formed the foliated muds was apparently hyper-saline and displayed cyclical variability in
265 composition. As there was no flow, clays settled from suspension, and became deposited as a thin layer
266 of mud (the red foliation) (Figures 4 and 5). The orange-red colour and silt-grade grains are similar to the
267 altered shale clasts in the coal breccia, and likely represent clays sourced from shales altered by acid mine
268 waters (c.f. Younger 1995). The top of each cycle is white to off white, clay-rich layers with a distinctly
269 salty taste and appeared to contain precipitates. The deposits first built up as small pods in topographic
270 lows on top of collapse breccias, suggesting that the hyper-saline fluid formed puddles on the breccia,
271 and deposition through evaporation occurred prior to the next pulse. This type of deposit is commonly
272 seen where brines periodically flood areas of topography (in this case the mine floor), essentially acting
273 as a mini-basin which is infilled during reflux (Warren, 2016).

274 In the Durham and Northumberland coalfields, the presence of hypersaline barite rich brines have been
275 reported (Younger, 1995). Locally this has led to the development of Baryte ($BaSO_4$) and Witherite ($BaCO_3$)
276 veins within the Westphalian Coal Measures (Dunham, 1983), which are locally mined (Dunham, 1948).
277 The Eccles Colliery, located 5.5 km west of the field site (British National Grid = NZ 304 695), primarily
278 worked both the Main and High Main Seams and had problems with barium-rich groundwater (Grey and
279 Judd, 2003). This required the installation of a Blanc-fixé plant that produced around 3000 tons of $BaSO_4$
280 per year (Palumbo-Roe and Colman, 2010). Alternation of Ba-rich brines with acidic minewaters could
281 have led to the alternate deposition of baryte and ochre in the abandoned mineworkings, mimicking the
282 mixing reaction used for the industrial process. Witherite is almost exclusively produced through the
283 precipitation of barium sulphide solutions with either carbon dioxide (equations 5 & 6) or soda (Kresse et
284 al., 2007). CO_2 , locally termed blackdamp, is abundant within coalmine workings and the evidence at
285 Whitley Bay suggests the workings were periodically flooded, providing H_2O into the system (Stage 1-3).
286 Therefore, the conditions were present for the precipitation of witherite from upwelling barium rich
287 hypersaline fluids, given the likely presence in the mineworkings of sulphate-reducing bacteria.



290 Due to the presence of both altered and unaltered collapse breccia, we suggest that the water table, and
291 hence the composition of groundwater, varied annually. As groundwater levels rise due to meteoric water
292 inputs, the products of pyrite oxidation will dissolve and the acidity of the groundwater will increase (as
293 discussed in Stage 3). This will cause the proportion of acidic mine water relative to brines to increase
294 and promote the breakdown of clays within the shales (Younger et al., 2002), which become entrained
295 into the hypersaline fluid and carried in suspension. When the meteoric input and flow rate decreased,
296 dropping water levels lead to the deposition of the red-mud layer. At times when pyrite oxidation was
297 lower, the brine component of groundwater dominated and less clays were held in suspension. This led
298 to the deposition/precipitation of salty muds (possibly with light-coloured baryte or witherite
299 precipitates) in place of the red muds. Due to the likely annual variation in the occurrence of highly saline
300 brines, and the periodicity observed in the foliated muds we suggest foliated muds were annular deposits
301 over a 7 to 13 year period.

302 Slump-deposits and soft sediment deformation within foliated muds occurs either a) where the dip of the
303 paleo-topography is high ($>8^\circ$), or b) in the vicinity of later collapse breccia pods (Fig. 5). Slump deposits
304 may either be caused by the rapid build-up of sediment on a slope (Moore, 1961), or following ground
305 motions, for example earthquakes (Keefer, 1984). Both processes could have been active in the workings,
306 with pulses of saline brines and/or flooding during winter storms causing rapid deposition of muds and
307 evaporites and ground motion caused by roof collapse. The slump deposits in both Fig. 5a and b show no
308 disruption of overlying layers, and have upright folds at the toe following an 'open-toe' deposition style
309 with units above on-lapping onto the deposit (c.f. Alsop *et al.* 2016). In contrast the deposit in Fig. 5c has
310 a longer run out, is thicker and overlying cycles are deformed through normal faulting at the head and
311 compressional features at the toe. We suggest the slumps in Fig. 5 a and b formed due to rapid
312 sedimentation on the paleo-topography present on the top of the collapse breccia, possibly triggered by
313 minor collapses. Fig. 5c, however, was deposited following a roof collapse which caused a slump to
314 develop, utilising a shallowly dipping clay layer as a decollement, similar to large scale processes caused
315 by earthquakes (Alsop et al., 2016). Collapse related slumps are found at different stratigraphic layers
316 within the foliated muds, suggesting the workings collapsed over several years.

