The sedimentology, architecture and depositional setting of the fluvial Spireslack Sandstone of the Midland Valley, Scotland: insights from Spireslack surface coal mine.

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Abstract: Spireslack surface coal mine exposes a section in the Carboniferous Lawmuir Formation (Brigantian) into the Upper Limestone Formation (Arnsbergian). This paper describes the stratigraphy exposed at Spireslack for the first time and, in so doing, names the Spireslack Sandstone, a distinctive erosively based, sandstone-dominated unit in the Upper Limestone Formation. The Spireslack Sandstone comprises two fluvial sandstone channel sets and an upper possibly fluvio-estuarine succession. From an analysis of their internal architectural elements, the channel sets are interpreted as a low sinuosity, sand-dominated, mixed load fluvial system in which avulsion and variations in sediment load played a significant role. The lower channel set appears confined to erosional palaeovalleys of limited lateral extent and significant relief. The upper channel set is much more laterally extensive and displays evidence of a generally lower sediment load with a greater degree of lateral accretion and flooding. Consequently, the Spireslack Sandstone may represent a system responding to base level changes of higher magnitude and longer duration than the glacioeustatic scale commonly attributed to Carboniferous fluvio-deltaic cycles. Spireslack Sandstone may represent an important correlative marker in the Carboniferous of the Midland Valley, and may provide an alternative analogue for some Carboniferous fluvial sandstone stratigraphical traps.

Keywords: Midland Valley of Scotland, Carboniferous lithostratigraphy, Lithofacies, Spireslack Sandstone, Fluvial architecture, Mississippian Sub-Period.

Carboniferous sedimentary rocks in the Midland Valley of Scotland have, in the past, provided large volumes of key strategic resources such as ironstone, shale, oil shale, fireclay, sandstone and limestone, and vast tonnage of coal. Moderately thick and numerous coal seams within the Limestone Coal Formation, one of the main coal-producing units across the Midland Valley of Scotland, were mined at Spireslack surface coal mine, and the neighbouring Grasshill and Ponesk mines (referred to collectively as 'SGP' throughout this study). Spireslack is one of several abandoned surface coal mines in East Ayrshire (Fig. 1a); surface coal mining there has left an open and accessible main void, *c.* 1 km long and up to 130 m deep. This void exposes the upper part of the Lawmuir Formation, the entirety of the Lower Limestone Formation, an almost complete section through the Limestone Coal Formation, and the lower to middle part of the Upper Limestone Formation (Fig. 1b). The neighbouring Grasshill and Ponesk sites also expose successions from the Lawmuir, Lower Limestone, Limestone Coal and Upper Limestone formations.

This work describes the stratigraphy and sedimentology of the Carboniferous rocks exposed at SGP for the first time, with a focus on the Spireslack site. Emphasis here is given to the geometry and depositional environment of the fluvial sandstone units present within the Upper Limestone Formation between the Index and Lyoncross limestones. These sandstone units are assigned to the 'Spireslack Sandstone' (Fig. 1b). Digital photogrammetry is used to capture sedimentary geometries in the Spireslack Sandstone and to produce scaled, photo-realistic, virtual outcrop models derived from a major engineered face in the south of the Spireslack site. The photogrammetry is augmented with detailed field observations of sedimentology and sedimentary geometry from the same fluvial strata that are exposed elsewhere across the SGP site. Taken all together, these data support a new interpretive insight into the nature of fluvial systems in this part of the Carboniferous stratigraphy of the Midland Valley of Scotland.

Geological Setting

Rocks of Carboniferous age occupy much of the Midland Valley of Scotland, formed originally as an ENE – WSW striking graben bounded to the NW by the Highland Boundary Fault system and to the SE by the Southern Upland Fault system (Fig. 1a). The graben (onshore) is *c.* 90 km wide and extends for *c.* 150 km from Ayrshire in the west, to East Lothian and Fife in the east. The bounding faults were active and involved in the control of sedimentation, initially as sinistral strike/oblique-slip faults and subsequently re-activated (post-Westphalian?) during dextral strike/oblique-slip deformation (Browne & Monro 1989; Ritchie *et al.* 2003; Underhill *et al.* 2008). The numerous Carboniferous basins formed within the Midland Valley of Scotland graben were separated from those to the south (the Tweed and Northumberland-Solway basins) by the Lower Palaeozoic rocks of the Southern Uplands block, a positive, mainly emergent structural high throughout the Carboniferous Period. The Scottish Highlands Lower Palaeozoic and Precambrian rocks to the north of the Highland Boundary Fault were similarly a positive and mainly emergent area at this time.

Following on from the preceding Viséan heterolithic clastic and non-marine carbonate and fluvio-deltaic succession (and associated major eruptive centres), marine influence reached its peak during the deposition of the mixed shelf carbonate and deltaic succession of the Namurian

Clackmannan Group (Browne *et al.* 1999; Fig. 1b). Syn-sedimentary tectonic movements were prevalent from the late Viséan, and especially during Namurian times, and are associated with north – south and NNE – SSW striking major growth folds such as the Midlothian-Leven Syncline of the Edinburgh area (Underhill *et al.* 2008). Further west in Ayrshire, Namurian rocks are associated with ENE – WSW striking faults controlling marked changes in depositional thicknesses (see for example discussion in Read *et al.* 2002, p. 276).

The SGP mines are located within the Muirkirk Syncline, a broad upright NE – SW striking fold, dissected by multiple NNE to NW-trending curvilinear faults (Fig. 2a). Strata are exposed on both limbs of this syncline across SGP, and dip 30° to 40° towards the SE in the 'main void' (Fig. 2b) at Spireslack. Elsewhere across the SGP area, dip and dip direction of the rocks are variable depending on their position within the Muirkirk Syncline. Folding was accompanied by faulting in a ductile-brittle stress regime; consequently, the folded strata are displaced by typically left-lateral (sinistral) oblique-slip faults. The faults are geometrically and kinematically consistent with an overall pattern of sinistral transpression at this time in the Carboniferous Period (Leslie *et al.* 2016).

The sections making up the succession exposed across SGP are latest Viséan to Namurian in age (*c.* 330 to 325 million years old). Marine limestone and mudstone units and shallow deltaic to fluvial sandstone and mudstone units are all present, interbedded with coal layers and related palaeosol units (seatearths). These marine and fluvio-deltaic strata were deposited as upward-coarsening cyclic packages, partly recording a reduction in water depth, whilst the locally upward-fining strata and coals were formed on floodplains, and in swamps and peat bogs. This cyclical nature is repeated in other rocks of the same age across the Midland Valley and southern Borders of Scotland, northern and central England, and the North Sea. The widespread occurrence of this cyclical sedimentation is believed to be linked to glacioeustatic oscillations in sea level (Smith & Read 2000; Wright & Vanstone 2001), although active tectonics, compaction and sedimentary processes such as lobe switching may also have played a role (Leeder 1988).

The succession exposed across SGP is assigned to the Lawmuir Formation of the Strathclyde Group and to the Lower Limestone, Limestone Coal, and Upper Limestone formations of the Clackmannan Group (Browne *et al.* 1999, Patterson *et al.* 1998; Figs 1b and 2a). Type sections and Geological Conservation Review (GCR) sections of these formations have been described from natural exposures within the district surrounding SGP: for example, discontinuous successions of the Lower Limestone and Upper Limestone formations are exposed at Garpel Water, Muirkirk (Whyte 2004). Carboniferous strata are recorded at Kennox Water, South Lanarkshire, and include the Lawmuir Formation, partial exposure of the Lower Limestone

Formation, excellent representative sections of the Limestone Coal Formation and incomplete exposure of the Upper Limestone Formation (Lumsden 1964, 1967a, 1967b, 1971). The rocks exposed at Spireslack, Grasshill and Ponesk have been audited and described by the British Geological Survey (BGS) (Ellen & Callaghan 2015, 2016; Ellen *et al.* 2016), and are currently under evaluation and review for designation as GCR sites by the BGS. The GCR proposal describes the Spireslack Conservation and Glenbuck Conservation sections, located in the main void at Spireslack and in an area nearby to the south, respectively (Fig. 2a).

Carboniferous Stratigraphy of the SGP sites

The Carboniferous stratigraphical succession exposed across the SGP sites extends from the Lawmuir Formation in the Brigantian, up into the upper part of the Arnsbergian Upper Limestone Formation (Fig. 1b). The characteristics of these formations at these sites are described in the following sections, and are largely based on data collected from the Spireslack surface coal mine, where the succession is exposed most continuously, and preserved well.

Lawmuir Formation (Brigantian)

The Lawmuir Formation comprises a variable succession of sandstone, siltstone, mudstone with ironstone. The formation includes the Muirkirk Under Limestone that is *c.* 60 cm thick overall and comprises at least three discrete grey and bioclastic limestone units (containing *Gigantoproductus* and compound coral bands), separated from one another by grey silty mudstone. This limestone, like other limestone units present throughout Scottish Carboniferous strata, marks a regionally persistent interglacial flooding surface (*cf.* Read *et al.* 2002); however, limestone units in the Lawmuir Formation are not as laterally persistent as those in the overlying Lower Limestone Formation. A thin coal seam lies below this marine unit. Purple-grey mudstone, siltstone and sandstone otherwise dominate, though they are often weathered and strongly fractured, the latter in response to faulting. The upper section of the formation comprises a 10 m thick succession of dark-grey fossiliferous mudstone with red-brown ironstone ribs.

Lower Limestone Formation (Brigantian – Pendleian)

The Lower Limestone Formation consists predominantly of marine mudstone and fluvio-deltaic mudstone and siltstone interbedded with laterally extensive marine shelf limestone, the latter likely deposited in clear water. The limestone units exposed here are similar to those that can be traced across the greater part of the Midland Valley of Scotland (Wilson 1989), reflecting marine transgressions that are probably related to glacioeustatic sea level oscillations (Read 1994b). Note however, that the Inchinnan Limestone – widely recognized above the Hurlet Limestone over much of the Midland Valley – is either not present or not yet recognised at Spireslack, or elsewhere across SGP. The base of the formation is taken at the bottom of the Hurlet Limestone, characterised by a pale brown and nodular rubbly kaolinitic top containing large productid brachiopods (*Gigantoproductus*) and coral colonies. The top of the formation is taken at the top of the Hosie Limestone which comprises a succession of five separate limestone units, each between 0.5 m to 0.7 m thick and interbedded with siltstone and mudstone units up to 1.2 m thick. It is possible that the lowest of these limestone units is the Blackhall Limestone (named locally as the Muirkirk Wee Limestone). The uppermost limestone unit of the Hosie Limestone forms the robust engineered NW wall of the main void (Fig. 2b). This limestone surface hosts abundant trace fossils; dark grey branching structures up to 10 cm long *(?Planolites*, and *Rhizocorallium*), along with millimetre-sized dark grey narrow traces (*?Chondrites*). In addition, trilobite (*Paladin sp.*), brachiopod and hybodont shark spine remains have been identified.

Limestone Coal Formation (Pendleian)

The Limestone Coal Formation comprises a fluvio-deltaic succession of upward-coarsening and upward-fining cycles consisting of mudstone, siltstone, sandstone, seatearth, sideritic ironstone and coal. The formation is *c.* 95 m thick as exposed in the semi-continuous section in the high wall of the main void at Spireslack (Fig. 2b). The base of the formation is taken at the top of the Hosie Limestone, whilst its top is taken at the base of the Index Limestone; the latter is also exposed in and along most of the high wall section.

Two regionally significant marine incursions are represented by the Johnstone Shell Bed and the Black Metals Marine Band. The latter is not currently safely accessible on the Spireslack site but is easily recognised in the high wall section of the main void by its association with three distinctive layers of variably continuous ironstone. The stratigraphically lower Johnstone Shell Bed (a dark-grey mudstone) contains a marine fauna, which in the Muirkirk area is known to consist of *Pleuropugnoides* sp., *Productus concinnus*, *Schizophoria cf. resupinata* and *Pernopecten sowerbii* (Patterson *et al.* 1998). Identification of the marine fauna exposed at Spireslack itself is yet to be undertaken but includes *Lingula sp.* Both marine bands may be traced widely over most of the Midland Valley of Scotland Namurian outcrop, and probably reflect major transgressions (Read 1994a).

