Duckmantian-age Coal Measures sequences in Sheffield

John Hunter

Abstract: In 2018 an opportunity arose for a local geology trust to undertake a 'rescue-recording' of a temporary exposure of a minor Pennine Middle Coal Measures sandstone body at a housing development site near Sheffield. The observations made there were compared to permanent outcrops of a larger, laterally equivalent sandstone body, the Woodhouse Rock, at a second site nearby. The field information was combined with borehole log data to interpret sedimentary depositional cycles in a specific stratigraphic interval across a larger area in the sub-surface. The Woodhouse Rock has been traced as a palaeochannel extending as far east as Bawtry. Its characteristics differ from those of the minor sandstones, and raise questions about its origin. An outcrop of the Swallow Wood Coal on the development site has also been conserved as a permanent geological feature.

Status of the exposure

The outcrop visited and recorded is a Local Geological Site (LGS), a term which denotes non-statutory, locally-designated sites of geological interest and value in the UK. Although not protected in law, the designation of a site as an LGS is a material consideration in planning decisions. In 2017 an application to build houses on an area of derelict land in Sheffield (called "Nunnery Junction Triangle"), which includes an LGS, was submitted to the local Council by a developer. The site is within the Pennine Coal Measures Group. A small team of local geo-conservation volunteers forming the Sheffield Area Geology Trust (SAGT) was included in the list of consultees contacted by the planning officer.

The site is a 19th-century railway cutting that was abandoned by British Rail in the 1980s. It forms the northeastern side of a triangular junction area named for its association with the nearby (long-abandoned) Nunnery Colliery. The other two sides of the junction are also cuttings and each side has its own LGS number. The development scheme involves infilling the cutting LGS-G300 with inert, recycled material up to its original ground level. The whole of LGS-G298 and part of LGS-G301 contain live railway lines and are not currently accessible (Fig. 1). The rock exposures along all three sides of the junction, taken together, present a three-dimensional outcrop containing a complete cycle from the Pennine Middle Coal Measures Formation.

Whereas the loss of an LGS is never ideal, the Nunnery Junction site lies on private land and, in common with most Coal Measures surface sites today, it had largely disappeared beneath a cover of turf and shrubby vegetation. SAGT raised no objection to the development scheme for LGS-G300 providing the geological features could be re-exposed, cleaned and recorded by high-resolution photography before any groundworks took place. It was also important that a small part of site LGS-G301 containing an outcrop of the Swallow Wood Coal should be exposed and permanently conserved. These recommendations were accepted by the planning officers, approved, and incorporated as a condition in the decision notice.

Recording of the site

During 2018, the developer assisted SAGT by providing a mechanical excavator (with operator) to remove vegetation, slumped soil and loose rock from the west side of the LGS-G300 cutting over a length of about 250 m. SAGT members followed up with many days of digging out and sweeping clean the rock faces, to prepare them for the photography (Kennett, 2019). These photographs form a permanent record of the site prior to its burial. The length of the outcrop within the narrow cutting imposed constraints on the photography and seven tripod set-ups were required to capture its entire extent as a series of overlapping, digital panoramic photographs.

Each panoramic photograph was created by seamless merging of up to 39 images taken in three rows. After processing, each photograph file is around 300 Mb, enabling zooming-in to show considerable detail in subsequent use on-screen. Prints of the photographs were used for rapid field recording in the limited time available, and when this work was completed, the rock exposures were re-buried under soil by the developer.

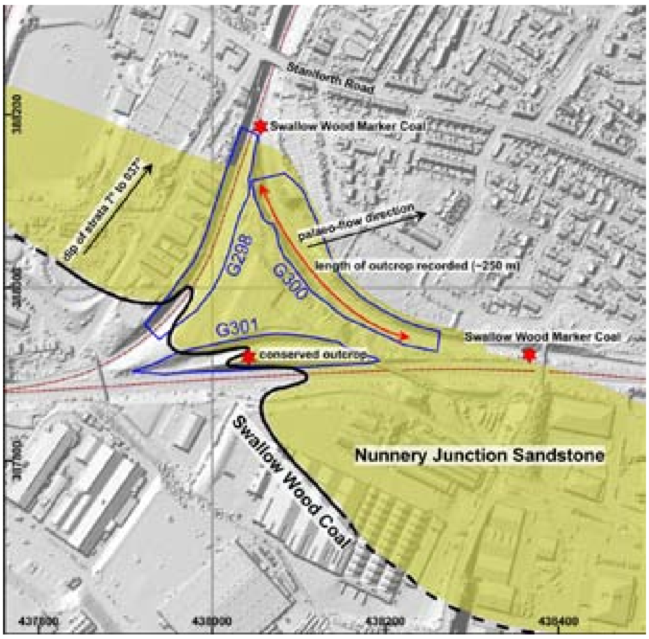


__Figure 1__. Locations of LGS boundaries and principal geological features on a LIDAR base (contains BGS data).

Site location and stratigraphy

The Nunnery Junction site is located in Darnall, a suburb on the eastern side of Sheffield [SK381880]. The railway cuttings expose an outcrop of the Swallow Wood Coal and an overlying clastic sedimentary sequence (Fig. 2). In Derbyshire this seam is called the Second Waterloo Coal. These strata are of Duckmantian age, which is within the Pennsylvanian Subsystemi according to the International Commission on Stratigraphy. On the 1:50,000 British Geological Survey (BGS) map (Sheet 100), the coal outcrop has been traced through Darnall, and the overlying clastic sequence is shown as a thin, unnamed sandstone of limited extent. Southeast of Nunnery Junction, a few kilometres along strike and at the same stratigraphic horizon, the map shows a more prominent sandstone body called the Woodhouse Rock. It thickens to occupy most of the sequence between the Swallow Wood and Barnsley (Top Hard) coal seams (Fig. 3).

The Woodhouse Rock forms a prominent topographic ridge and is exposed in road cuttings and old quarries. In contrast, the Nunnery Junction sandstone forms no distinctive surface features, has no natural exposures and was not quarried. Hence, the Nunnery Junction project in 2018 was a rare opportunity to investigate the characteristics of a minor Coal Measures sandstone unit extending laterally along 250 metres of outcrop. The results of the field work on this small site, however, have greater value when combined with a study of the sequence between the Swallow Wood and Barnsley coals over a wider area, using information from the BGS borehole database. To this end, graphical logs were created using descriptive lithology records from colliery shafts and National Coal Board (NCB) boreholes. Data from 150 shafts and boreholes that penetrate the entire interval (or a part of it) have been converted into a simplified graphical format. This log set currently extends over an area of 480 km^2 (Fig. 3). Although the density of logs is sparse near the outcrop, a reasonable number of high-quality NCB logs, from both surface and underground boreholes, exist from Harworth, Maltby, Dinnington and other collieries.