317 **Stage 5: Final collapse of stall:**

318 Eventually pillars degraded to the point where they could no longer support the overlying stratigraphy
319 and the roof collapsed. The collapse and subsidence of overlying units is accommodated through normal
320 faults which dip away from the zone of collapse. This caused triangular zones of deformation, with
321 subsidiary faults coming off the main strands (Fig. 3). The minor faulting pattern was controlled by the
322 topography of the pre-existing collapse lithologies. For example, to the north of the partially collapsed
323 pillar material was brought down by several small-offset fault strands which bound 'lenses' (c.f.
324 Gabrielsen *et al.* (2016)) of undeformed shale and ironstone.

325 The orange alteration of the collapse lithologies at Whitley Bay (Fig. 4) suggests that they were at least
326 partially saturated at the time of collapse, with soft sediment deformation observed in collapse breccias,
327 foliated muds, and coal breccias (Figs. 3b, 5). While Stage 5 occurred following the deposition of foliated
328 muds to the north of the outcrop, in the rest of the outcrop Stage 4 is followed by a return of Stage 3 and
329 the deposition of collapse breccia pods (Fig. 3). Where collapse breccia is not found, foliated mud is
330 thickest with the greatest number of cycles observed (13 as compared to 7 to 8 to the south). This
331 suggests that the void near pillars was open to flow far longer than the rest of the workings. If our
332 interpretation that the cycles represent annual pulses of saline-rich brines is correct this then suggests
333 the stall closest to the pillar remained a conduit for flow six years longer than the centre of the void.

334 While the exact stacking patterns at Whitley Bay are representative of a single location, the processes are likely
335 comparable to other pillar and stall workings. Abandoned coal mines in the UK are known to have collapsed
336 following post-mining groundwater recharge (e.g. Bathgate, (Carter *et al.*, 1981)) and the degradation of the pit
337 props (Donnelly, 2006) with collapses remaining a major geotechnical risk to this day (Donnelly *et al.*, 2009; Gee
338 *et al.*, 2017; Helm *et al.*, 2013). Stage 4 (the deposition of foliated muds) may not be widely observed and occurs
339 at Whitley Bay because the workings were above a variable water table influenced by cyclical pulses of deep
340 saline brines. Previous work has suggested that collapse occurs as a single event, over days to weeks (Carter *et al.*,
341 1981; Marino and Gamble, 1986), however, our data suggests that at-least part of the workings remain open
342 to flow for a significantly longer period of time (7 to 13 years). Wide spread regional subsidence in ex-mining

343 areas is well known (e.g. Gee *et al.* (2017)), but it may be that these small sections which remain open to flow are
344 not large enough to cause noticeable surface deformation when they fail.

345 **5.2 Comparison between the sedimentology of mine and cave collapse.**

346 A good analogue for the lithologies and processes described in this study is the collapse and sedimentation of
347 modern and paleo-cave systems (e.g. (Labourdette *et al.*, 2007; Loucks, 2007, 1999; Mcmechan *et al.*, 2002).
348 Loucks *et al.* (2004) identified 5 paleo-cave facies from core and outcrop data which display distinct properties
349 showing clear parallels to the facies observed at Whitley Bay (Table 3). The key differences in the depositional
350 systems include: the thickness and lateral extent of the facies; properties of the zone of damage; initial lithological
351 properties; and finally that the collapsed mine workings leave a low permeability, clay-rich layer and not a highly
352 permeable coarse chaotic collapse breccia (Loucks *et al.*, 2004).