At least six significant units of sandstone are exposed in the high wall of the main void at Spireslack (Fig. 3). Each unit of sandstone is observed to be laterally continuous across the high wall (from NE to SW), between 2 m and 10 m in thickness. Each maintains its general thickness across their exposure, in sharp contrast to the sandstone units in the succeeding Upper Limestone Formation. In the Limestone Coal Formation, the sandstone units display planar cross-bedding and current ripples, and contain organic fragments and ironstone nodules in layers. The sandstone facies are contained within stacked bar, point bar and chute channel features. These sandstones record episodes where water depth fell gradually, forming fluvio-deltaic complexes that would have prograded basin-wards. Swamps and peat mires, formed above marshy waterlogged palaeosols (seatearths), were associated with the prograding fluvio-deltaic complexes (Read *et al*. 2002). Seatearths within Spireslack contain abundant fragments of organic material, consisting commonly of *Stigmaria* roots or *Lepidodendron* trunks.

Several of the formerly most economically important Muirkirk sub-basin coal seams are exposed within the main void and high wall sections, each typically overlying seatearths. In upwards stratigraphical order these are the: McDonald, Muirkirk Six Foot, Muirkirk Thirty Inch, Muirkirk Nine Foot, Muirkirk Four Foot, Muirkirk Three Foot, Muirkirk Ell and Index coal seams (Fig. 1b). These coals formed in equatorial floral provinces dominated by heterosporous lycopod tree rainforests and thick raised peat mires (Phillips & Peppers 1984; Clymo 1987).

Upper Limestone Formation (Pendleian to Arnsbergian)

The Upper Limestone Formation comprises cycles of sandstone, with mudstone, siltstone and marine limestone layers, including the regionally significant Index Limestone, the base of which marks the base of the formation. At Spireslack, the Index Limestone is a 1.3 m thick grey, hard compact bioclastic limestone. This limestone contains abundant *Gigantoproductus cf. irregularis*, *Latiproductus cf. latissimus*, *Pleuropugnoides* sp., *Schellwienella* sp., *Myalina* sp. and *Polidevcia attenuata* (Patterson *et al.* 1998), and represents a maximum flooding episode (Read *et al*. 2002). A conspicuous buff to reddish brown coloured seatearth and a thin (often less than 20 cm thick) impersistent band of the Index Coal occurs immediately beneath this limestone. The Index Limestone is overlain by a 7 – 10 m thick, black, silty marine mudstone (locally including the silty Huntershill Cement Limestone), itself overlain by an erosive-based multi-storey coarse-grained fluvial to possibly estuarine sandstone (Fig. 3), which is exposed well in at least four places throughout SGP (Fig. 4). On the Spireslack site, this unit is exposed in both the main void (Fig. 3), and in a 700 m wide by 40 – 80 m tall engineered face at the Glenbuck Conservation Section (Figs 2 and 4d). The sandstone unit is also exposed at Ponesk and Grasshill (Figs 2 and 4a, c). This sandstone unit is assigned here to the ‘Spireslack Sandstone’; its fluvial components and their interpretation are the focus of the work in the following sections.

The highest limestone in the formation exposed at Spireslack is the Calmy Limestone; it is exposed at top of the NE end of the high wall and comprises a succession of at least four massive, thick limestone beds alternating with siltstone and mudstone layers in a package at least 10 m thick overall. The Gill Coal Seam sits beneath the lowermost exposed limestone in this succession. This coal seam is up to 1 m thick and contains significant development of pyrite mineralisation. The stratigraphical position of Orchard Limestone is inferred to be at the base of the high wall below the outcrop of the Calmy Limestone but is not currently accessible due to flooding. No strata above the Calmy Limestone are exposed in the main void at Spireslack.

Methodology

High-resolution photogrammetric data were collected from the Glenbuck Conservation Section (Fig 4d) to produce a three-dimensional virtual outcrop model from which elements of the section's sedimentology could be deduced and described. Individual photographs were captured on centres spaced at 2 m, and with approximately eighty-five percent overlap between images, using a Nikon D800E camera with a NIKKOR 24 – 120 mm 1:4 lens. Image collection points were indexed to GPS base-station points placed at 25 m intervals horizontally along the natural outcrop in order to locate the virtual outcrop model in space, whilst constraining the model scaling to lie within an error of 3.7 m.

Following data collection, images where imported into Agisoft Photoscan©, to create a photo-realistic virtual outcrop model. Photographs were aligned in the software by analysing common mid-points. Structure for motion algorithms (Barazzetti *et al.* 2010), GPS co-ordinates, and a pixel-scale best-match search were used to generate a dense point cloud dataset. For further details on this photogrammetric technique see Buckley *et al.* (2006), Pringle *et al.* (2006), James & Robson (2012), Abdullah *et al.* (2013) and Bemis *et al.* (2014).

The virtual outcrop model provides a photo-realistic and scaled representation of the natural outcrop from which sedimentary architectures, bounding surfaces, geometrical relationships and hierarchies can be measured, described and interpreted. This approach has provided valuable insight into the geometries and scales of internal architectural features in the Spireslack Sandstone, in a situation where safe access to the face is not currently possible without specialist equipment.

In order to tie together constituent facies and architectural geometries for the Spireslack Sandstone, the photogrammetric data from the Glenbuck Conservation Section were augmented with detailed logging of facies and recording of geometrical relationships from exposures at the SW end of the main void (Fig. 2a, Locality b; Fig. 4b). Additional sedimentary logs through the Spireslack Sandstone and associated strata were recorded from exposures at the Ponesk and Grasshill mines to provide data on localized variations in succession. Overviews of the four localities are shown in Fig. 4, and summaries of the exposures are given below.

The Spireslack Sandstone

The engineered face of the Glenbuck Conservation Section (Fig. 4d) exposes sedimentary rocks from the Index Limestone to the Lyoncross Limestone (Fig. 1b). The Index Limestone at the base of the exposure is overlain conformably by 4.5 – 6 m of marine mudstone. The Spireslack Sandstone is a composite sandstone unit, and comprises two distinct basal sandstone bodies that overlie the mudstone across a major erosive and locally down-cutting, mappable surface (Fig. 4d). The lower body comprises almost entirely of lenticular units of structureless or crossbedded sandstone, but east along the face it is cut into by an upper body that is considerably more heterogeneous in its lithology and architectural element assemblage. A laterally extensive, 14 m thick, asymptotically crossbedded sandstone with heterolithic toesets heavily bioturbated by *Teichichnus* septate burrows overlies the sandstone bodies. A 15 m thick succession of sandstone and siltstone in conformable planar interbeds overlies this unit, and forms the uppermost component of the Spireslack Sandstone. A mudstone-dominated siliciclastic marine succession (Fig. 4d) overlies the Spireslack Sandstone and is, in turn, overlain by the 1 m thick crinoidal Lyoncross Limestone. This limestone provides correlation with successions elsewhere across SGP. The Lyoncross Limestone is overlain by a mudstone, followed by a further erosive and locally down-cutting fluvial sandstone body that forms the top of the Glenbuck Conservation Section.

In the main void of the Spireslack Conservation Section, the Spireslack Sandstone varies in thickness from *c.* 3 m to *c.* 18 m along the high wall (Fig. 3 and Fig. 4b). In Fig. 3 the Spireslack Sandstone as a whole is seen to thin from *c.* 10 m to 3 m thick in the southwesterly part of the high wall, before being cut across by a left-lateral, strike-slip fault that has an offset of *c.* 40 m. On the opposing NE wall of this fault, the sandstone maintains a thickness of *c.* 16 m for approximately 210 m before thinning again along strike in a northeasterly direction to *c.* 3 m thick.

The SW end of the high wall (Fig. 4b) exposes a complete section from the Index Limestone through the Spireslack Sandstone, dipping toward the SE. Here, the Index Limestone is overlain by 6 m of laminated and fissile siltstone, followed across an erosive surface by 18 m of fluvial sandstone, 12 m of interlayered mudstone and siltstone with subordinate layers of sandstone and thin coals, and a 7 m thick sandstone that marks the end of the exposure in this section. Some 50 m further to the SW, another section through this part of the succession reveals *c.* 15 m of laminated and fissile siltstone overlying the Index Limestone, followed by 5 m of the basal sandstone units of the Spireslack Sandstone, before mining spoil and rubble mark the end of the exposure.

At Ponesk and Grasshill mines (Fig. 2a; Figs 4a and 4c), the full thickness of the Spireslack Sandstone is not exposed. The unit is at least 8 m thick at Ponesk, with a sharp, typically planar, erosive base (Fig. 4a), although locally load casts are preserved. *Stigmaria* roots are preserved in abundance. At Grasshill, the sandstone is at least 8 m thick and the erosive base cuts down into the underlying mudstone partially to remove the Huntershill Cement Limestone (Fig. 4c).

Architectural analysis of the Spireslack Sandstone

An analysis of sedimentary log data (Figs 5 and 6) from the SW edge of the Spireslack main void (Fig. 4b), augmented by observations from the Glenbuck Conservation Section and Ponesk and Grasshill mines, permits identification of twelve discrete sedimentary facies within the two distinct basal sandstone bodies. For clarity and conciseness in the written text, descriptions and interpretations of these facies are included within Fig. 7.

From the sedimentary log data, and with correlation to bounding surfaces interpreted from the virtual outcrop model (Fig. 8), six distinct architectural elements are recognised. Each element is described in turn in the sections below, and is summarised in Fig. 9. Bounding surface and architectural element nomenclature follows that of Miall (1988, 1996, 2014).

Channel element (CH)

U-shaped elements (in sections perpendicular to flow) have basal fifth-order scour bounding surfaces, are topped by fourth-order surfaces (Fig. 8), and comprise massive sandstone (Sm1 & Sm2), trough-crossbedded sandstone (St1 & St2), some ripple-laminated sandstone (Srl) and lenses of clast-supported conglomerate (Cc). Full preservation of the element is rare – most examples are truncated by basal fifth-order scour surfaces from other elements of this type – but where fully preserved the element has an average width to depth ratio of *c*. 18:1 (Fig. 10) and with an upward fining infill common.

The basal fifth-order surface – commonly displaying scouring and loading – is overlain by *c*. 50 cm sets of trough-crossbedded sandstone (St1 & St2), climbing at very low and subcritical angles, or by lenticular, generally structureless sandstone bodies sometimes displaying poorly developed foresets near the base (Sm1 & Sm2). Foreset preservation and set development is more common in the base-centre of the element where the fifth-order surface cuts down furthest into the underlying sediments. Gravel to pebble lenses, up to 15 cm in width, are common near the bases of elements, along with a few isolated and outsized clasts up to pebble grade, rip-up clasts of siltstone and wood fragments. Third-order scour surfaces that cut and truncate both crossbedded sets and lenticular structureless sandstone are common. In a few places, higher up the succession, the preserved element is completed by ripple-laminated sandstone (Srl) below the fourth-order surface.

Elements of this geometry and fill are interpreted as channels cutting down into elements of a larger-scale channel set (Bridge 1993; Gibling 2006; Wakefield *et al.* 2015). Their width to depth ratio suggests that these channels may be fixed (Leeder 1973; Ethridge & Schumm 1978; Miall 1996), and this is supported by abundant third-order scour surfaces attributed to in-channel avulsion and bedform reactivation. Structureless sandstone, with intermittent foresets, suggests a high sediment load, leading to rapid deposition supressing bedform development and migration (Bridge & Best 1988; Todd 1996) and generating load casts on the basal fifth-order surface (Allen 1983; Miall 1996). Small-scale, trough-crossbedded sets of sandstone climbing sub-critically within the base of channels suggest development and migration of sinuous crested bedforms at times of lower sediment load, especially in the deeper parts of the flow towards a centre thalweg. Lenses of conglomerate and outsized pebble clasts attest to bedload transport and deposition in localized high-energy eddies (Froude *et al*. 2017). The arrangement of the facies in vertical succession, the general fining upward trend to the channel fill, and the ripple-laminated sandstone facies beneath the top fourth order surface (where preserved) demonstrate a gradual and progressive infill of channel elements under progressively lower energy conditions and with a progressive decrease in sediment load.