Previous description and interpretation

The few published descriptions of this specific stratigraphic sequence in the Sheffield area are mainly in older BGS memoirs. The memoir for the exposed Yorkshire Coalfield (Green et al, 1878) contains the earliest detailed account. These authors were able to inspect all of the Nunnery Junction cuttings before public access was restricted and before the outcrops disappeared beneath encroaching vegetation. They also examined the railway cutting at Holmes, near Rotherham, and interviewed managers of nearby collieries. In the Barnsley area however, complicated block faulting caused them to confuse the Haigh Moor Coal with the Swallow Wood Coal.

The early memoirs on the concealed coalfields (Gibson & Wedd, 1913: Gibson, 1913) contain no relevant detail. The correlation errors made by Green et al in 1878 were repeated in the new memoir for Barnsley (Mitchell et al, 1947). The error was acknowledged in a later supplement, but no corrected interpretation was provided. Wilcockson's (1947) contoured isopachyte maps for the Yorkshire Coalfield are too generalised and are plotted using gross sandstone thicknesses.

The geological memoir for Sheffield (Eden et al, 1957), contains an updated summary of the sequence based on the Nunnery Junction outcrops, with some additional data from the few nearby collieries then working. Meanwhile, the memoir for Chesterfield (Smith et al, 1967), gives an expanded description of the sequence in its area, but data gaps near the boundary with the adjacent Sheffield map made the correlation of minor coal seams less certain. The updated memoir for the concealed coalfield in Yorkshire and Nottinghamshire (Edwards, 1951) contains regional maps showing seam splitting lines and coal seam isopachytes, but does not discuss the lithofacies of the siliciclastic sediments.

None of these early publications was able to make use of descriptive lithological logs from coal exploration boreholes drilled in the area by the NCB in the 1970s

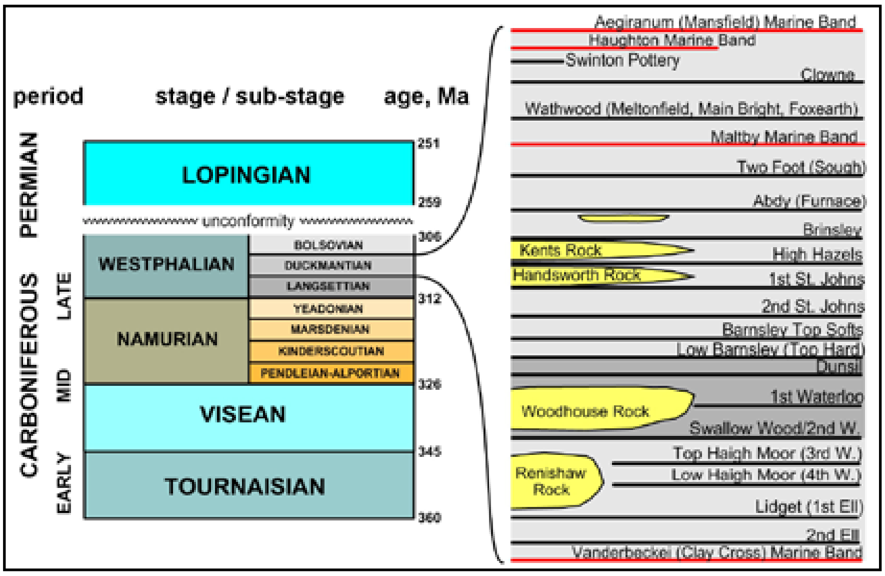
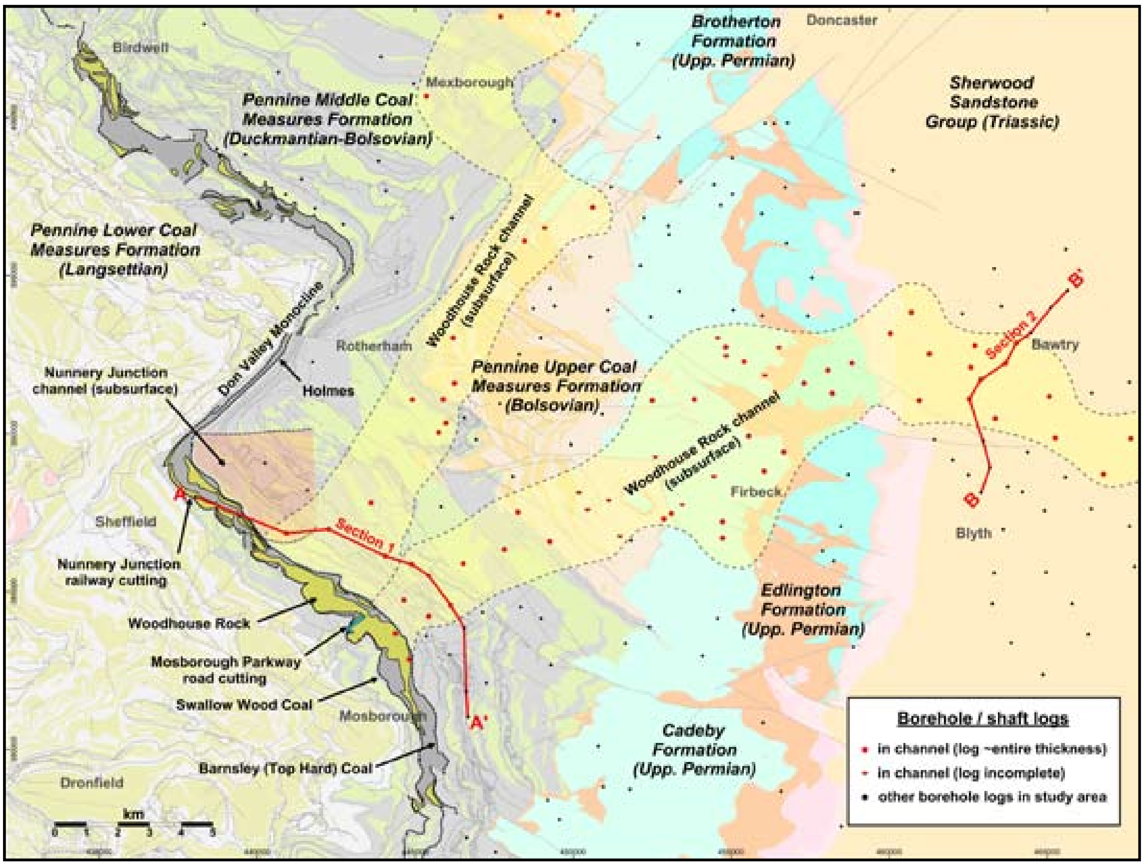


Figure 2. Stratigraphy of the Duckmantian Coal Measures in the Sheffield area, with the sequence at Nunnery Junction shown in the darker grey (after Waters et al, 2009).