Cave collapse facies Louchs et al. (2004)	Equivalent mine collapse facies identified in this study
<i>Continuous Strata Facies:</i> Competent, coherent bedded carbonates, with only local evidence of deformation.	Interbedded siliciclastic lithologies with high clay content in the succession.
<i>Discontinuous Strata Facies:</i> Characterised by localised folding and faulting, with some local brecciation. Bedding is generally continuous along strikes. The unit is highly fractured and has local development of mosaic breccia.	Localised faulting and the rotation of bedding is observed; however, bedding can still be observed.
<i>Highly Disturbed Strata Facies:</i> Highly deformed, discontinuous bedded strata with considerable amounts of crackle and mosaic brecciation. Small scale fault and folding common and interbeds of clastic material mark where individual collapse events are recorded.	Immediately above the worked seams deformation quickly interacts with deformation patterns from nearby stalls (Stage 3), which will only occur in caves where two sections of caves are in close proximity.
<i>Coarse-Clast chaotic breccia facies:</i> Very poorly sorted, matrix to clast-supported granule- to boulder-sized chaotic breccia. Finer interbeds common, interpreted as sediment transport into the cave (Loucks, 1999). Overall volume of collapsed lithology increase by c. 40% (Labourdette et al., 2007). Where available rock is less than 2.5 times the volume a collapse sinkhole develops (e.g. Mylroie et al., 1991; Harris et al., 1995).	Similar to the collapse breccia, however, due to the shale roof of the High Main Seam, lower expansion of the breccia occurs during collapse, permeability will be low and only a small space is available to be filled with fines. The collapse of shallow workings can lead to sink hole development (Garrard and Taylor, 1988; Poulsen and Shen, 2013).
<i>Fine Chaotic Breccia:</i> Poorly to well sorted, matrix to clast-supported, granule- to cobble-sized chaotic breccia. Sediment fill commonly observed, but limited to small grain size. Sediment fill deposited by transport from within or outside the cave (Loucks, 1999).	Coal breccia develops from material left from mining operations and the spalling of pillars (Martin and Maybee, 2000). This then gets transported along the coal seam.
<i>Finer Grained Sediment Facies:</i> Consist of silt- to granular-size sediment, dominated by detrital carbonate. Siliciclastic clay may reach 4%, but generally accounts for less than 1%. Sediment is interpreted as being transported in an open chamber by traction, mass-flow and suspension mechanisms.	Foliated muds get deposited from the mixing of mine-waters and deep hyper-saline brines leading to the sedimentation of thin muds from evaporation, suspension and mass transport mechanisms.

353 **Table 3: Comparison between cave collapse lithologies and those observed in this study.**

354 **5.3. Implications for shallow mine geothermal**

355 Ground water flow through abandoned mine workings can be considerable; for example, discharge flow rates
356 from the workings of the Shilbottle Seam in Northumberland (UK) ranged from 0.8 ML/d to 2.6 ML/d (median =
357 1.7 ML/d) (Younger, 2004). Our work shows that where flow can occur along stalls prior to flooding, any collapse,
358 including early spalling of the roof, adds low permeability, clay-rich, lithologies to the system. Within the collapsed
359 breccia, several distinct packages were observed, occasionally showing alteration. This shows that Stage 3 did not
360 occur instantaneously, instead representing a gradual decrease in void space, the migration of the void upwards,
361 and the development of a topography at the base of the seam associated with the sagging and spalling of the

362 roof. During this time flow would still occur, however, whilst workings are only partly flooded, fluid pathways
363 would become longer and localised around pillars.

364 The presence of cycles within the foliated muds suggest that undersaturated fluid flow occurred over a period of
365 7 to 13 years. However, this might be a low estimate as it is not clear when pulses of hypersaline brines began.
366 For deeper workings this could also be triggered by regional groundwater rebound following the end of mining
367 operations (Burke and Younger, 2000). The thickest deposits of FM are in the vicinity to pillars, suggesting that
368 this is the best location for flow, particularly as collapse in these areas occurs later than the rest of the workings.
369 It is important, however, to consider not only the permeability of the lithologies which make up the mine
370 workings, but also fracture networks which can combine to form flow pathways (e.g. McCay *et al.* 2019). Pillars
371 display increased fracturing compared to the undeformed section (Fig. 6), and the low angle faults which bring
372 the final collapse propagate from the pillars into overlying units (Fig. 3). Tectonically deformed coal, which may
373 occur along the edge of pillars (Figs. 3 & 6), has a significantly reduced permeability (Ju and Li, 2009) which will
374 inhibit flow into stalls. While large open voids remain, the water capacity and permeability of the flooded
375 workings will remain high; however, after the final stages of collapse (post stage 3/4) the mine will become
376 increasingly less viable as a geothermal reservoir.

377 After mine abandonment the level of the seam is generally well constrained (Table 1), however, the location,
378 arrangement, and composition of pillar and stalls is often unknown (Bruyn and Bell, 1999). Likewise, the current
379 level of minewater might not reflect the flooding history. This uncertainty is of particular importance for
380 commercial geothermal projects due to the high cost of drilling (Lukawski *et al.*, 2016), with the geothermal
381 potential of a well differing considerably depending on if you intersect a pillar, open stall, or collapsed stall. Where
382 a stall is encountered, the fill type will depend on the stage of collapse and vary considerably along strike (Fig. 3).
383 In general, the presence of a clay-rich collapse breccia will be a sign of at least partial collapse and the presence
384 of shale and sandstone fragments/core with a brick-orange coloration suggests that perched mine waters have
385 developed prior to full saturation of the collapse lithologies and began to form low-permeable clay layers.
386 Although the collapse lithologies and clay layers have low permeability, they are also highly plastic and poorly
387 consolidated. During mine dewatering or minewater rebound it is common to observe rapid break outs of