Lateral accretion element (LA)

Lensoid elements, 60 – 80 m in lateral extent, 1.5 – 3.2 m thick, are basally bound by fifth-order surfaces that continue laterally beyond the element to become the fifth-order bounding surfaces at the bases of channels. In some examples from the main void (Locality d; Fig. 2a), the top of the element is marked by a fourth-order surface overlain by overbank sediments. However, in most occurrences in the Glenbuck Conservation Section (Fig. 8), the tops of the elements are truncated by fifth- or third-order surfaces that form the bases of channels or other barform elements respectively. The element is dominated by sets of low-angle sigmoidal crossbedded sandstone (Sla), some of which contain foresets draped with silts or muds. The sets are separated by first-order (set) or second-order (coset) bounding surfaces that display a sigmoidal geometry and have abundant asymmetrical ripples preserved along them. Coset (and some set) bounding surfaces terminate downward against the basal fifth-order surface with an asymptotic geometry. Where the top of the element is preserved, ripple-laminated sandstone facies (Srl) overlies the sets of low-angle sigmoidal sandstone to give the fill of the element a slight fining-upward trend. Preserved examples of this element commonly show third-order bounding surfaces extending through the full thickness.

Sigmoidal crossbedded sets overlying a fifth-order surface that is coincident with that forming the base of a channel suggests lateral accretion of sediment during the initial backfilling stage of the channel. Ripple lamination and preserved ripples on coset bounding surfaces represent shallow submergence and 'wash-over' across the bar top (Wakefield *et al*. 2015). Bounding surfaces truncating down through foreset or set surfaces indicate reactivation at bedform and barform scale respectively and likely reflect variations in discharge (Bridge 1993; Bridge *et al.* 1995), or modification of the direction of migration of the barform in response to modification of the channel (Leopold & Wolman 1957; Jackson 1976; Ritter *et al.* 1973; Nanson 1980; Nanson & Croke 1992).

Downstream accretion element (DA)

Tabular elements with a lateral extent of 37 – 58 m and a thickness of 0.5 – 2.5 m are typically bound at their bases by fourth- and fifth-order surfaces and topped by fourth-order surfaces. Basal fifth-order surfaces commonly extend out with the element to form the fifth-order surface at the base of channel elements. The element comprises fine to medium, planar (Spx) and trough crossbedded sandstone facies (St2) in sets 0.8 – 1.2 m thick that are bound by surfaces that climb sub-critically. In a few places, the direction of dip of the foresets changes across set-bounding surfaces. The sets commonly form cosets 2 – 2.5 m thick with asymmetrical ripples preserved along set and coset bounding surfaces. Although the element is dominated by sets and cosets of crossbedding, logged sections from the main void (Figs 5 and 6) demonstrate that these are overlain by ripple-laminated sandstone (Slr), horizontally bedded sandstone (Shb), and laminated siltstone (Fpl): all three facies form sedimentary packages too thin to be observed clearly in the photogrammetry from the Glenbuck Conservation Section (Fig. 8).

The geometry and internal sedimentology suggest in-channel barforms. Where the basal surfaces are fourth-order, barforms developed on top of existing barforms, without significant erosion, to form compound barforms (Jackson 1975; Miall 1977, 1996; Almeida *et al.* 2016). Barform tops are preserved locally (fourth-order surfaces) or are more typically eroded by channels and other downstream accreting elements. Sub-critically climbing planar- and trough-crossbedded sets represent the downstream migration of straight and sinuously crested bedforms respectively under 'normal' to relatively low sediment loads, and the preservation of ripples on set surfaces indicates smaller bedforms migrating over larger bedforms under lower energy conditions. The bi-directionality of foresets within some barforms may indicate a degree of lateral accretion on the outside margins of a downstream accreting bar (Rust 1972; Miall 1977). The presence of ripple-laminated sandstone and siltstone and the general fining-up trend reflect reduction of energy and shallowing as the barform builds towards the surface. Horizontally laminated sandstone with primary current lineation indicate upper flow regime conditions developed in shallow water on bar tops at times of high discharge. Siltstone may suggest deposition from suspension in standing water pools on the top of an emergent barform, although no direct evidence of emergence has been observed.

Chute Channel (CC)

Small scale, 2.1 – 3.7 m in extent and 0.2 – 0.5 m thick, U-shaped elements are observed with erosive basal surfaces that cut down into underlying lateral and downstream accretionary elements. The top surface extends laterally out with the element to become the top surface of the barform. In the Glenbuck Conservation Section (Fig. 8), the fill of the elements appears structureless, but the scale of these elements compared with that of the model renders an analysis of internal architecture difficult from photogrammetry alone, and no logged sections display sediments that can be attributed reliably to this element.

The limited extent of elements of this type, their erosive nature, and their direct association with lateral and downstream accretion elements, suggest that they are chute channels. The erosion of barform tops to form chute channels occurs during periods of high discharge when barform tops become submerged (Ghinassi 2011; Wakefield *et al.* 2015).

Sheetflood (SF)

Thin tabular elements, no more than 4 m thick but laterally extensive, are bound by planar fourth-order surfaces at their bases and at their tops. The elements comprise horizontally laminated sandstone (Shl), undulatory-bedded sandstone (Sub), ripple-laminated sandstone (Srl) and, occasionally, trough-crossbedded sandstone (St2), each in thin packages no more than 80 cm thick.

Horizontally laminated sandstone, typically with plant debris incorporated into the basal laminae, immediately overlie the basal fourth-order surface, followed in isolated cases by trough-crossbedded sandstones in thin packages comprising no more than two sets, or more commonly a single set, climbing sub-critically. These sediments are overlain by ripple-laminated sandstone that typically preserves symmetrical ripple-forms with mud drapes, and undulatory-bedded sandstone with plant debris, numerous roots, and symmetrical, asymmetrical and interference mud-draped ripple marks on bed surfaces.

Elements of this type, with a tabular geometry and containing both upper and lower flow regime sediments in thin packages, are interpreted to be overbank flood deposits (Williams 1971; Miall & Gibling 1978). Each individual, erosively based, fining upward succession represents an individual flood (Miall 1996; 2014). The lack of a sediment grade greater than medium-sand suggests that flood events were relatively low in energy, but may have been sufficiently high in sediment load, or waned rapidly enough, to generally prevent significant bedform development and migration. Horizontally laminated sandstone most likely reflects upper flow regime plane-bed conditions accompanying flooding (Arnott & Hand 1989; Carling 2013; Guan *et al.* 2016). Undulatory-bedded sandstone of similar grainsize may represent similar conditions in which bedforms developed but did not migrate significantly. Rapid deposition of the sediment load of the flow waned preserved these bedforms and gives the bedding an undulatory appearance in cross-section (McCabe 1977). Symmetrical and interference ripples within these strata indicate wind rippling of slowly moving or stationary shallow water during the later stages of flooding.

The lateral extent of each flood event is greater than the extent of the available outcrop at all localities studied. Consequently, it is not possible to determine the geometry of flood events from the data available: individual floods may represent point-sourced crevasse splays, or regionally sourced overbank flooding.

Overbank (OB)

Elements that extend laterally beyond the limits of individual outcrops, but are no more than 1 m thick, are bound at their base by fourth-order surfaces that mark the tops of channel, bar or sheetflood elements. The top of the element is never preserved and is typically marked by an erosive surface at the base of a channel, a bar, or a sheetflood element. Two facies only comprise the element – laminated siltstone (Fpl) and coal – both generally incorporating abundant plant debris and roots.

Elements of this type are interpreted to be overbank deposition on a generally wet floodplain characterized by areas of long-lived standing water. Laminated siltstone represents deposition from suspension in standing water from the latter stages of flooding. The presence of coal suggests stagnant, palustrine and anoxic conditions (Nanson & Croke 1992; Bridge 2009; Gulliford *et al.* 2017), and a lack of desiccation suggests persistent sub-aqueous conditions.

Depositional environment

The sedimentology of the fluvial units of the Spireslack Sandstone suggests a low sinuosity, sand-dominated, mixed-load fluvial system in which channel fill was characterized by both lateral and downstream simple and compound accretionary barforms, migratory bedforms, and bedload transport of gravel (Fig. 11). However, variations in sediment load, in addition to the common factors of sediment grade, energy conditions and fluvial processes, exerted a significant control upon the facies deposited and ultimately preserved.

Variations in sediment load are usually a consequence of variations in discharge (Schumm 1981; Syvitski *et al.* 2000; Bhattacharya *et al.* 2016) and fluvial systems displaying significant variations in discharge are often characterized as 'braided' (Miall 1977; Lesemann *et al.* 2010; Ashmore *et* *al.* 2011; Lee *et al.* 2015; Storz-Peretz *et al.* 2016). Within the fluvial sediments of the Spireslack Sandstone, reactivation surfaces at a range of scales, variations in set size and geometry, and chute channels suggest some degree of variability in discharge for the fluvial system. However, classically braided systems and the models derived from them (Leopold *et al.* 1964; Miall 1977, 2014; Schumm 1981) are inconsistent with many observations from the Spireslack Sandstone, particularly the relative proportion of bedload transport (Galloway 1981; Friend 1983), the channel width/depth ratio (Blum 1994; Gibling 2006; Paola *et al.* 2009), and the maturity of the overbank (Miall 1996, 2014). Although a degree of discharge variability may account for the sedimentary characteristics observed, the Spireslack Sandstone demonstrates a higher degree of channel stability and longevity than that readily associated with classical braided systems; perhaps itself in part a consequence of mature, vegetated and stable overbank regions.

Channel fill can be well characterized from log and cross-sectional datasets such as those available to this study, but assessing sinuosity from the same datasets only (i.e. without a plan-form view of the channels), and without a thorough palaeocurrent study, is somewhat more difficult. Lateral accretion suggests some sinuosity, although both the presence and the amount of lateral accretion in any fluvial section are not necessarily reliable indicators of the degree of sinuosity (Bridge 1993; Bridge *et al.* 1995; Miall, 2014). Although a degree of sinuosity probably existed within the Spireslack fluvial system, width/depth ratios of *c*. 18:1, coupled with no evidence of hollow elements (Cowan 1991; Miall, 2014) suggest that the channels were, to some degree, fixed (Leeder 1973; Ethridge & Schumm 1978; Miall 1996; Gibling 2006). This interpretation is supported by evidence for significant development of overbank characterized by standing water and palustrine conditions replenished by frequent flooding.

Despite likely widespread development, the preservation of overbank sediment is rare throughout most of the fluvial Spireslack Sandstone (Fig. 11). Overbank facies are dominantly preserved as ‘lenses’ of limited lateral extent (that are the remnants left after erosional down-cutting by channels and bars), or preserved as rip-up material that likely originated from a very local source, given the low resilience of the material to transport. Overbank is preserved in significant proportions, and as laterally continuous strata, only at the very top of the fluvial section of the Spireslack Sandstone. Given the low levels of sinuosity in the system, frequent avulsion perhaps accompanying a low rate of creation of accommodation space (Wright & Marriott 1993; Blum & Törnqvist 2000; Miall 2014), were likely controlling factors in the lack of overbank preservation, rather than lateral accretion of channels.

While a low sinuosity, sand-dominated, mixed-load fluvial system provides a suitable interpretation for the fluvial Spireslack Sandstone, variations in the relative proportions of different elements, their sizes and their relationships up-section suggest notable variations in fluvial style through time. Consequently, the fluvial Spireslack Sandstone can be separated into two distinct but related bodies, each representing an individual channel set with defining characteristics (Fig. 11).