Figure 3. Geology of the Sheffield area; outcrops of the beds between the Swallow Wood and Low Barnsley coals are shown in the stronger colours (contains BGS data).



and 1980s. These logs were compiled from wireline geophysical records and recovered rock core. The log descriptions made from the smooth-ground surfaces of drill core are extremely detailed, and they provide better quality information than can be obtained today from weathered outcrops or from fresh but damaged rock faces at active excavation sites.

In more recent literature, general descriptions and interpretation of the Coal Measures of the Pennine Basin are those of Guion et al (1995), Rippon (1996), Aitkenhead et al (2002) and Waters and Davies (2006). Rippon used NCB sub-surface data to plot regional maps showing the distribution and orientation of Westphalian palaeochannels in British coal basins. One of these maps included channels associated with the Swallow Wood Coal between Sheffield and Doncaster, but no other detailed information was provided. An East Midlands 3D block model created by Bailey et al (2002) to investigate fluvial channel interconnectivity for hydrocarbon reservoir simulation included the sequence exposed at Nunnery Junction, but the northern limit of their model lies to the south of the site. Furthermore, the detailed correlations of their digitised borehole data and 3D images of individual stratigraphic surfaces were not included in the published version.

The most recent paper to describe and interpret the relevant sequence describes a site near Denby, in Derbyshire, 60 km to the south (Davies-Vollum et al, 2012). Despite this distance, the stratigraphic data and the accompanying interpretation of facies make that paper the most useful comparative reference.

Figure 4. The newly-cleared outcrop of the Swallow Wood Coal in the southern face of the gully at LGS-G301, with the basal sandstone scour above the coal seam at upper left.

Figure 5. *The basal sandstone scour above the upper leaf of the Swallow Wood Coal at LGS-G301, with slumped mudstone and a vertical cut-bank into the lacustrine mudstone overlying the coal.*

The exposures at Nunnery Junction

The Swallow Wood Coal forms the base of the sequence exposed at Nunnery Junction. Its outcrop crosses two live railway lines in separate cuttings, as well as a small, abandoned gully that previously contained a spur track. It is present as two leaves of coal, separated by a 0.75 m thick dirt band that is a palaeosol, or seatearth, now weathered to a soft, pale grey clay (Fig. 4). The upper leaf is 0.75 m thick and the lower leaf, which is also underlain by a soft, clayey seatearth, is 0.3 m thick. The Swallow Wood Coal was worked underground in several nearby collieries, as late as the 1980s, but only where the dirt band was thin enough for the two leaves to be mined as a single seam. Eden et al (1957) noted that the ash content of Swallow Wood Coal ranged from 2.3% to 14.2%, but did not describe any spatial variation.

A section of the coal outcrop within the gully (LGS-G301), some 20 m in length, has been cleared of its soil cover and will be preserved as a permanent geological feature within a small conservation area, which also includes a biodiversity component. This is the only undisturbed, visible surface outcrop of an economically-worked coal seam in the South Yorkshire Coalfield, and it will be fenced off with restricted access at the edge of the housing development.

The upper and lower contacts of both leaves of coal are sharp and planar. The upper leaf is overlain by a pale-grey lacustrine mudstone containing a few thin beds of small clay-ironstone nodules associated with scattered freshwater shelly fossils (*Anthracosia* and *Carbonicola* spp.). Weathering has degraded the mudstone, and no other obvious fossil species have been found so far. On the left (eastern) side of the

Figure 6. *Panoramic photograph number 5, of the sandstone channel at Nunnery Junction over a cutting length of about 50 m; the interpreted overlay shows internal structural details, and orange-coloured shapes that mark sideritic nodules (photo: Phil Wolstenholme, Sheffield Area Geology Trust).*

***Figure** 7. Fine-grained, silty sandstone with thin laminations and current-bedding structures emphasised by micaceous-carbonaceous partings; coin diameter is 23 mm.*

cleaned outcrop, the mudstone has been eroded by a deep basal scour belonging to the overlying sandstone unit. The side of the scour is vertical and represents a sharp, fluvially-cut bank (Fig. 5). Some slumped mudstone mixed with sand occurs at the base of the scour, which rests on top of the coal. There is no basal conglomerate and the sandstone immediately above the slump zone has regular, thin, planar bedding.

On the north side of the River Don valley, the mudstone roof measures above the Swallow Wood Coal contained sufficient beds of ironstone nodules to have justified underground mining to supply local blast furnaces in the 19th century. This occurred at Greasbrough and at Skiers Spring, near Elsecar. In the Nunnery Junction area, any high-grade ironstone that may have been present was probably eroded by the local sandstone channel.

When LGS-G300 existed as a railway cutting, it exposed a cross-section through the sandstone unit, oriented parallel to strike. The western side of this long outcrop was cleared and recorded by SAGT on panoramic photographs, one of which forms Figure 6. The other six photographs show broadly similar features. The basal contact of the sandstone was not revealed in the cutting, but site investigation boreholes drilled by a contractor showed that the coal seam closely underlies the sandstone throughout the triangular junction area and the strata dip at 7° towards 037°. The same

***Figure** 8. Climbing ripple-drift lamination revealed on an etched joint surface.*

Figure 9. An example of a layer of siderite concretions within a siltier zone above a sandstone bed.

borehole data showed that the maximum thickness of the sandstone unit is around 13 metres.

The sandstone body consists of multiple, stacked bed-sets each up to a metre thick, which commonly have a steeper inclination than the dip of the unit as a whole (as determined from the site investigation boreholes). Some individual beds are noticeably lens-shaped in cross-section, with sharply-converging lateral terminations. The lithology is a fine-grained, silty sandstone that grades repeatedly into interbedded zones or layers of siltstone. Fresh rock surfaces are pale grey in colour, but most of the outcrop has weathered to a pale buff. During the original excavation of the cutting, the more massive sandstone beds mostly broke apart along joints, leaving clean, near-vertical rock faces, but the siltier zones have a fractured, rubbly surface.