388 collapsed roof-fall debris. For example, Younger (2002) reported that the large uncontrolled release of acidic mine
389 water from the Wheal Jane abandoned tin mine was caused by dewatering removing collapsed roof material that
390 hydraulically connected two sections of the mine. This suggests that blockages caused by the collapse of stalls
391 could be cleared, and void spaces connected through surcharging or the pumping of high-pressure water to
392 dislodge the plastic clays and collapse breccias.

393 We show that the future water capacity and permeability of unsaturated pillar and stall workings decreased as
394 the degradation of pillars cause the roof to sag, spall, and eventually collapse. Workings in the final stages of
395 collapse (post stage 3; Fig. 7), have a greatly reduced volume for fluid flow, and an increased number of potential
396 flow pathways into overlying units. When assessing a site for geothermal potential it is therefore integral that the
397 phases of collapse and flooding are considered. These findings combined with those outlined by Malolepszy
398 (2003) will be key for assessing the water capacity and permeability structure of target workings.

399 **6 Conclusions**

400 We present for the first time a detailed study of the internal structure of a collapsed pillar and stall coal mine.
401 The internal structure of the workings at Whitley Bay comprises of 8 distinct facies, with lithology, kinematics,
402 stacking patterns and structure informing the collapse processes. A 5-stage model of stall collapse is proposed,
403 each acting to decrease the permeability of the mine. Stage 1 represents the methods used in initial coal
404 extraction, and provides the initial framework for the rest of the collapse, during this time small fragments of coal
405 were deposited on the seam floor, which increased in size when the seam was abandoned (Stage 2). Following
406 working (Stage 3) the roof began to spall, gradually collapsing through multiple events (at least 19 at Whitley Bay),
407 and acid mine water began to form. In Stage 4 the presence of hypersaline brines led to the cyclical deposition
408 salty muds. Assuming annual cyclicity, this suggests that the stalls were open to unsaturated flow for at least 7 to
409 13 years. Finally (Stage 5), the roof collapses along several normal faults, which form triangle zones and lead to
410 the subsidence of the overlying stratigraphy. The last section to collapse is closest to the pillar, occurring 6 years
411 after the rest of the workings.

412 Our findings have significant implications for the shallow mine geothermal sector, raising a number of factors
413 which need to be considered when assessing a potential site. Even when a stall is intersected the stage of collapse

414 will affect whether significant flow can be maintained. The water capacity and permeability of a potential mine
415 geothermal site degrades through time as the roof spalls, and finally collapses. The well-connected fault and
416 fracture network which overlies the workings can enhance or degrade the geothermal potential of a site. While
417 this work is limited to a single unsaturated site, we suggest the processes are widespread and apply to deeper
418 workings prior to final abandonment and flooding. We propose that pillar and stall workings be considered as a
419 heterogeneous, clay-rich anthropogenic layer whereby properties vary through time as collapse progresses.

420 **References**

- 421 Alsop, G.I., Marco, S., Weinberger, R., Levi, T., 2016. Sedimentary and structural controls on seismogenic slumping
422 within mass transport deposits from the Dead Sea Basin. *Sediment. Geol.* 344, 71–90.
423 <https://doi.org/10.1016/j.sedgeo.2016.02.019>
- 424 Banks, D., Athresh, A., Al-Habaibeh, A., Burnside, N., 2019. Water from abandoned mines as a heat source:
425 practical experiences of open- and closed-loop strategies, United Kingdom. *Sustain. Water Resour. Manag.*
426 5, 29–50. <https://doi.org/10.1007/s40899-017-0094-7>
- 427 Banks, D., Younger, Paul L, Road, H., Younger, P L, Arnesen, R.-T., Iversen, E.R., Banks, S.B., 1997. Mine-water
428 chemistry: the good, the bad and the ugly. *Environ. Geol.* 32, 157–174.
429 <https://doi.org/https://doi.org/10.1007/s002540050204>
- 430 Bell, F.G., 1986. Location of abandoned workings in coal seams. *Bull. Int. Assoc. Eng. Geol.* 33, 123–132.
431 <https://doi.org/https://doi.org/10.1007/BF02594714>
- 432 Bruyn, F.G., Bell, D.I.A., 1999. Subsidence problems due to abandoned pillar workings in coal seams. *Bull. Eng.*
433 *Geol. Environ.* 57, 225–237.
- 434 BSi, 2015. BS 5930 - COP for ground investigations. BSi Standards Ltd.
- 435 Burke, S.P., Younger, P.L., 2000. Groundwater rebound in the South Yorkshire coalfield: a first approximation
436 using the GRAM model. *Q. J. Eng. Geol. Hydrogeol.* 33, 149–160. <https://doi.org/10.1144/qjegh.33.2.149>
- 437 Carter, P., Jarman, D., Sneddon, M., 1981. Mining Subsidence in Bathgate, a Town Study, in: Gredds, J.D. (Ed.),
438 Proceedings of the Second International Conference on Ground Movements and Structures. Pentech Press,
439 London, Cardiff, pp. 101–124.
- 440 Chadwick, B.A., Holliday, D.W., Holloway, S., Hulbert, A.G., Lawrence, D.J.D., 1995. The structure and evolution of
441 the Northumberland-Solway Basin and adjacent areas. London:HMSO.
- 442 Chadwick, R.A., Holliday, D.W., 1991. Deep crustal structure and carboniferous basin development within the
443 iapetus convergence zone, northern England. *J. Geol. Soc. London.* 148, 41–53.
444 <https://doi.org/10.1144/gsjgs.148.1.0041>