Geometries present in the Glenbuck Conservation Section indicate that the lower of these channel sets (Fig. 11b) is dominated by stacked channel elements (Fig. 8), each upwards of a metre thick, and each filled primarily with structureless coarse sandstone (Sm1), coarse trough-crossbedded sandstone (St1) and lenses of conglomerate (Cc). Sedimentary log data (Fig. 5) show that this channel set is dominated by facies that generally result from a higher sediment load. However, textural characteristics suggest that fluvial (Newtonian) transport processes still dominate over gravity-driven flow. Increases in the portion of crossbedded facies upward through this channel set may suggest a decrease in sediment load through time.

The barform elements present within the lower channel set (Fig. 8) are exclusively of downstream accreting type (DA). In the Glenbuck Conservation Section, changes in the dip of foresets within barforms up section, along with increasing symmetry of channel forms, may suggest a slight increase in sinuosity in the fluvial system through time. This is perhaps accompanied by general rotation of the dominant palaeoflow from face-parallel to face-oblique (with respect to the section), although this is difficult to confirm without significant palaeocurrent data.

By contrast, geometries present in the Glenbuck Conservation Section indicate that the upper channel set (Fig. 11a) is characterized by smaller channel elements than those preserved in the lower set. Sedimentary log data (Fig. 5) indicate that their fill comprises facies of generally finer grain and lower sediment load, dominated by well-developed sets and cosets of trough-crossbedded sandstone arranged into barforms. Both lateral accreting (LA) barforms and overbank preservation are more prevalent than in the lower channel set. The geometry and relationships between laterally accreting barforms and channels visible in the Glenbuck Conservation Section suggests a general face-oblique to face-perpendicular palaeocurrent, possibly with slightly increased sinuosity to the system compared with the underlying channel set.

Discussion

Fluvial sandstones within the Carboniferous strata of the Midland Valley of Scotland (and elsewhere in the UK) are generally attributed to well-developed, delta-top fluvial systems representing the last in-fill of accommodation space that was developed periodically from glacioeustatic cycles of parasequence scale (Read 1994b; Read *et al.* 2002). Indeed, exposures of the Limestone Coal Formation in the main void at Spireslack comprise several shallowing upward sediment cycles that are capped with fluvial sandstone and that could be characterized easily as cycles of this nature. Detailed further examination of the sedimentology is required to confirm this.

The sedimentology of Carboniferous delta-top fluvial systems are well documented in exposures across the UK. Meandering fluvial systems, displaying classical levee and crevasse splays with associated high-water-table coal and peat deposits developed on poorly drained, well vegetated overbanks, have been reported from Namurian and Westphalian strata (Besley 1988; Waters 2009). From the Pennine Basin, low-sinuosity fluvial systems are also documented (Bristow 1988; 1993) and may be promoted by high rates of deltaic progradation (Okolo 1983). They preserve channels with width to depth ratios of *c*. 40:1 (Okolo 1983) within laterally extensive sheet sandstone deposits *c*. 60 km wide (Hampson *et al*. 1999), as avulsion drives lateral cannibalisation and recycling of abandoned channel material. Low-sinuosity fluvial systems dominated by structureless facies have also been reported (Martinsen 1990), attributed to deltaic river mouth settings with significantly variable discharge.

While documented examples from each of these settings display characteristics comparable to those of the fluvial Spireslack Sandstone, none describes fully its sedimentology and its geometry. In examples where sedimentology can be considered comparable to the Spireslack (e.g. Okolo 1983; Martinsen 1990), the geometry and scale of the fluvial system is typically incomparable. Systems with comparable geometry and scale, do not display comparable sedimentology (Bristow 1993). Sedimentological differences, coupled with significant erosion of the Spireslack Sandstone into underlying strata make a simple delta-top setting for this fluvial system difficult to justify.

Relevance of the Spireslack Sandstone to basin evolution

The spatial extent of this study is insufficient to provide a full, robust and objective interpretation of the evolution of the Spireslack Sandstone within the context of the Carboniferous environment of the basins of the Midland Valley of Scotland. However, fluvial sedimentology and stratal relationships in the Spireslack Sandstone that are difficult to attribute to delta-top systems, coupled with varied stratigraphy across all of the four locations studied, warrant some discussion in this context.

The Index Limestone, in keeping with the other limestones of the Upper Limestone Formation, is interpreted to represent marine conditions and maximum water depth following marine flooding (Read *et al*. 2002). As such, it provides useful stratigraphical correlation between the localities studied. Fig. 12 demonstrates generalized vertical sections for the four localities using the Index Limestone as a datum.

At the SW end of the main void (Locality b1; Fig. 12), 6 m of siltstone are present between the Index Limestone and the Spireslack Sandstone. The lowermost 9 m of the Spireslack Sandstone can be attributed to the relatively high energy, high sediment load, lower channel set. These strata are overlain by a further 9 m of upper channel set strata generally reflecting a calmer, less energetic fluvial setting. Increases in channel isolation up section, increases in overbank preservation up section, and the development of coal toward the top of the set suggest increasingly 'wetter' conditions through this channel set. A similar story is portrayed by the succession of the Glenbuck Conservation Section (Locality d; Fig. 2a), where 5 m of siltstone overly the Index Limestone, followed by comparable thickness of the lower and upper channel sets of the Spireslack. Sediments of heterolithic bars containing septate burrows (*Teichichnus*) commonly associated with tidal settings (Pemberton *et al*. 2001) overlie the upper channel set.

Approximately 50 m to the SW of the main void (Log b2, Fig. 12), the thickness of siltstone overlying the Index Limestone increases to 16 m and the siltstone is overlain across an unconformity immediately by sediments of the upper channel set. To the NE, along the high wall of the main void (Fig. 12), photographic interpretation suggests that strata attributable to the lower channel set of the Spireslack Sandstone thin significantly. At Ponesk (Locality a; Fig. 2a, Fig. 12), strata attributable to the lower channel set are absent (Fig. 4a), and the basal beds of the Spireslack belong to the upper channel set. At Grasshill, the Spireslack Sandstone cuts down into marine strata (Locality c; Fig. 2a, Fig. 4c) leaving a minimum of 2.5 m of siltstone overlying the Index Limestone. Here, the lower 9 m of the Spireslack sandstone are comparable in sedimentology to the lower channel set (Fig. 12).

Although these data present only limited insight into variations in stratigraphy across SGP, they suggest that the lowermost channel set is laterally confined within a steep-sided palaeo-valley. The main axis of the valley may lie at the SW end of the main void and likely extends through to the Glenbuck Section (Fig. 12). The SW limit of deposition of the lower channel set (and, by inference, the valley it is contained within) is approximately 50 m SW from the end of the main void (Log b2 on Fig. 6; Fig. 12) where sediments of the upper channel set immediately overly siltstone. A further confined valley containing sediments of the lower channel set may be present at Grasshill, although oblique-slip faulting between this locality and the main void makes this uncertain: the exposures here may be of the same valley offset laterally across the site.

The uppermost channel set shows no systematic variation in thickness or sedimentology across the four locations studied. Consequently, it is difficult to interpret the limits of deposition for this channel set. It may be the product of a fluvial system depositing within a broader palaeovalley to that of the lower channel set, the width of which is at least comparable to the spatial distribution of the localities, or the product of a fluvial system developed upon a broad braid plain.

Based upon these observations, sixth-order bounding surfaces marking the erosive bases of both channel sets can be inferred across the Spireslack site (Figs 3, 5, 6, 12). The geometry and scale of these surfaces compared with the scale of channels within both channel sets suggest that erosion is unlikely to be the result of localized fluvial incision. It is difficult to conceive of a method whereby erosion of this magnitude could occur without a drop in base level, and the sedimentology of the lower channel set is comparable to that of a high-energy, sediment-laden fluvial system generated in response to base level fall. However, the sedimentology of the upper channel set, particularly increasing channel isolation and overbank preservation upward, suggests a general increase in accommodation space accompanying base level rise. The increasingly marine nature of the strata overlying the Spireslack Sandstone support this hypothesis.

The full meaning and relevance of these deductions to the evolution of the basins of the Midland Valley during the Carboniferous Period is not clear from the limited data presented here. It may be tentatively suggested that the fluvial components of the Spireslack Sandstone may represent a system responding to changes in base level accompanying a relative sea-level oscillation of higher magnitude and longer duration that those oscillations generally considered responsible for the cycles of the Upper Limestone Formation. Other authors have recognised similar situations within the fluvio-deltaic strata of the Carboniferous of England and Ireland from both outcrop and borehole data (Hampson *et al.* 1997), albeit in younger Namurian strata. The regional nature of their studies allowed them to attribute regionally erosive unconformities at the bases of major fluvial sandstones to 'Exxon-style' sequence boundaries that could be correlated across and between basins. The overlying fluvial sandstones – generally displaying fining upward trends – were attributed to deposition during the lowstand systems tract of the sequence overlying the boundary (Hampson *et al.* 1997). A similar model may be applicable here, but the causal mechanisms for the relative sea level oscillation may be eustatic or tectonic in nature, or combinations of both.

Consequently, the base of the Spireslack Sandstone may be an important correlative surface in the evolution of the Namurian environment of the Midland Valley of Scotland. From the presented study, this interpretation remains equivocal. A detailed sedimentological examination and facies analysis of the overlying and underlying succession to the Spireslack Sandstone across SGP, coupled with similar studies of age-comparable strata locally and regionally within the Midland Valley basins, may help to clarify these ideas.

Relevance to reservoir characterization

Models of fluvial systems and their sedimentology are used commonly to characterize fluvial hydrocarbon reservoirs and to produce geocellular models for fluid migration studies. Classical models of meandering, braided and anastomosing systems, coupled with assessments of rates of subsidence versus rates of avulsion and lateral accretion, are used to assess the likely net-to-gross, to assess the connectivity of sandstone bodies, and to predict petrophysical properties. Classical models are used despite research suggesting that many modern fluvial systems (and, by inference, many fluvial systems preserved in the rock record) do not 'fit' these models in terms of their sedimentology (Gibling *et al.* 2011; Miall 2014).

In the Spireslack Sandstone, the highest quality reservoir sands are provided by clean channel fill and in-channel bar elements, rather than by laterally accreting bars, despite some sinuosity and variations in sediment load. Channel stacking and sandstone body connectivity is likely a consequence of avulsion (combined with low rates of accommodation creation and/or confinement) rather than overprinting from lateral accretion. The Spireslack Sandstone may provide a valuable analogue for Carboniferous fluvial reservoirs where other models do not provide an adequate explanation for reservoir characteristics.

From a study of limited lateral and stratigraphical extent such as this one, it is difficult to determine the extent to which the Spireslack Sandstone provides an analogue for Carboniferous fluvial reservoirs more generally. However, if further studies can confirm a sequence stratigraphical relevance for the Spireslack Sandstone, then the model presented, and exposures of the Spireslack Sandstone across the SGP site, may provide appropriate analogues for stratigraphical traps developed in other Carboniferous fluvial sandstones that fit this particular evolutionary model. The spatial extent to which this model may be applicable will be determined by the causative mechanisms for relative sea level oscillation.

Conclusions

Spireslack and the neighbouring mines of Grasshill and Ponesk in the Midland Valley of Scotland expose successions of Carboniferous strata assigned to the Lawmuir Formation through into the Upper Limestone Formation. This work describes the SGP Carboniferous rocks in detail as comprising marine limestone (including the Hosie and Index limestones) and mudstone, fluvio-deltaic sandstone, seatearth and economically important coal seams, deposited as generally upward-coarsening cyclic packages.

Numerous sandstone units are exposed within the Namurian succession across SGP, including the mappable unit of the Spireslack Sandstone that is named in this work for the first time. This work has shown that the fluvial parts of the Spireslack Sandstone represent the preserved deposits of a low sinuosity, sand dominant, mixed-load fluvial system in which avulsion and variations in sediment load play a relatively significant role in defining the sedimentology. Differences in the size and relative proportions of architecture elements through the succession define two distinct channel sets. A lower and slightly older channel set is largely confined to erosional palaeovalleys of limited lateral extent that remove significant proportions of the underlying strata above the Index Limestone. This channel set is characterized by facies indicative of a high sediment load preserved in channel elements and downstream accreting bars. The upper younger channel set is much more laterally extensive and displays evidence of a generally lower sediment load with a greater degree of lateral accretion and flooding.