The lower bounding surfaces between separate beds include truncated bedding and erosive scours. There is also evidence of non-erosional, accretionary deposition with preserved dune bedforms. Much of the sandstone is finely laminated, emphasised by micaceous-carbonaceous partings (Fig. 7). Trough cross-bedding, planar bedding and climbing ripple lamination (Fig. 8) are present throughout the exposed cross-section. The entire sandstone body has the characteristics of a fluvial channel formed from coalesced, accreting sand

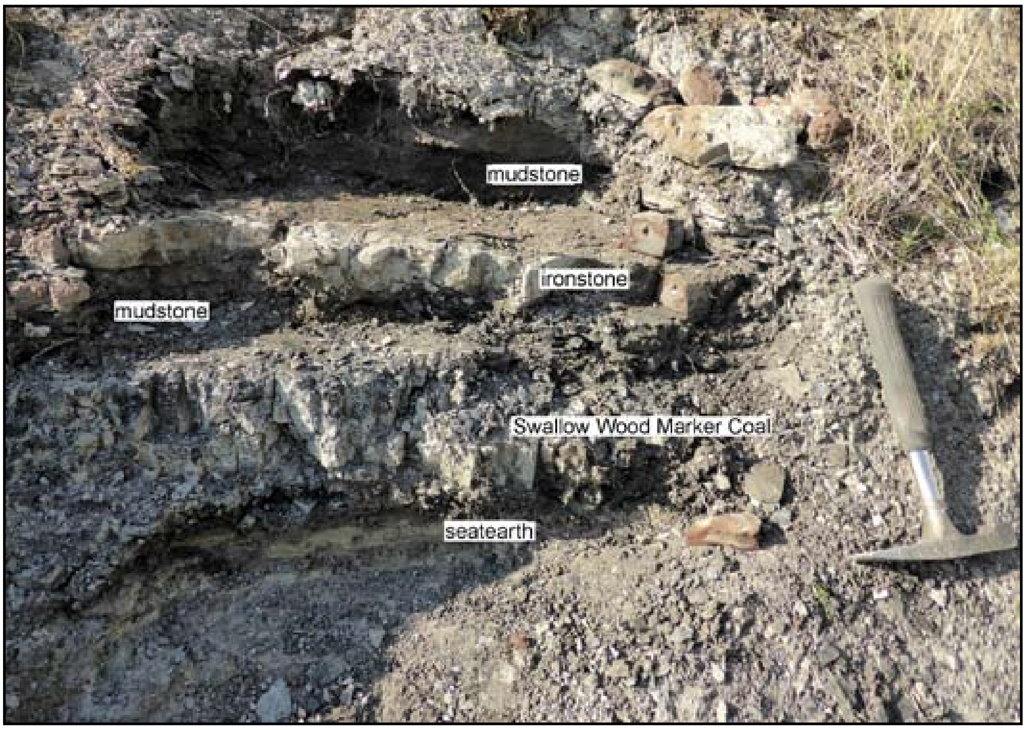


Figure 10. An exposure of the Swallow Wood Marker Coal and associated facies excavated at the northern end of the Nunnery Junction site.

bars, deposited from pulses of sediment transported by variable river currents. The width of the channel, as indicated by its outcrop extent, is around 3 km.

More than 40 palaeo-flow-indicating measurements were made, on bedding surfaces, foresets, scours and dune crests. These gave a spread of azimuths ranging from north to southeast, but with a principal flow direction towards the northeast and east, consistent with the 'western transport system' (Mid-Langsettian to Late Duckmantian) of Chisholm and Hallsworth (2005). Joint surfaces were also measured, but the structural data do not form part of this stratigraphic study.

Multiple, thin, discontinuous beds of sideritic concretions with flattened ovoid shapes are a distinctive feature of the LGS-G300 sandstone (Figs 6 and 9). Called 'galliard' or 'cank' balls in historic shaft logs, they formed diagenetically in unconsolidated sediment and contain admixed silt and clay with a massive, structureless texture. Their typical occurrence in silty zones between sandier beds suggests formation by chemical reactions taking place along a shallow redox-pH interface in pore-water within riverbed sediment during pauses in deposition. As further sediment accumulated, the pore-water interface migrated upwards in stages through the riverbed, keeping pace with deposition and producing additional concretionary zones at intervals throughout the sandstone body. Mineralogically, the concretions are probably very similar in composition to the ironstone nodules in the lacustrine mudstone facies, but with a lower iron content and no syneresis cracks. Laminations in the host siltstone are usually draped over the concretions. Rare, isolated, small concretions in sandstone beds may be reworked clasts.

No obvious upper surface to the sandstone body could be found, but two small exposures of an overlying thin coal called the Swallow Wood (or Waterloo) Marker Coal, were excavated at either end of the LGS-G300 cutting, along with its clayey seatearth and overlying lacustrine mudstone containing ironstone concretions (Fig. 10). The coal cleat (its pervasive joint set) has a mineral coating that soon oxidises when exposed to air. This seam can be recognised on borehole logs throughout the area, never increasing much in thickness, and was also recorded at the Denby site (Davies-Vollum et al, 2012).

The Woodhouse Rock

Continuous outcrops of this sandstone body form both sides of the impressive Mosborough Parkway (A57) road cutting at Beighton (LGS-G517, at SK431840), even though the views are now largely screened by self-seeded shrubs and trees. Nevertheless, the Woodhouse Rock shows a very different character to the Nunnery Junction sandstone. A stacked, multi-story, accretionary sand channel, it lacks the siltstone component, is more massive and cemented, and occurs in thicker beds. The fine laminations with micaceous-carbonaceous partings are absent, as are zones of climbing ripples. It displays prominent planar, and locally trough cross-bedding, with planar erosional surfaces (Fig. 11). One example of preserved current ripples was found on an internal bedding surface, showing a paleo-flow direction of 040°. There are fewer sideritic concretions and some appear to be post-diagenetic, as they are aligned parallel to joints.

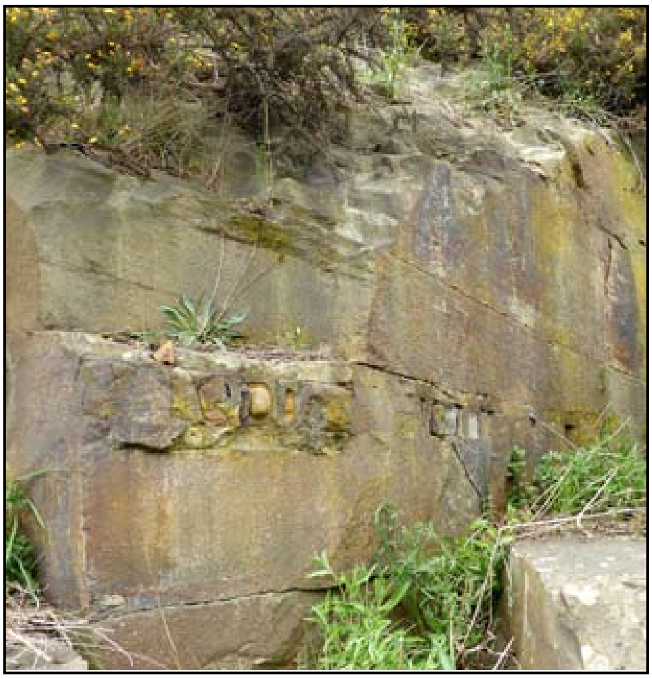


***Figure 11**. Planar cross-bedding in massive sandstone that is part of the Woodhouse Rock, exposed next to the Mosborough Parkway, at Beighton.*

Duckmantian cycles near Sheffield

The stratigraphy of the sequence between the Swallow Wood and Barnsley Coals shown in Figure 3 is illustrated by two borehole-correlated cross-sections, both extending down to the Lidget Coal (Figs 12 and 13). In the Sheffield area, a sedimentary cycle usually begins with up to several metres of laminated, lacustrine mudstone that directly overlies the coal seam at the top of the previous cycle. This facies represents a widespread freshwater flooding event that drowned the living lycophyte mire or swamp forest and its accumulated peat substrate. The sharp contact between the resulting coal and its overlying mudstone implies that the submerged forest plants quickly decayed and collapsed into a vegetable ooze on the bed of a lake, soon covered by settling mud.