- 445 Cope, J.C.W., Ingham, J.K., Rawson, P.F., 1992. Atlas of palaeogeography and lithofacies. Geol. Soc. London Mem.
446 No. 13.
- 447 Daunton, M.J., 1981. Down the pit: work in the Great Northern and South Wales coalfields, 1870-1914. Econ. Hist.
448 Rev. 34, 578–597.
- 449 Dearman, W.R., Money, M.S., Strachan, A., Coffey, J.R., Marsden, A., 2000. A regional engineering geological map
450 of the Tyne and Wear County, NE England. Bull. Int. Assoc. Eng. Geol. 19, 5–17.
- 451 Dochartaigh, B.E.O., 2009. A scoping study into shallow thermogeological resources beneath Glasgow and the
452 surrounding area. Br. Geol. Surv. Res. Rep. IR/09/024, 17pp.
- 453 Donnelly, L.J., 2006. A review of coal mining induced fault reactivation in Great Britain. Q. J. Eng. Geol. Hydrogeol.
454 39, 5–50.
- 455 Donnelly, L.J., Culshaw, M.G., Bell, F.G., 2008. Longwall mining-induced fault reactivation and delayed subsidence
456 ground movement in British coalfields. Q. J. Eng. Geol. Hydrogeol. 41, 301–314.
457 <https://doi.org/10.1144/1470-9236/07-215>
- 458 Donnelly, L.J., Culshaw, M.G., Bell, F.G., Tragheim, D., 2009. Ground deformation caused by fault reactivation:
459 some examples, in: The 10th IAEG International Congress. Nottingham, UK, pp. 1–13.
- 460 Fielding, C.R., 1985. Coal depositional models and the distinction between alluvial and delta plain environments.
461 Sediment. Geol. 42, 41–48.
- 462 Fielding, C.R., 1984. Upper delta plain lacustrine and fluviolacustrine facies from the Westphalian of the Durham
463 coalfield, NE England. Sedimentology 31, 547–567.
- 464 Fielding, Christopher R., 1984. A coal depositional model for the Durham Coal Measures of NE England. J. Geol.
465 Soc. London. 141, 919–931.
- 466 Fielding, C.R., 1982. Sedimentology and stratigraphy of the Durham coal measures, and comparisons with other
467 British coalfields. Durham University.
- 468 Gabrielsen, R.H., Braathen, A., Kjemperud, M., Valdresbraten, M.L.R., 2016. The geometry and dimensions of