The model proposed here for the fluvial component of the Spireslack Sandstone differs in character from that of near-flat, delta-top meandering models commonly attributed to the Carboniferous fluvial strata. The characteristics of the proposed model may be tentatively attributed to changes in base level that are of higher magnitude and longer duration than the glacioeustatic scale commonly attributed to Carboniferous fluvio-deltaic cycles. As such, the Spireslack Sandstone may represent an important correlative unit in the evolution of the Carboniferous basins of the Midland Valley of Scotland during the Namurian. The model highlights significant variation in the nature of Carboniferous fluvial systems. As such, it may provide a valuable alternative analogue for Carboniferous fluvial reservoir characteristics where other models prove to be wholly or partially inadequate.

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Fig. 1: (**a**) Generalised Carboniferous geology of the Midland Valley of Scotland, with location of the Spireslack, Grasshill and Ponesk surface coal mines (SGP). Base image derived from NEXTMap Britain elevation data from Intermap Technologies; (**b**) Stratigraphical framework for coal-bearing strata across SGP, based largely on data collected from the Spireslack surface coal mine (where the strata are exposed most continuously) in the Midland Valley of Scotland.

Fig. 2: (**a**) 1:50 000-scale geological map of the area of coal mining at Glenbuck, encompassing Spireslack, Grasshill and Ponesk surface coal mines. The strata at the sites have been folded into a broad southwesterly plunging syncline, which is offset by many minor faults with a dominant north to north-northeasterly alignment. Base image derived from NEXTMap Britain elevation data from Intermap Technologies (**b**) Aerial photograph showing the main features of the Spireslack Conservation Section, highlighted by the hatched rectangle in the geological map in (**a**). The photograph along the main void in the Spireslack Conservation Section shows the engineered northwestern wall of the void, marked by the Top Hosie (McDonald) Limestone and the southeastern high wall section, consisting mostly of strata from the Limestone Coal Formation. Aerial photograph © UKP/Getmapping Licence No. UKP2006/1.

Fig. 3: Photogrammetry and interpretation of the Spireslack Sandstone as it is exposed in the high wall of the main void at Spireslack. A laterally continuous unnamed sandstone unit within the Limestone Coal Formation (LCF) is also highlighted in pale orange. A white dashed line marks the Index Limestone.

Fig. 4: Spireslack Sandstone. (**a**) exposure in Ponesk surface coal mine (**b**) exposure at the SW end of Spireslack Conservation Section (**c**) exposure at Grasshill surface coal mine (**d**) exposure in the Glenbuck Conservation Section. For detail of this section, see Fig. 8. Locations a – d are marked on Fig. 2a.

Fig. 5: Sedimentary log b1 of the Spireslack Sandstone from the SW end of the main void (Locality b; Fig. 2). Facies code relate to those listed in Fig. 7, and element codes relate to those listed in Fig. 9. For key to all other symbols and colours please see Fig. 6.

Fig. 6: The top of sedimentary log b1 (continued from Fig. 5), and log b2. Both logs are from the SW end of the main void (Locality d; Fig. 2a). Facies codes relate to those listed in Fig. 7, and element codes relate to those shown listed in Fig. 9.

Fig. 7: Lithofacies for the Spireslack Sandstone. sr = sub-rounded, r = rounded, wr = well-rounded, ms = moderately sorted, ws = well sorted, cs = clast supported, qtz = quartz, fspar = feldspar. LFR = Lower Flow Regime, UFR = Upper Flow Regime. For facies code key, see Fig. 6.

Fig. 8: Virtual outcrop model derived from photogrammetric image of the Spireslack Sandstone at the Glenbuck Conservation Site, with interpreted line drawing below. Architectural elements have been interpreted from bounding surfaces hierarchies and relationships, see text from descriptions. All bounding surface nomenclature has been taken from Miall (1988, 1996, 2014).

Fig. 9: Description and definition of architectural elements in the fluvial Spireslack Sandstone.

Fig. 10: Reservoir characteristics of the two channel sets seen in the Glenbuck Conservation Section, including the average width to depth (w/d) ratio of channel forms, net-to-gross and channel to overbank ratio. Although channel to overbank ratios stay the same, the net-to-gross value (expressed here as percentage net fine- to coarse-grained sandstones) for the upper channel set is lower, indicating its more heterolithic nature.

Fig. 11: Facies models for the fluvial strata of the Spireslack Sandstone with key features referred to in the text highlighted. The size and relative proportions of different elements define two separate channel sets. Variation in flow direction between the two sets is suggested from photogrammetry only and is relative: no north direction is implied. Vertical exaggeration is approximately 3.

Fig. 12: Generalized vertical sections from localities a to d across the SGP site, and the NE end of the main void, based upon field measurements and photogrammetry. All sections are relative to the top of the Index Limestone and highlight the differences in thickness and occurrence of the fluvial channel sets of the Spireslack Sandstone, as well as differences in erosion level. Note the prevalence of the lower channel set at the SW end of the Spireslack Conservation Section, in the Glenbuck Conservation Section and at Grasshill. The channel sets represent mappable units bound by sixth-order surfaces at their bases that can be correlated to the log data (Figs 5 and 6) and the photogrammetry data (Fig. 8).

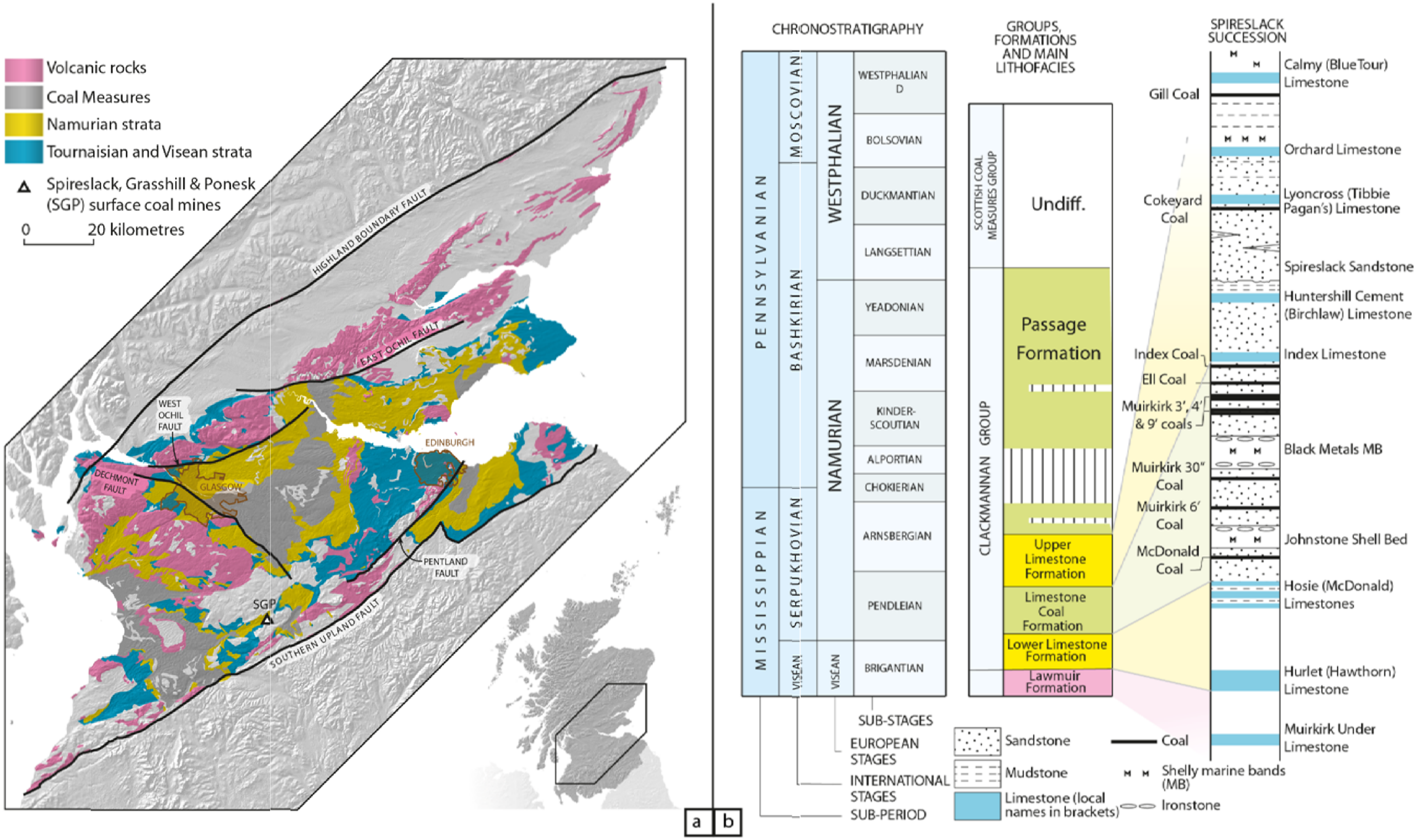

Volcanic rocks
Coal Measures
Namurian strata
Tournaisian and Visean strata
Spireslack, Grasshill & Ponesk (SGP) surface coal mines
0 20 kilometres
HIGHLAND BOUNDARY FAULT
EAST OCHIL FAULT
WEST OCHIL FAULT
DECHMONT FAULT
GLASGOW
EDINBURGH
PENTLAND FAULT
SGP
SOUTHERN UPLAND FAULT
a
b
CHRONOSTRATIGRAPHY
PENNSYLVANIAN
MISSISSIPPIAN
MOSCOVIAN
BASHKIRIAN
SERPUKHOVIAN
VISEAN
WESTPHALIAN
NAMURIAN
VISEAN
WESTPHALIAN D
BOLSOVIAN
DUCKMANTIAN
LANGSETTIAN
YEADONIAN
MARSDENIAN
KINDER-SCOUTIAN
ALPORTIAN
CHOKIERIAN
ARNSBERGIAN
PENDLEIAN
BRIGANTIAN
SUB-STAGES
EUROPEAN STAGES
INTERNATIONAL STAGES
SUB-PERIOD
GROUPS, FORMATIONS AND MAIN LITHOFACIES
SCOTTISH COAL MEASURES GROUP
CLACKMANNAN GROUP
Undiff.
Passage Formation
Upper Limestone Formation
Limestone Coal Formation
Lower Limestone Formation
Lawmuir Formation
SPIRESLACK SUCCESSION
Gill Coal
Cokeyard Coal
Index Coal
Ell Coal
Muirkirk 3', 4' & 9' coals
Muirkirk 30" Coal
Muirkirk 6' Coal
McDonald Coal
Calmy (Blue Tour) Limestone
Orchard Limestone
Lyoncross (Tibbie Pagan's) Limestone
Spireslack Sandstone
Huntershill Cement (Birchlaw) Limestone
Index Limestone
Black Metals MB
Johnstone Shell Bed
Hosie (McDonald) Limestones
Hurlet (Hawthorn) Limestone
Muirkirk Under Limestone
Sandstone
Mudstone
Limestone (local names in brackets)
Coal
Shelly marine bands (MB)
Ironstone