The first few centimetres of mudstone immediately overlying the drowned peat are usually dark and carbonaceous, but the succeeding paler-grey mudstones are commonly characterised by fossil bivalve shells, and also the tube-worm *Spirorbis*, concentrated in relatively thin 'mussel beds'. The shelly fossils, and scattered remains of freshwater fish, provide evidence for clear-water conditions. However, the preservation of bivalves in multiple discrete beds suggests intermittent mass-dying events, possibly by smothering from sudden influxes of muddy water or suffocation by anoxic conditions. Soon after burial, redox and pH gradients generated by

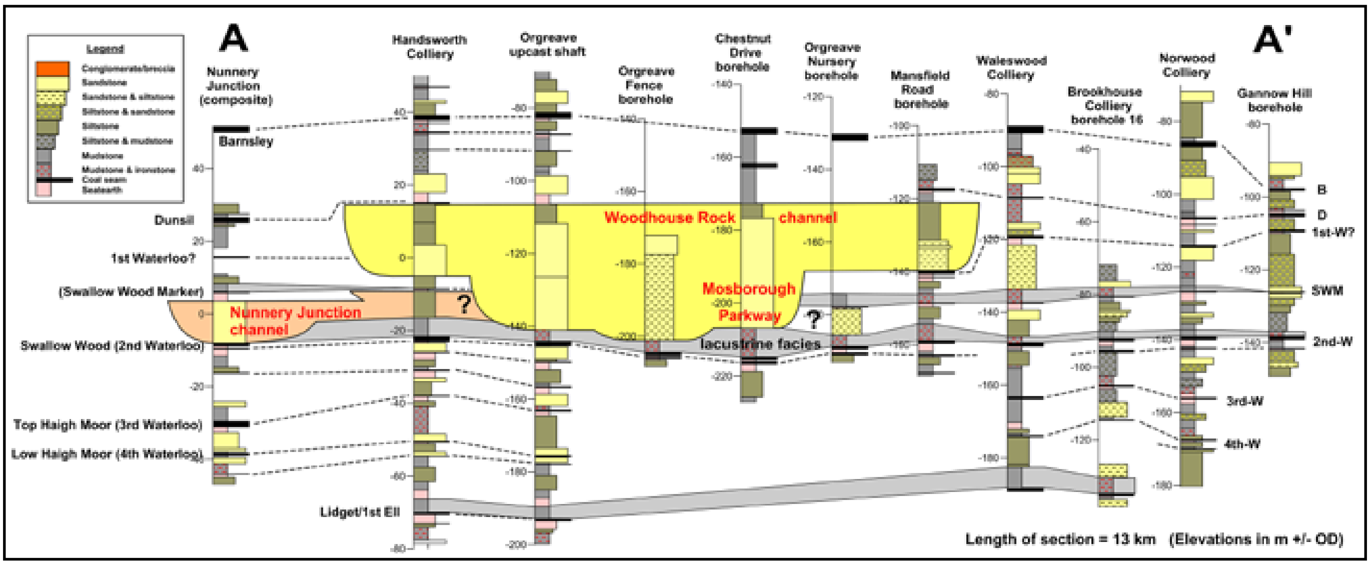


Figure 12. Correlated borehole and shaft log cross-section A-A', located on Figure 3.

the decaying organic matter in the soft, wet sediment became sites of chemical reaction with pore waters. Dissolved iron was deposited as nodular concretions and as thin, discontinuous layers of sideritic, clay-ironstone. Ironstone nodules also precipitated around decaying plant fragments and some developed as flattened, pillow-shaped masses or semi-continuous beds that show no evidence of nucleation around any organic remains.

The upper part of each cycle normally displays evidence of a change from a quiescent lacustrine environment to conditions of higher-energy sediment transport. It generally consists of either a coarsening or fining-upward sequence of mudstones, siltstones and fine-grained sandstones, culminating in the formation of the next coal seam, above a palaeosol. These packages of coarser clastic sediments can display characteristics of either lacustrine-deltaic or fluvial channel-floodplain deposition. They indicate a relative lowering of surface water depth and a return to swampy conditions, enabling dense, peat-forming forests to become re-established. Many of the erosive bases of sand-filled fluvial channels cut deeply into the underlying lacustrine mudstone, with some extending down to the peat layer at the base. Ironstone nodules liberated from the eroded mudstone were concentrated as clasts in basal channel conglomerates.

Where they have not been eroded, the vertically repeated lacustrine mudstone facies (with ironstone nodules and bivalve fossils) directly overlying coal seams are readily identifiable in the lithology logs and are correlatable between most of the boreholes (Figs 12 and 13). However, the depositional environment of the coarser sediment packages occupying the upper parts of the cycles cannot be so easily defined. Determining from these borehole logs whether a sediment package within the upper part of a cycle is of fluvial or distributary channel or crevasse splay origin is subjective, and such interpretations cannot be mapped between adjacent boreholes with any certainty. An exception is the fluvial channel now known to exist at Nunnery Junction. The log for Nunnery Junction (Fig. 12) was compiled from surface measurements made at three separate localities (Eden et al, 1957, p.208). Compaction draping and variations in thickness of individual cycles can indicate the positions of some channel axes, as shown by the sediment package in the Serlby borehole above the Lidget Coal (Fig. 13).

The typical lithological descriptions recorded on the NCB borehole logs for the coarser clastic sediment packages within sequences are: repetitive, gradational intercalations of muddy siltstone, siltstone with thin fine-grained sandy beds and fine-grained sandstone with thin silty beds. This is a continuum of oscillating deposition within a limited grain-size range. Micaceous-carbonaceous laminations and a variety of sedimentary structures are also common. This general description can also be applied to the Nunnery Junction sandstone, which can be regarded as a representative example of the fluvial clastic facies in the upper sections of a single cycle.

A succession of four sedimentary cycles from the Third Waterloo (Top Haigh Moor) Coal to the Bottom First Waterloo Coal, which are part of the sequence shown in Figures 12 and 13, was recorded at the Denby site (Davies-Vollum et al, 2012). At that locality, each cycle also begins with a lacustrine mudstone facies, but the subsequent coarsening-upwards sequences of clastic sediments have been identified by those authors as accretionary lacustrine-deltaic deposits with distributary channels. There is no evidence of deep, fluvial erosion at that site, although the investigation area was limited to about a square kilometre.