- 469 fault-core lenses. *Geol. Soc. London, Spec. Publ.* 439, 1–21. <https://doi.org/10.1144/SP439.4>
- 470 Galloway, R.L., 1898. *Annals of Coal Mining and the Coal Trade*, Vol 1. ed. London.
- 471 Garrard, G.F., Taylor, R.K., 1988. Collapse mechanisms of shallow coal-mine workings from field measurements.
472 *Geol. Soc. London, Eng. Geol. Special Publ.* 5, 181–192.
- 473 Gee, D., Bateson, L., Sowter, A., Grebby, S., Novellino, A., Cigna, F., Marsh, S., Banton, C., Wyatt, L., 2017. Ground
474 Motion in Areas of Abandoned Mining : Application of the Intermittent SBAS (ISBAS) to the. *Geosciences*
475 7, 1–26. <https://doi.org/10.3390/geosciences7030085>
- 476 Godyń, K., 2016. Structurally Altered Hard Coal in the Areas of Tectonic Disturbances – An Initial Attempt at
477 Classification. *Arch. Min. Sci.* 61, 677–694. <https://doi.org/10.1515/amsc-2016-0047>
- 478 Hamm, V., Sabet, B.B., 2010. Geothermics Modelling of fluid flow and heat transfer to assess the geothermal
479 potential of a flooded coal mine in Lorraine , France. *Geothermics* 39, 177–186.
480 <https://doi.org/10.1016/j.geothermics.2010.03.004>
- 481 Healy, P.R., Head, J.M., 1984. Construction over abandoned mine workings. No 34.
- 482 Helm, P.R., Davie, C.T., Glendinning, S., 2013. Numerical modelling of shallow abandoned mine working
483 subsidence affecting transport infrastructure. *Eng. Geol.* 154, 6–19.
484 <https://doi.org/10.1016/j.enggeo.2012.12.003>
- 485 Jackson, I., Lawence, D.J., Frost, D.V., 1985. Geological notes and local details for Sheet NZ 27 Cramlington,
486 Killingworth and Wide Open (SE Northumberland). *Mem. Br. Geol. Surv. Sheets* 14.
- 487 Johnson, G.A.L., 1984. Subsidence and sedimentation in the Northumberland Trough. *Proc. Yorksh. Geol. Soc.* 45,
488 71–83.
- 489 Ju, Y., Li, X., 2009. New research progress on the ultrastructure of tectonically deformed coals. *Prog. Nat. Sci.* 19,
490 1455–1466. <https://doi.org/10.1016/j.pnsc.2009.03.013>
- 491 Keefer, D.K., 1984. Landslides caused by earthquakes. *GSA Bull.* 95, 406–421. [https://doi.org/10.1130/0016-](https://doi.org/10.1130/0016-7606(1984)95<406:lcb>2.0.co;2)
492 [7606\(1984\)95<406:lcb>2.0.co;2](https://doi.org/10.1130/0016-7606(1984)95<406:lcb>2.0.co;2)

- 493 Koken, M., Constantinescu, G., 2008. An investigation of the flow and scour mechanisms around isolated spur
494 dikes in a shallow open channel: 1. Conditions corresponding to the initiation of the erosion and deposition
495 process. *Water Resour. Res.* 44. <https://doi.org/10.1029/2007WR006489>
- 496 Kresse, R., Baudis, U., Jäger, P., Riechers, H.H., Wagner, H., Winkler, J., Wolf, H.U., 2007. Barium and Barium
497 Compounds, in: *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley-VCH Verlag GmbH & Co. KGaA,
498 Weinheim, Germany. https://doi.org/10.1002/14356007.a03_325.pub2
- 499 Labourdette, R., Lascu, I., Mylroie, J., Roth, M., 2007. Process-like modeling of flank-margin caves: from genesis
500 to burial evolution. *J. Sediment. Res.* 77, 965–979. <https://doi.org/10.2110/jsr.2007.086>
- 501 Lawrence, D.J., Jackson, I., 1986. *Geology of the Ponteland-Morpeth District*. Mem. Br. Geol. Surv. Sheets 9 a.
- 502 Leeder, M.R., 1988. Recent developments in Carboniferous geology: a critical review with implications for the
503 British Isles and N.W. Europe. *Proc. Geol. Assoc.* 99, 79–100.
- 504 Leeder, M.R., 1982. Upper Palaeozoic basins of the British Isles-Caledonide inheritance versus Hercynian plate
505 margin processes. *J. Geol. Soc. London* 139, 479–491. <https://doi.org/10.1144/gsjgs.139.4.0479>
- 506 Leeder, M.R., 1974. Lower border group (Tournaisian) fluvio-deltaic sedimentation and palaeogeography of the
507 Northumberland basin, in: *Proceedings of the Yorkshire Geological Society*. pp. 129–180.
508 <https://doi.org/10.1144/pygs.40.2.129>
- 509 Lokhande, R.D., Prakash, A., Singh, K.B., Singh, K.K.K., 2005. Subsidence control measures in coalmines : A review
510 64, 323–332.
- 511 Loredó, C., Ordóñez, A., Garcia-ordiales, E., Álvarez, R., Roqueñi, N., Cienfuegos, P., 2017. Science of the Total
512 Environment Hydrochemical characterization of a mine water geothermal energy resource in NW Spain. *Sci.*
513 *Total Environ.* 576, 59–69. <https://doi.org/10.1016/j.scitotenv.2016.10.084>
- 514 Loredó, C., Roqueñi, N., Ordóñez, A., 2016. Modelling flow and heat transfer in flooded mines for geothermal
515 energy use: A review. *Int. J. Coal Geol.* 164, 115–122. <https://doi.org/10.1016/j.coal.2016.04.013>
- 516 Loucks, R.G., 2007. A Review of Coalesced , Collapsed-Paleocave Systems and Associated Suprastratal
517 Deformation. *Acta Carsologica* 36, 121–132.