Figure 1

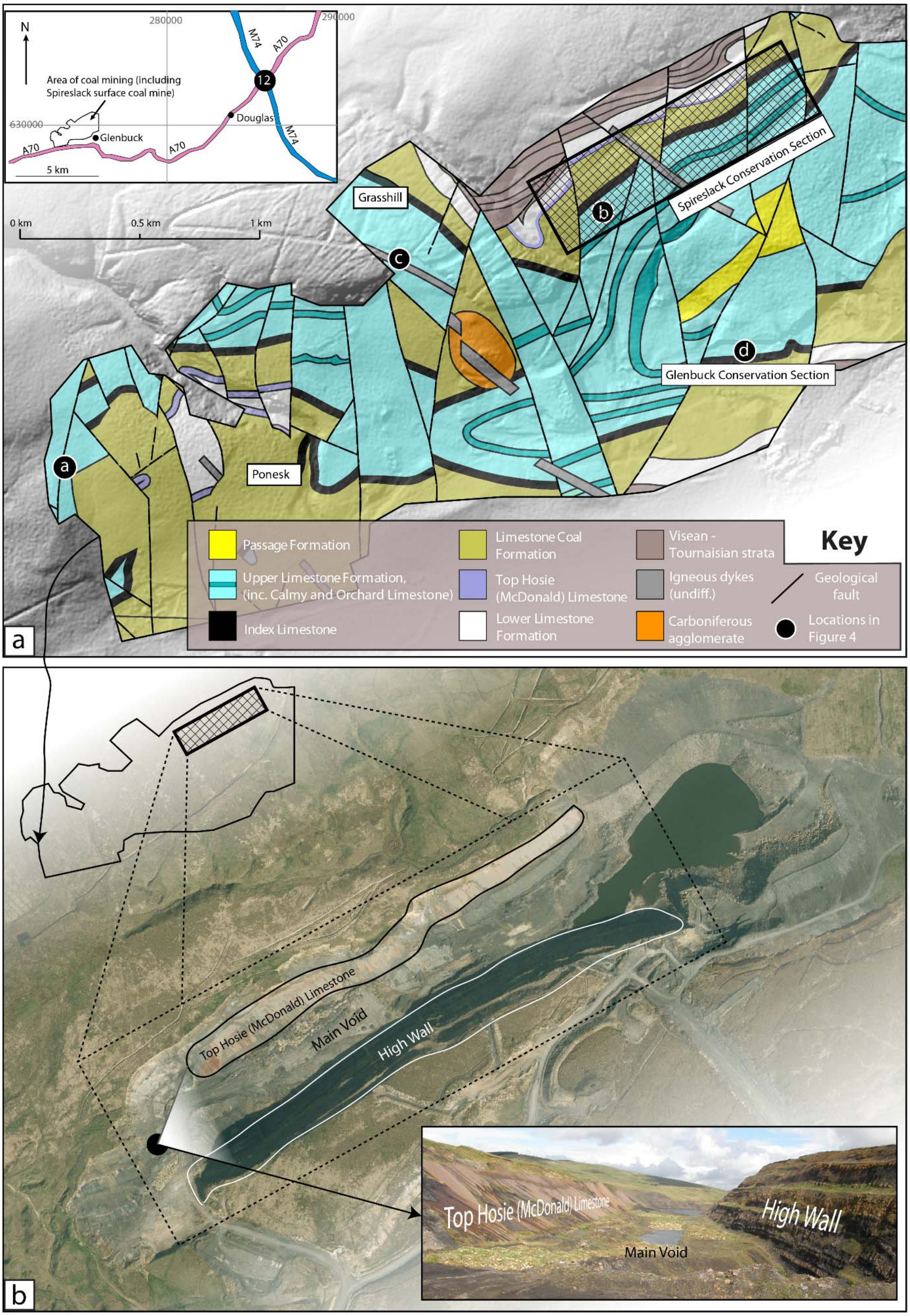


Figure 2

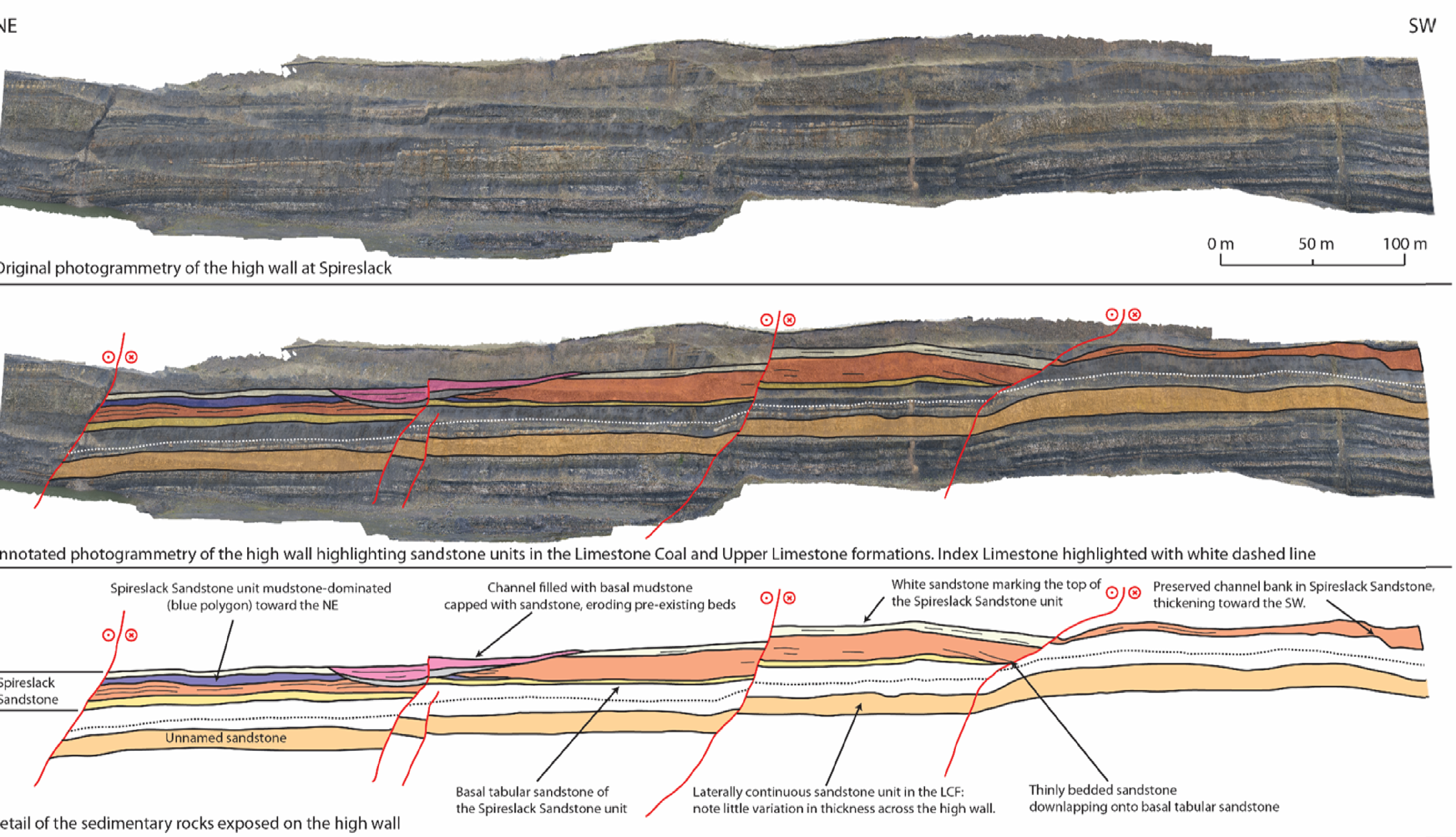

NE
SW
0 m
50 m
100 m
Original photogrammetry of the high wall at Spireslack
nnotated photogrammetry of the high wall highlighting sandstone units in the Limestone Coal and Upper Limestone formations. Index Limestone highlighted with white dashed line
Spireslack Sandstone unit mudstone-dominated (blue polygon) toward the NE
Channel filled with basal mudstone capped with sandstone, eroding pre-existing beds
White sandstone marking the top of the Spireslack Sandstone unit
Preserved channel bank in Spireslack Sandstone, thickening toward the SW.
Spireslack Sandstone
Unnamed sandstone
Basal tabular sandstone of the Spireslack Sandstone unit
Laterally continuous sandstone unit in the LCF: note little variation in thickness across the high wall.
Thinly bedded sandstone downlapping onto basal tabular sandstone
etail of the sedimentary rocks exposed on the high wall

Figure 3

943

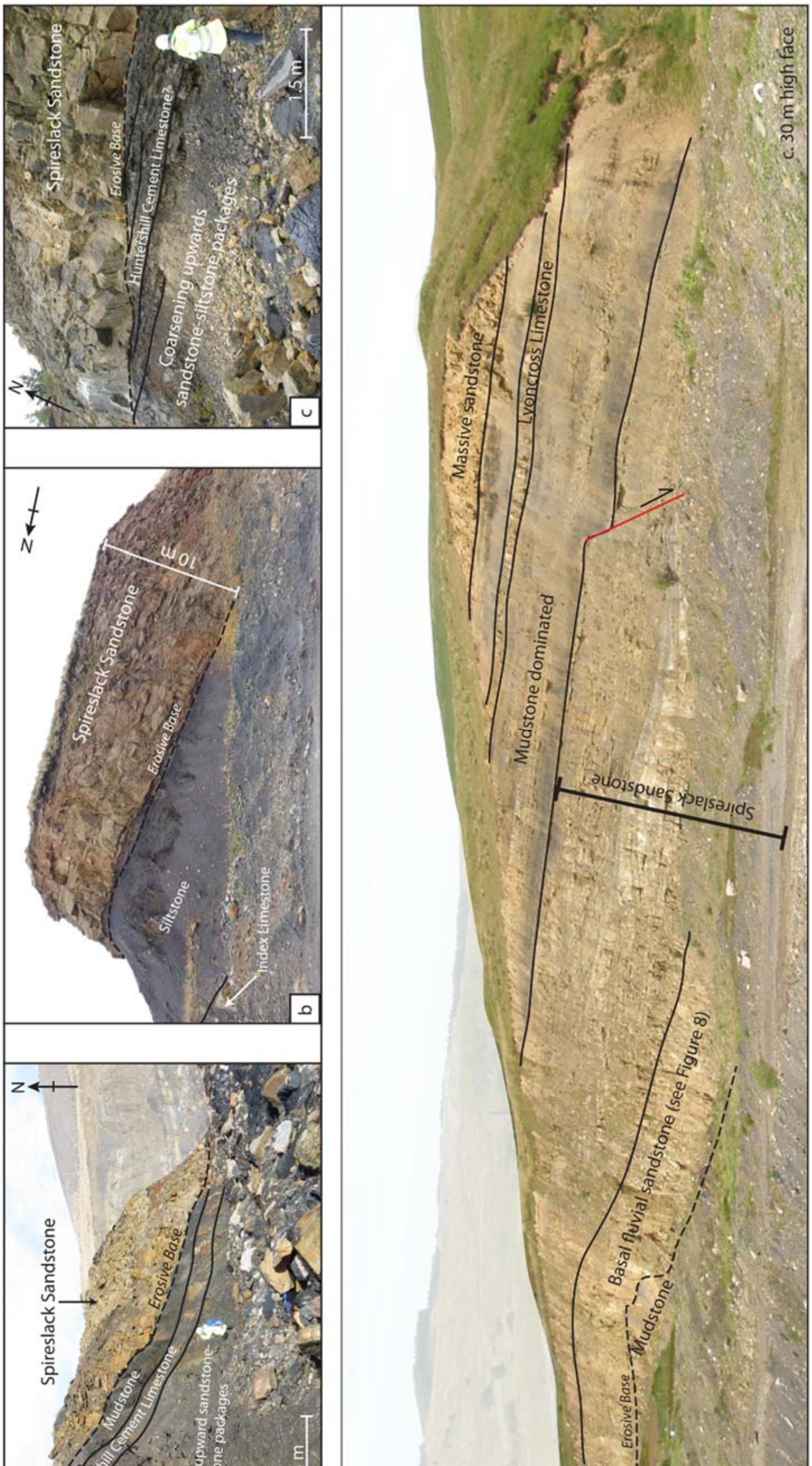

Spireslack Sandstone
Erosive Base
Mudstone
N
Spireslack Sandstone
Erosive Base
Siltstone
Index Limestone
10 m
N
b
Spireslack Sandstone
Erosive Base
Huntershill Cement Limestone?
Coarsening upwards
sandstone-siltstone packages
1.5 m
N
c
Massive sandstone
Lyoncross Limestone
Mudstone dominated
Spireslack Sandstone
Basal fluvial sandstone (see Figure 8)
Mudstone
Erosive Base
c. 30 m high face