The contrasting character of the Woodhouse Rock is also evident on Figures 12 and 13. Lithology logs from boreholes intersecting this sandstone describe a thick zone comprised predominantly of sandstone, commonly with conglomeratic or 'pseudo-breccia' zones (i.e. large clasts of siltstone with disturbed sandstone laminae) and prominent cross-bedding. The

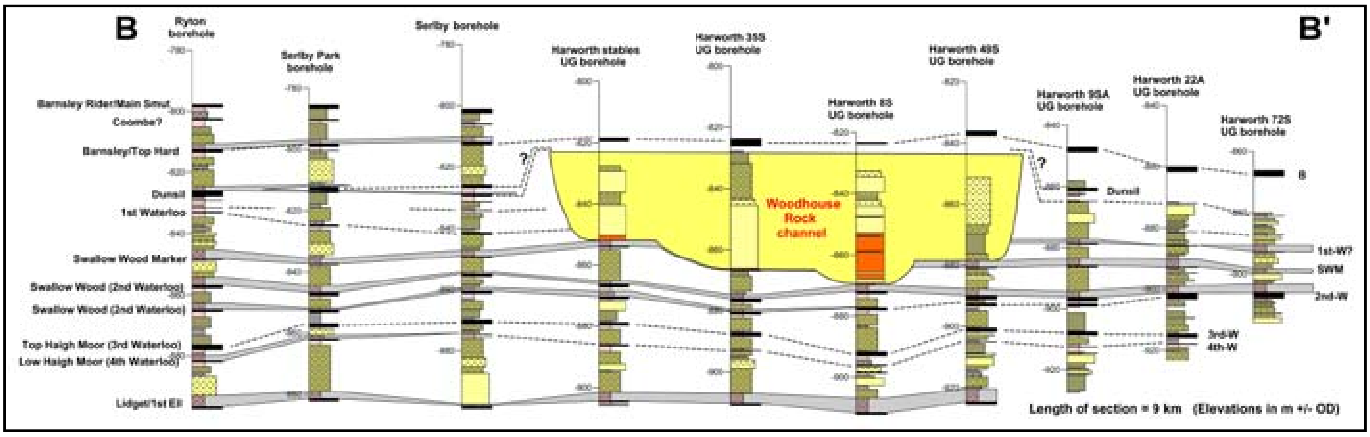


***Figure 13**. Correlated borehole and shaft log cross-section B-B', located on Figure 3.*

higher sections of this unit become siltier, and defining its upper boundary is therefore a matter of conjecture. At its maximum thickness, the Woodhouse Rock is equivalent to two complete cycles (Swallow Wood Marker to First Waterloo, and First Waterloo to Dunsil) and also the majority of a third cycle (Swallow Wood to Swallow Wood Marker).

One possible interpretation is that the deposition of the Woodhouse Rock channel was contemporaneous with its laterally-equivalent strata, inviting comparison with the Silkstone Rock (Guion et al, 1995). Convincing evidence for gradational intercalation is not obvious, however, and the channel can also be interpreted as truncating multiple intervals of lacustrine facies and associated coal seams, having formed as a single, higher-energy erosional-depositional event. It is the latter interpretation, as an infilled, incised valley, that is presented on Figures 12 and 13. It is unfortunate that many of the boreholes drilled through the Woodhouse Rock from colliery workings at the Barnsley Coal horizon did not include a cored section through the Dunsil Coal zone. Depending upon the identification of coal seams in some of the logs, the Dunsil Coal appears to drape over the top of the channel in some cross-sections, while in others it could be interpreted as truncated.

The edges of the sinuous sub-surface Woodhouse Rock channel can be clearly defined in plan-view using borehole and shaft logs (Fig. 3). It came as a surprise, however, to discover that the outcrop of the Woodhouse Rock consists of two such channels in close proximity, which diverge and follow separate directions. It is possible that both channels were contemporaneous and formed part of a distributive network, comparable with the distributaries of, for instance, the Mississippi delta plain. Alternatively, they may not have been contemporaneous with each other, even though they both occur within the same stratigraphic interval. The quality of the available data is insufficient to determine how these channels formed. The width of the southernmost channel averages 3–4 km and is comparable to that of the Silkstone Rock channel in the Worksop area. The minor channel at Nunnery Junction cannot be mapped in the sub-surface using the borehole data.

Westphalian sedimentation

During the Westphalian Stage, the regional depositional environment within the Pennine Basin is interpreted as an extensive, lowland delta plain in palaeo-equatorial latitudes (Aitkenhead et al, 2002; Waters et al, 2009). The basin was prone to frequent flooding, and as fluvio-deltaic drainage systems advanced across the plain, infilling large lakes, semi-emergent land surfaces were colonised by dense lycophyte forests. The proximity of the present-day coalfield area to a contemporary coastline is unknown and, according to the palaeogeographic map for the Pennsylvanian on R. C. Blakey's website (www.deeptimemaps, accessed July 2019), the distance between the Pennine Basin and the open sea could have exceeded 1000 km. Nevertheless, its low elevation made it vulnerable to widespread, eustatically-driven marine transgressions.

Flooding events were the beginnings of new accretionary sedimentation cycles in the basin. Most of these inundations were freshwater, but the intermittent and widespread saltwater incursions that were common in the Pennine Basin during the Upper Namurian also continued into the Westphalian. The latter events deposited thin layers of dark, muddy sediment, often containing marine ammonoid fossils. Marine bands in the Pennine Basin can be correlated with those identified in Westphalian basins in other European countries, confirming that global sea level fluctuation, rather than local basinal subsidence, was the most likely cause. Specific marine bands are used to define chronostratigraphic divisions within the Westphalian of the Pennine Basin.

Most marine bands are overlain by paler, lacustrine mudstone, indicating that the basin remained flooded but that the saline water was displaced by inflowing freshwater carrying suspended sediment. Less-frequent 'Estheria bands' are considered to indicate temporary conditions of diluted salinity resulting from minor marine incursions. Some coal seams in the Yorkshire and Nottinghamshire Coalfield, such as the Parkgate Coal, have an elevated sulphur content, even when not directly overlain by a marine band

(Spears, 2015). This observation was used to suggest that the coastline may have been closer than Blakey's palaeogeographic map implies, and that seawater may still have infiltrated the drainage system in the absence of a major marine transgression.