- 518 Loucks, R.G., 1999. Paleocave carbonate reservoirs: origins, burial-depth modifications, spatial complexity and
519 reservoir implications. *Am. Assoc. Pet. Geol. Bull.* 83, 1795–1834.
- 520 Loucks, R.G., Mescher, P.K., Mcmechan, G.A., John, A., Jackson, K.G., Veritas, P.K.M., Drive, P., 2004. Three-
521 dimensional architecture of a coalesced , collapsed- paleocave system in the Lower Ordovician Ellenburger
522 Group , central Texas 5, 545–564. <https://doi.org/10.1306/12220303072>
- 523 Lukawski, M.Z., Silverman, R.L., Tester, J.W., 2016. Uncertainty analysis of geothermal well drilling and completion
524 costs. *Geothermics* 64, 382–391. <https://doi.org/10.1016/j.geothermics.2016.06.017>
- 525 Lund, J., 2001. Geothermal Heat Pumps - An overview. *GHC Bull.* 22, 1–8.
- 526 Malolepszy, Z., 2003. Man-made, low-temprature reservoirs in abandoned workings of underground mines on
527 example of Nowa Ruda coal mine, Poland, in: *International Geothermal Conference*. Reykjavík, pp. 23–29.
- 528 Malolepszy, Z., Demollin-Schneiders, E., Bowers, D., 2005. Potential Use of Geothermal Mine Waters in Europe,
529 in: *Proceedings World Geothermal Congress*. Antalya, Turkey, pp. 24–29.
- 530 Marino, G.G., Gamble, W., 1986. Mine subsidence damage from room and pillar mining in Illinois. *Int. J. Min. Geol.*
531 *Eng.* 4, 129–150.
- 532 Martin, C.D., Maybee, W.G., 2000. The strength of hard-rock pillars. *Int. J. Rock Mech. Min. Sci.* 37, 1239–1246.
533 [https://doi.org/10.1016/S1365-1609\(00\)00032-0](https://doi.org/10.1016/S1365-1609(00)00032-0)
- 534 McCay, A.T., Shipton, Z.K., Lunn, R.J., Gale, J.F., 2019. Mini thief zones: Subcentimeter sedimentary features
535 enhance fracture connectivity in shales. *Am. Assoc. Pet. Geol. Bull.* 103, 951–971.
536 <https://doi.org/10.1306/0918181610617114>
- 537 Mcmechan, G.A., Loucks, R.G., Mescher, P., Zeng, X., 2002. Characterization of a coalesced , collapsed paleocave
538 reservoir analog using GPR and well-core data 67, 1148–1158.
- 539 Menéndez, J., Ordóñez, A., Álvarez, R., Loredó, J., 2019. Energy from closed mines: Underground energy storage
540 and geothermal applications. *Renew. Sustain. Energy Rev.* 108, 498–512.
541 <https://doi.org/10.1016/j.rser.2019.04.007>