Figure 4

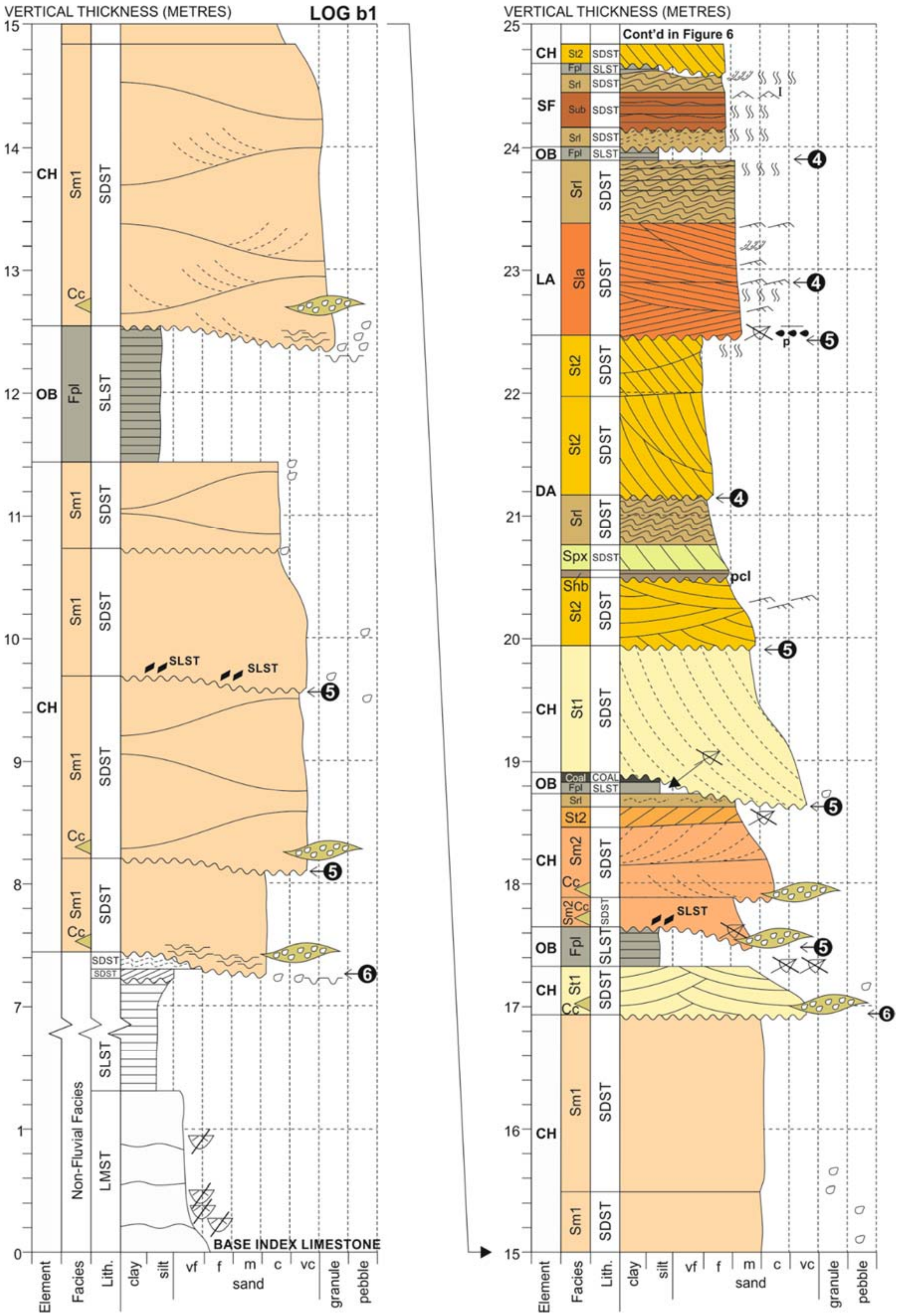
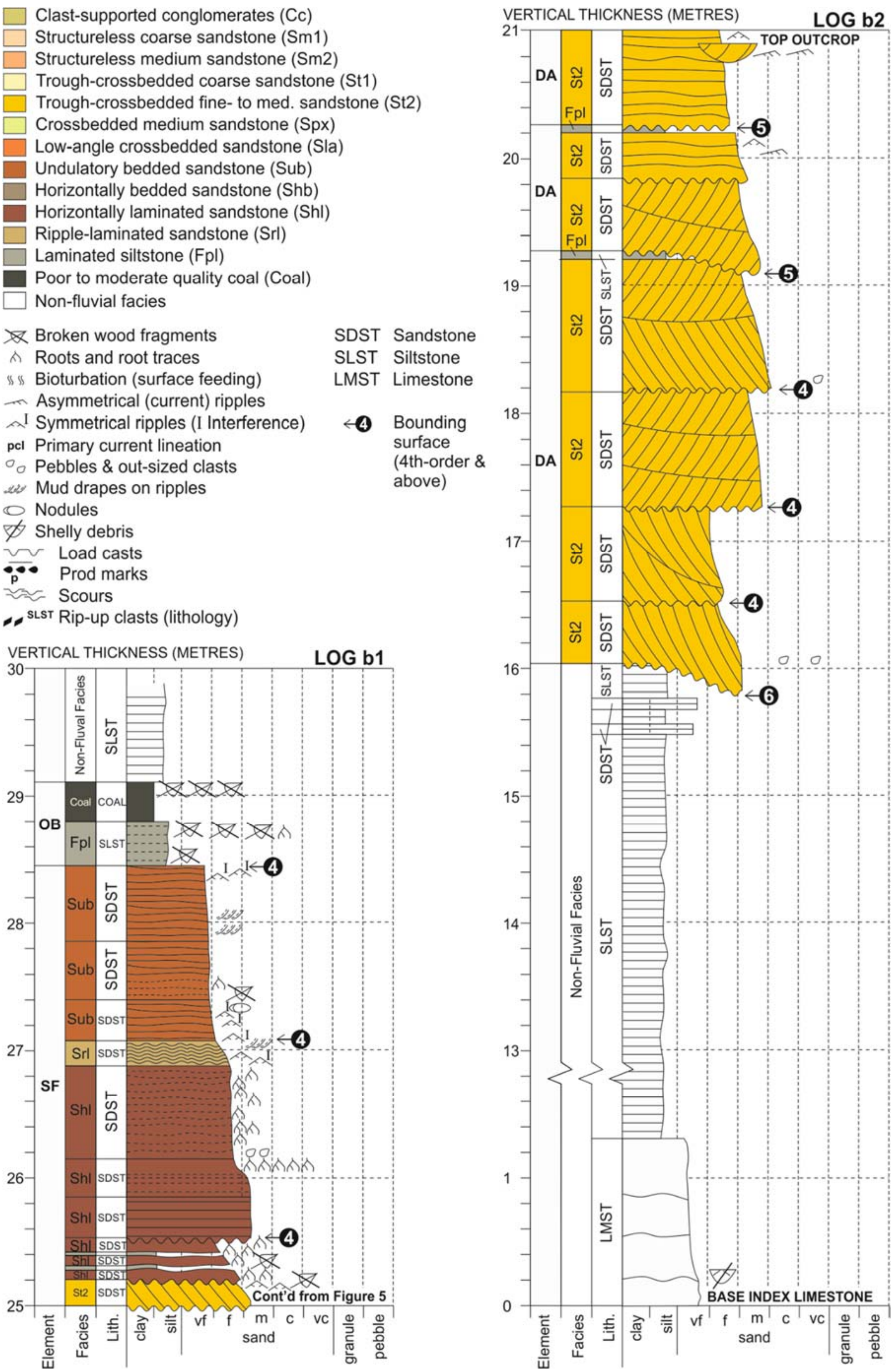


Figure 5



947

948 **Figure 6**

Facies code	Texture	Sedimentary structure	Intepretation
Cc	Conglomerates, granules and sporadically pebbles a-sr, cs.	Sporadically slightly normally graded (where grain size varies).	Bedload transport at base of flow.
Sm1	Sand, coarse to very coarse, cream with orange speckle, generally r-wr, ms-ws & cs. Mainly qtz, some fspar, occasional mica. Rip-up & pebbles at base.	Structureless, typically in lenticular units. Sporadic, intermittent and poorly developed trough-crossbedding at the base, load casts & scours.	Newtonian flow deposit under high sediment load conditions.
Sm2	Sand, generally medium or finer, white, wr & ws. Mainly qtz, occasional fspar. Sporadic rip-up & wood fragments.	Structureless, some normal grading (where grain size varies). Occasional intermittent and poorly developed trough-crossbedding at base or throughout. Common lenses of Cc.	High sediment load, intermittent development and migration of dune-forms.
Shb	Sand, medium, white, sr, ws & cs. Dominantly qtz.	Horizontally bedded with primary current lineation on bed planes.	UFR - upper plane bed deposition.
St1	Sand, medium to coarse, white, sr-r, ws & cs. Mainly qtz, some fspar.	Trough-crossbedding in single or multiple sets, sporadically poorly developed and intermittent. Sometimes contains lenses of Cc at or near the base.	Migration of sinuous-crested duneforms and dune trains in LFR with moderate sediment load.
St2	Sand, fine to medium, white to cream, wr, ws & cs. Mainly qtz, some fspar.	Trough-crossbedding in single or multiple sets. Asymmetrical ripple forms preserved on set surfaces.	Migration of sinuous-crested duneforms, dune trains and barforms in LFR.
Spx	Sand, medium, white to cream, wr, ws & cs. Mainly qtz, sporadic fspar.	Planar crossbedding in single or multiple sets.	Migration of straight-crested duneforms, dune trains and barforms in LFR.
Sla	Sand, fine to medium, wood fragments. Dominantly qtz.	Low-angle crossbedding in lenticular sets. Common current ripples on set surfaces, some bioturbation.	Lateral accretion of barforms in LFR with washover.
Srl	Sand, fine, sr-wr, ws & cs. Dominantly qtz.	Current ripple lamination in single or multiple sets - some ripple forms preserved.	Migration of ripple forms in LFR.
Sub	Sand, fine, purple-cream, r-wr, ms-ws, cs. Qtz with sporadic fspar.	Generally planar bedded in beds 2 - 5 cm thick but with irregular, sporadically rippled bed planes and muddy laminations. Some current ripple lamination and symmetrical ripple forms & interference ripples.	Unconfined shallow flow - some development of ripple forms under high sediment load and wave influence from wind on standing to slow moving shallow water.
Shl	Sand, med. - fine, cream, wr & ws. Qtz with sporadic fspar.	Laminated, rooted and bioturbated. Occasional ripple forms on laminations.	Settling from suspension in standing to slowly moving water with occasional bedform development.
Fpl	Silt. Sporadic wood fragments.	Laminated, sometimes poorly developed, occasionally structureless.	Settling from suspension.