In the Sheffield area, the coarser siliciclastic sediment overlying non-marine, lacustrine mudstone within a depositional cycle probably represents the infilling of lakes by prograding, fluvio-deltaic systems. The decline in water depths caused by infilling enabled vegetation to become re-established on floodplains, as indicated by preserved palaeosols, discontinuous thin coals and plant impressions in silty-mudstone. However, the development of laterally-extensive, coal-forming mires or peat swamps appears to have required specific environmental conditions. They were not confined to narrow, diachronous belts associated with continuous delta progradation, but only became established when ideal growing conditions existed across the region. A primary requirement was a stable, waterlogged land surface with optimum rates of subsidence. Temporary climatic changes, such as increased humidity, rainfall and pCO_2, may have also been important factors.

Undecayed dead vegetation accumulated on the floor of the mire or swamp in areas of stagnant shallow water, forming a layer of peat. Roots penetrating beneath the peat layer destroyed bedding lamination in the underlying sediment, while pore-water containing humic compounds leached alkali elements from its mineral component, creating pot-clay and ganister-type seatearths. Coal seams are typically composite and banded and vary in thickness from only a few centimetres up to 2–3 m (in the East Pennine Coalfield). The Duckmantian was a period of maximum species diversity for arborescent lycophytes and other related plant groups in the Pennine Basin (Cleal, 2005). The peak of plant species diversity coincided with the formation of the thick, high-quality Barnsley Coal peat layer and declined thereafter. Even though coal-forming peat layers originated from lycophyte forests, fossilised in-situ lycophyte stumps are not commonly found inside coal seams. Stumps, toppled trunks and whole stigmarian root systems were more likely to be preserved as fossil casts in the sediments enclosing the coal seams, in situations of rapid burial in sandy crevasse channels or during sudden riverbank collapse.

Slow-flowing surface water courses with limited sediment load meandered through the peat swamps in shallow creeks. The banks of the creeks were defined by strongly-anchored vegetation, and also possibly by levees (overbank deposits), although specific evidence for the latter cannot be demonstrated from the data reviewed for this study. Muddy creek beds and lake floor deposits eventually became the dirt bands that split coal seams into multiple leaves. The rate of peat accumulation kept pace with the deposition of mud and silt in these channels, but after burial and compaction, the greater compression of peat into coal caused it to drape around the dirt bands. Regionally-extensive dirt bands were probably the consequence of deposition in larger lakes that formed after occasional, limited floods, or possibly because of local subsidence.

In sequence stratigraphy terminology, the multiple marine bands are condensed sections that represent transgressive systems tracts and maximum flooding surfaces, i.e. the consequence of global glacioeustatic sea-level rises (Catuneanu et al, 2011). Falling relative sea levels resulted in forced regression, with sub-aerial erosion, rejuvenation of rivers and sediment bypass of coastal plains. Valleys were incised into previous sedimentary layers during sea level lowstands and, as sea levels began to rise again, these valleys were infilled with landward-aggrading fluvial sands. Several Namurian sandstone bodies in the Pennine Basin have been interpreted as incised valley fills driven by glacio-eustacy, although the possibility of local tectonic-forcing of the erosive phase cannot always be eliminated (Hampson et al, 1999).

In the Westphalian, the Crawshaw Sandstone, of early Langsettian age, has also been interpreted as a large-scale, sand-filled, incised valley, but unequivocal evidence for incised valley fills in the remainder of the Langsettian is more difficult to confirm. Mid-Langsettian to Bolsovian fluvial systems are typically narrower, thinner and have less erosive depth (Rippon, 1996). The deepest erosional down-cuttings by fluvial sand-bodies observed by Rippon in underground colliery workings was usually no greater than 5 m, locally reaching 8 m. Interfluve palaeosols showing clear evidence of deep weathering and oxidation of elevated ground have not been recognised where they might be expected to occur. Colliery workings, however, were restricted to practically-exploitable limits within economically recoverable seams, therefore, data derived from underground workings might not be entirely representative of a more complete stratigraphic sequence.

It has been proposed that some Westphalian, large-scale, multi-storey sand-bodies, particularly the Silkstone Rock (Langsettian age), exhibit a gradational facies relationship with laterally equivalent strata (Guion et al, 1995). These authors mapped a systematic variation in the percentage ash (non-organic material) content of the Threequarters Coal in borehole samples on the southern side of the Silkstone Rock channel. The ash content data, in combination with subsurface mapping in mine workings and stratigraphic interpretation of borehole logs, were presented as evidence for contemporaneous deposition by an aggrading channel system. Despite the large dimensions of the outcrop of this sand-body however, surface exposures of the Silkstone Rock are very limited, and no visible examples proving these critical lateral relationships are currently known.

In the Duckmantian and Bolsovian, Waters and Condon (2012) have suggested that local marine band erosion beneath four other multi-storey sand-bodies (the Thornhill, Woolley Edge, Oaks and Mexborough Rocks) may indicate that some valley incision and infilling has occurred. The Woodhouse Rock at Beighton has not eroded through a marine band, but if its formation involved incision and infilling, the depth of incision could be as much as 30 m, depending how its upper surface is defined. There were no underground mine workings in this sequence in the Sheffield area and analytical data from coal seams are unlikely to exist. The NCB exploration boreholes will probably be the only data source available for further studies, even though stratigraphic correlations between some boreholes involve uncertainty.

Intermixed within the Westphalian marine-band cyclicity are the common, higher-frequency, sedimentary cycles involving repetitive deposition of lacustrine and fluvio-deltaic clastics, culminating with a coal seam. A satisfactory explanation for this pattern of sedimentation in the Pennine Basin has not yet been demonstrated unequivocally. The remoteness of the Westphalian Pennine Basin from the open sea makes the control of coal-bearing cycles solely by transgressive-regressive marine influence difficult to demonstrate. Other suggested causes of these higher-frequency cycles have included avulsion of fluvial systems (delta-switching), basinal subsidence and sediment compaction.

An increasingly favoured model to explain Westphalian cyclicity is the variation in the Earth's orbit resulting from gravitational interaction with other planets in the solar system (Milankovitch Cycles). The Earth's climate was affected by these orbital variations, causing expansion and contraction of polar ice masses, particularly when the Gondwanan continent extended to the South Pole. Long- and short-duration orbital eccentricity, ranging between 413 ka and 112 ka respectively, has been evaluated as a potential forcing mechanism for marine flooding events within the Namurian and Westphalian of the Pennine Basin (Waters and Condon, 2012). Unfortunately, the current lack of reliable Westphalian age date determinations prevents a precise correlation between marine bands and known Gondwanan climatic events.

Higher-frequency, limited-amplitude orbital variations are associated with obliquity of the Earth's tilt (~21–17 ka cycles) and precession (wobble) of its axis (~34 ka cycles). These variations have been proposed as potential drivers of high-frequency, arid-humid climatic fluctuations, independent of sea level changes, and such millennial-scale climate fluctuations may have influenced bedding sequences in the Mid-Carboniferous succession of Northern England (Tucker et al, 2009). The concept of orbitally-forced climatic rhythms has also been proposed as a potential driver of regional, peat-forming, vegetation growth events for the Pennsylvanian-age coalfields of the eastern United States (DiMichele et al, 2010). Whether Westphalian non-marine, coal-bearing sedimentary cycles in the Pennine Basin can be ascribed to climate rhythms is a hypothesis that has yet to be investigated.