- 542 Monaghan, A.A., Dochartaigh, B.O., Fordyce, F., Loveless, S., Entwisle, D., Quinn, M., Smith, K., Ellen, R., Arkley,
543 S., Kearsey, T., Campbell, S.D., Fellgett, M., Mosca, I., 2017. UKGEOS - Glasgow Geothermal Energy Research
544 Field Site (GGERFS): Initial summary of the geological platform. Br. Geol. Surv. Open Rep. OR/17/006, 205.
- 545 Moore, D.G., 1961. Submarine Slumps. J. Sediment. Res. 31, 343–357. [https://doi.org/10.1306/74d70b78-2b21-](https://doi.org/10.1306/74d70b78-2b21-11d7-8648000102c1865d)
546 [11d7-8648000102c1865d](https://doi.org/10.1306/74d70b78-2b21-11d7-8648000102c1865d)
- 547 Murchison, D., Pearson, J., 2000. The anomalous behaviour of properties of seams at the Plessey (M) horizon of
548 the Northumberland and Durham coalfields 79, 865–871.
- 549 Nef, J., 1965. The Rise of the British Coal Industry, 2nd ed, The British Journal of Psychiatry. Frank Cass & Co. Ltd.,
550 Abingdon. <https://doi.org/10.1192/bjp.111.479.1009-a>
- 551 Page, W., 1907. The Victoria History of the Counties of England: A History of Durham (Volume 2), Vol 2. ed.
552 Archibald Constable and company limited, London, UK.
- 553 Patsa, L., Zarrouk, S.J., Patsa, E., Van Zyl, D., Arianpoo, N., 2015. Geothermal Energy in Mining Developments:
554 Synergies and Opportunities Throughout a Mine’s Operational Life Cycle, Proceedings World Geothermal
555 Congress.
- 556 Poulsen, B.A., Shen, B., 2013. Subsidence risk assessment of decommissioned bord-and-pillar collieries. Int. J.
557 Rock Mech. Min. Sci. 60, 312–320. <https://doi.org/10.1016/j.ijrmms.2013.01.014>
- 558 Salmi, E F, Karakus, M., Nazem, M., 2019. Assessing the effects of rock mass gradual deterioration on the long-
559 term stability of abandoned mine workings and the mechanisms of post-mining subsidence – A case study
560 of Castle Fields mine. Tunn. Undergr. Sp. Technol. 88, 169–185. <https://doi.org/10.1016/j.tust.2019.03.007>
- 561 Salmi, Ebrahim F, Malinowska, A., Hejmanowski, R., 2019. Investigating the post-mining subsidence and the long-
562 term stability of old mining excavations : case of Cow Pasture Limestone Mine , West Midlands, UK. Bull.
563 Eng. Geol. Environ. 1–18.
- 564 Sanner, B., 2001. Shallow Geothermal Energy. GHC Bull. June.
- 565 Smailes, A.E., 1938. Population Changes in the Colliery Districts of Northumberland and Durham. Geogr. J. 91,
566 220. <https://doi.org/10.2307/1787541>

- 567 Smails, A.E., 1935. The development of the Northumberland and Durham coalfield. *Scott. Geogr. Mag.* 51, 201–
568 214. <https://doi.org/10.1080/14702543508554344>
- 569 Soper, N.J., Webb, B.C., Woodcock, N.H., 1987. Late Caledonian (Acadian) transpression in north-west England:
570 timing, geometry and geotectonic significance. *Proc. Yorksh. Geol. Soc.* 46, 175–192.
- 571 Stumm, W., Morgan, J.J., 1981. *Aquatic chemistry: an introduction emphasizing chemical equilibria in natural*
572 *waters.* John Wiley & Sons, Hoboken, NJ.
- 573 Tingay, J., Ellis, M., 2016. *Hartley Cove to the River Tyne Coastal Strategy Coastal Processes Quality Management*
574 *Quality Management.* North Tyneside.
- 575 Turner, B.R., Richardson, D., 2004. Geological controls on the sulphur content of coal seams in the
576 Northumberland Coalfield, Northeast England. *Int. J. Coal Geol.* 60, 169–196.
577 <https://doi.org/10.1016/j.coal.2004.05.003>
- 578 Wardell, K., Wood, J.C., 1965. Ground instability problems arising from the presence of shallow old mine
579 workings. *Proc. Midl. Soc. Soil Mech. Found. Eng.* 7, 7–30.
- 580 Warren, J.K., 2016. Hypersaline Fluid Evolution During Burial and Uplift, in: *Evaporites.* Springer International
581 Publishing, pp. 763–832. https://doi.org/10.1007/978-3-319-13512-0_8
- 582 Woodcock, N.H., Mort, K., 2008. Classification of fault breccias and related fault rocks. *Geol. Mag.* 145, 435–440.
583 <https://doi.org/10.1017/S0016756808004883>
- 584 Younger, P.L., 2004. Environmental impacts of coal mining and associated wastes: A geochemical perspective.
585 *Geol. Soc. Spec. Publ.* <https://doi.org/10.1144/GSL.SP.2004.236.01.12>
- 586 Younger, P.L., 1998. Coalfield abandonment: geochemical processes and hydrochemical products., in: Nicholson,
587 K. (Ed.), *Energy and the Environment-Geochemistry of Fossil, and Renewable Resources.* Environmental
588 *Geochemistry Series No. 1,* Aberdeen (UK), p. 200.
- 589 Younger, P.L., 1995. Hydrogeochemistry of minewaters flowing from abandoned coal workings in County Durham
590 The Durham minewater study Scope of the study. *Q. J. Eng. Geol. Hydrogeol.* 28, S101–S113.

591 Younger, P.L., 1994. Minewater pollution; the revenge of Old King Coal. *geoscientist* 4, 6–8.

592 Younger, P.L., Banwart, S.A., Hedin, R.S., 2002. *Mine water: hydrology, pollution, remediation*, Vol. 5. ed. Springer

593 Science & Business Media.

594