Figure 7

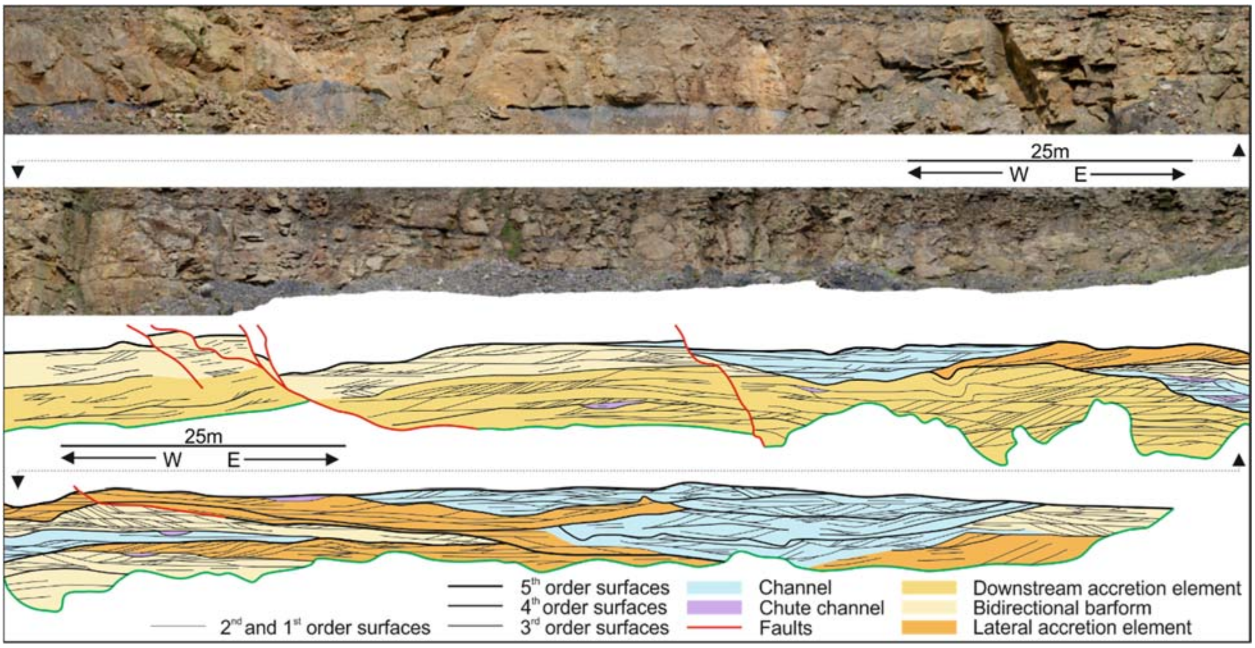


Figure 8

Name	Element code	Facies	Description
Lateral accretion element	LA	Sla, Srl	Lateral extent of 60 to 80 m and 1.5 to 3.2 m thick, lensoidal shape, truncated in every observed occurrence.
Downstream accretion element	DA	St2, Shb, Stx2	Lateral extent of 37 to 58 m and 0.5 to 2.5 m thick, lensoidal shape, truncated in most observed occurrences.
Channel	CH	Cc, Sm1, Sm2, St2, Srl	U-shaped concave-up erosive base, lateral extent of 34 to 59 m and 2.2 to 3.7 m thick, truncated in every observed occurence.
Chute Channel	CC	Sm2, Srl	Smaller scale channel form erosively downcutting into the top of a barform, lateral extent of 2.1 to 3.7 m and 0.2 to 0.5 m thick.

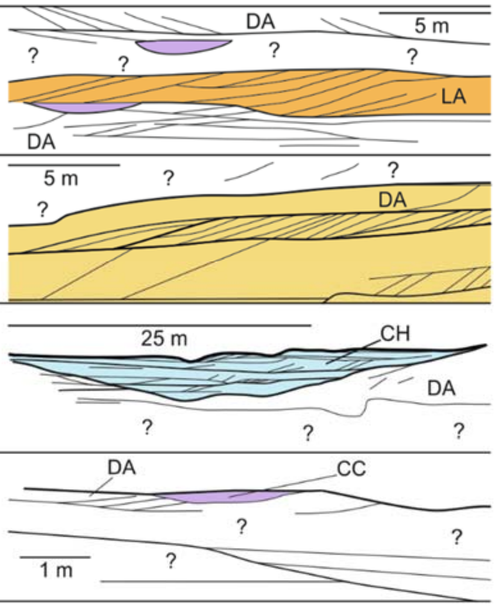


Figure 9

	Lower channel set	Upper channel set
Average w/d ratio of channel forms	Average w = not possible due to palaeocurrent direction Average d = 4.15 -	Average w = 73.75 Average d = 4.18 Average w/d = 17.85
Net-to-gross	96%	88%
Channel to overbank ratio	100%	100%

Figure 10

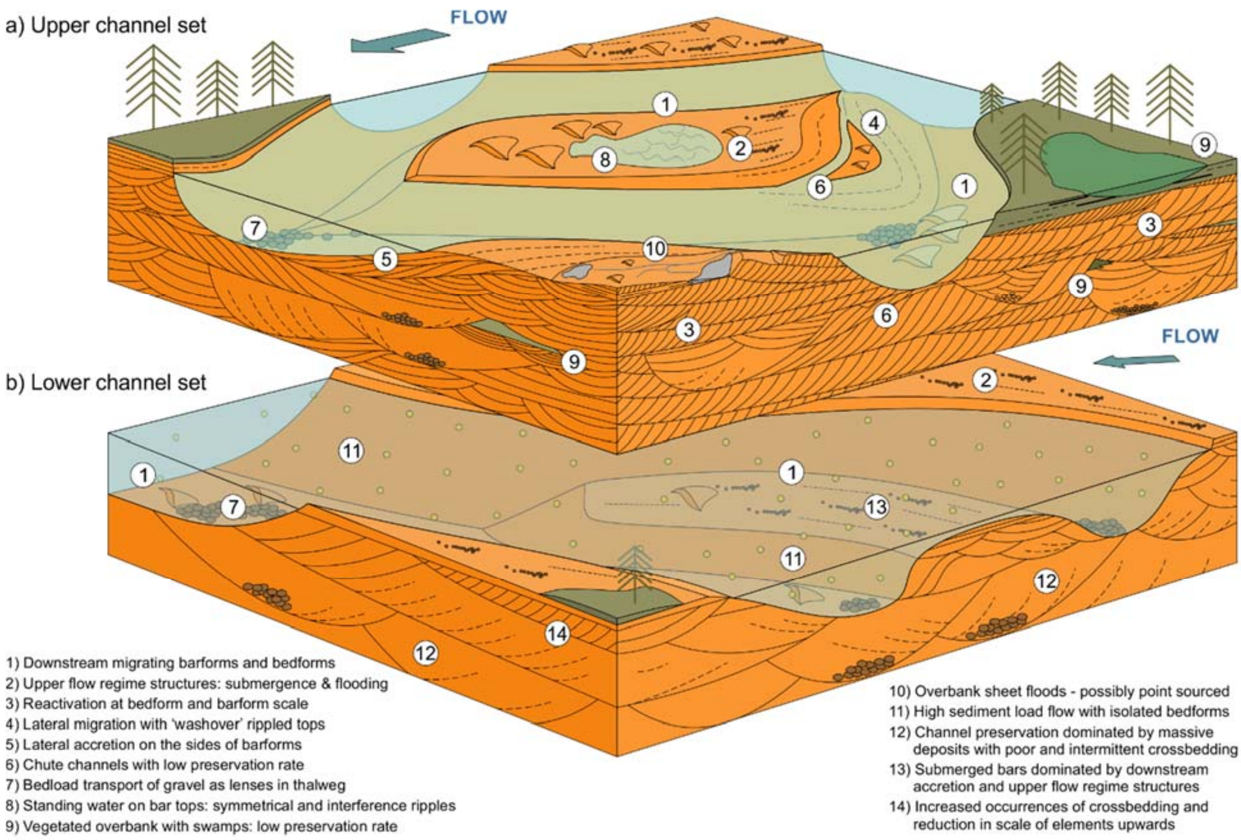
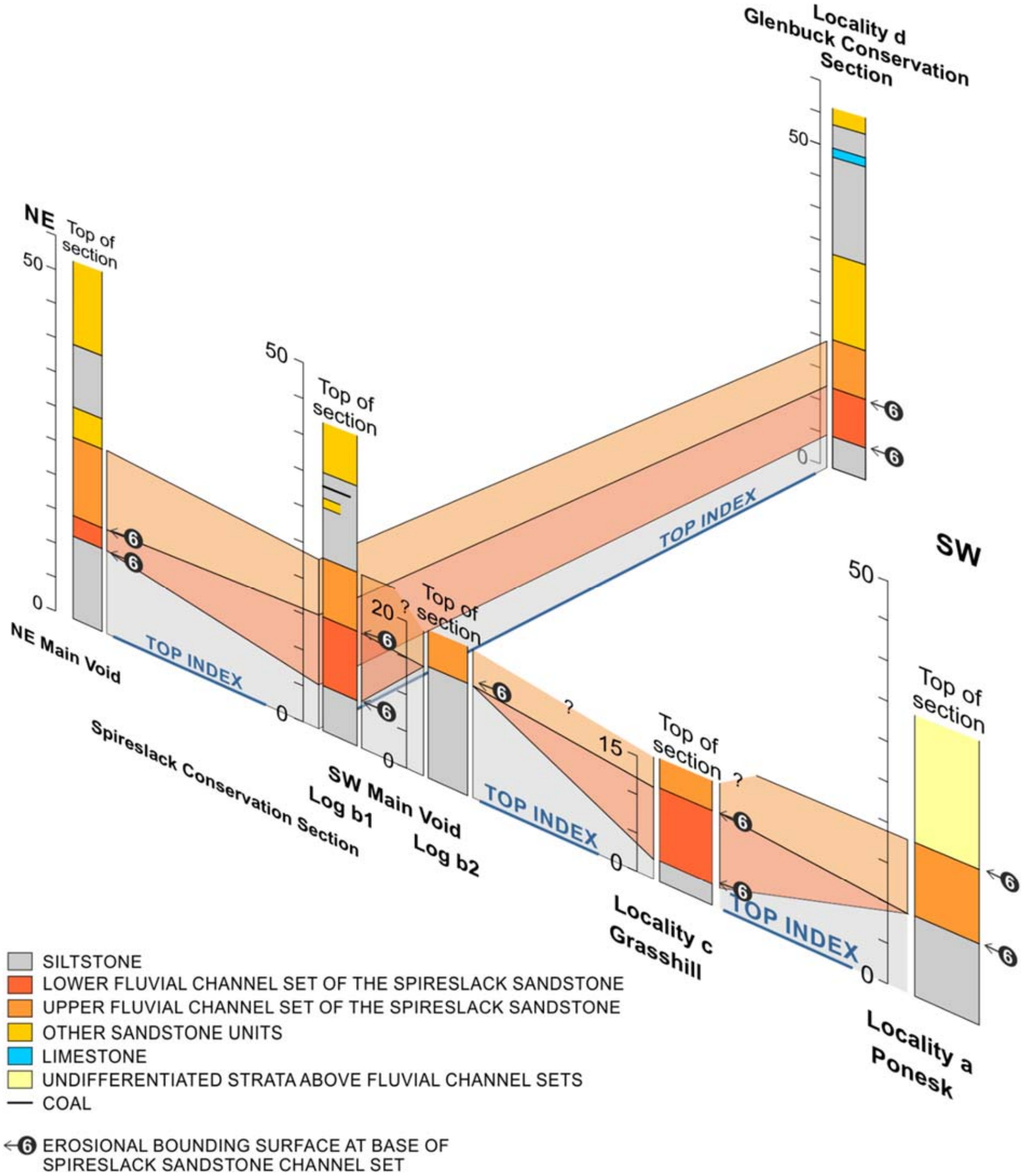


Figure 11



Locality d
Glenbuck Conservation Section
NE
Top of section
50
0
NE Main Void
TOP INDEX
Spireslack Conservation Section
Log b1
SW Main Void
Log b2
20
15
Locality c
Grasshill
SW
Locality a
Ponesk
?
SILTSTONE
LOWER FLUVIAL CHANNEL SET OF THE SPIRESLACK SANDSTONE
UPPER FLUVIAL CHANNEL SET OF THE SPIRESLACK SANDSTONE
OTHER SANDSTONE UNITS
LIMESTONE
UNDIFFERENTIATED STRATA ABOVE FLUVIAL CHANNEL SETS
COAL
6 EROSIONAL BOUNDING SURFACE AT BASE OF SPIRESLACK SANDSTONE CHANNEL SET

Figure 12