Conclusions

The project undertaken by SAGT at Nunnery Junction in 2018 to record and partially conserve the geological interest at the site prior to development was a rare opportunity. It was also an exemplar of collaboration between a site developer, a planning authority and a local, specialised volunteer group, working together for a worthy geo-conservation goal. The availability of the BGS borehole database enabled a synthesis of both surface and subsurface data to be extended over a wider area. Detailed study of the latter has emphasised the cyclicity of Westphalian sedimentary deposition.

The rocks exposed are predominantly sandstones and lie between the Swallow Wood and Swallow Wood Marker Coals within the Pennine Middle Coal Measures and are of Duckmantian (Westphalian) age. Both of the coal seams were also exposed, and a section of the Swallow Wood Coal has been cleaned and will be conserved for future appreciation. The sandstone body is interpreted as a channel, the 'Nunnery Junction Channel', deposited by fluvial currents flowing predominantly towards the northeast and east. Outcrops of a more substantial sand body at an equivalent stratigraphic horizon, the Woodhouse Rock, occur to the southeast of Nunnery Junction. The relationship between the Nunnery Junction Channel, the Woodhouse Rock and surrounding strata was investigated with cross sections produced using data from NCB shaft sections and boreholes. The subsurface data revealed that the Woodhouse Rock consists of two separate belts of channel sandstones that appear to diverge towards the northeast.

Despite the abundance of available data, it has not been possible to establish whether the channels were contemporaneous with each other and also with the laterally-equivalent strata, or whether they cut downwards, eroding at least two cycles. Conversion of additional descriptive borehole logs into graphic logs could help to increase the mapped extent and understanding of the Woodhouse Rock channels over a wider area in the sub-surface, although confirmation of lateral relationships cannot be guaranteed. Studies of this type, combining outcrop investigation with exploitation of the BGS borehole database, can contribute towards further understanding of Westphalian cyclic sedimentation in the East Pennine Basin.

Acknowledgements

The author is grateful to his colleagues in SAGT, and also to other volunteer associates, who contributed their time (and sweat) to complete this project, particularly Peter Kennett, John Cripps, Rick Ramsdale, Duncan McLean, Paul Rogers, David Turner and Pete York. Some of these individuals also reviewed an early draft of this paper. Phil Wolstenholme provided the photographic expertise, while Paul Guion kindly offered advice during a visit to the site and provided helpful comments on the draft text. The Planning Service at Sheffield City Council is thanked for appreciating the geological value of Nunnery Junction and Richard Lord and Julian Winter of Silkstone Environmental Ltd are thanked for their respective roles in managing SAGT's input towards discharging the planning condition. SAGT is particularly grateful to the developer, MHH Contracting Ltd, including the supervisor, Peter Westley, who tolerated our requests to expose an ever-increasing length of rock outcrop, and John Whyke, whose enthusiastic and expert operation of the excavator helped to reveal the maximum amount of geological interest in undamaged condition.

References

Aitkenhead, N. and 6 others, 2002. *British regional geology: the Pennines and adjacent areas*. British Geological Survey: Nottingham.

Bailey, W. R. and 8 others, 2002. The effect of faults on the 3D connectivity of reservoir bodies: a case study from the East Pennine Coalfield, UK. *Petroleum Geoscience,* **8**, 263–277.

Catuneanu, O. and 6 others, 2011. Sequence stratigraphy: methodology and nomenclature. *Newsletters Stratigraphy*, **44** (3), 173–245.

Chisholm, J. I. & Hallsworth, C. R., 2005. Provenance of Upper Carboniferous sandstones in east Derbyshire: role of the Wales-Brabant High. *Proc. Yorks. Geol. Soc.*, **55**, 209–233.

Cleal, C. J., 2005. The Westphalian macrofloral record from the cratonic central Pennines Basin, UK. *Zeitschrift Deutschen Gesellschaft Geowissenschaften*, **156**, 387–401.

Davies-Vollum, K. S., Guion, P. D., Satterfield, D. A. & Suthren, R. J., 2012. Lacustrine delta deposits and their effects on coal mining in a surface mine in Derbyshire, England. *Int. J. Coal Geology*, **102**, 52–74.

DiMichele, W. A., Cecil, C. B., Montañez, I. P. & Falcon-Lang, H. J., 2010. Cyclic changes in Pennsylvanian paleoclimate and effects on floristic dynamics in tropical Pangaea. *Int. J. Coal Geology*, **83**, 329-344.

Eden, R. A., Stevenson, I. P. & Edwards, W., 1957. Geology of the country around Sheffield. *Mem. Geol. Surv. G.B.,* Sheet 100.

Edwards, W., 1951. The concealed coalfield of Yorkshire and Nottinghamshire. *Mem. Geol. Surv*.

Gibson, W., 1913. The concealed coalfield of Yorkshire and Nottinghamshire. *Mem. Geol. Surv*.

Gibson, W. & Wedd, C. B., 1913. The geology of the northern part of the Derbyshire Coalfield and bordering tracts. *Mem. Geol. Surv*.

Green, A. H. and 6 others, 1878. The geology of the Yorkshire Coalfield. *Mem. Geol. Surv*.

Guion, P. D., Fulton, I. M. & Jones, N. S., 1995. Sedimentary facies of the coal-bearing Westphalian A and B north of the Wales-Brabant High. Geol. Soc. Spec. Publ., **82**, 45–78.

Guion, P. D., Banks, N. L. & Ripon, J. H., 1995. The Silkstone Rock (Westphalian A) from the east Pennines, England: implications for sand body geometry. *J. Geol. Soc.*, **152**, 819–832.

Hampson, G. J., Davies, S. J., Elliott, T., Flint, S. S. & Stollenhofen, H., 1999. Incised valley fill sandstone bodies in Upper Carboniferous fluvio-deltaic strata: recognition and reservoir characterization of Southern North Sea analogues. In: Fleet, A. J. & Boldy, S. A .R. (eds), *Petroleum Geology of Northwest Europe: Proc. 5th Conference*. Geological Society: London, 771–788.

Kennett, P., 2019. Recording the Nunnery Triangle. *Earth Heritage*, **51**, 29–30.

Mitchell, G. H. and 4 others, 1947. Geology of the country around Barnsley. *Mem. Geol. Surv. G.B.,* Sheet 87.

Rippon, J. H., 1996. Sand body orientation, palaeoslope analysis and basin-fill implications in the Westphalian A-C of Great Britain. *J. Geol. Soc.*, **153**, 881–900.

Smith, E. G. and 6 others, 1967. Geology of the country around Chesterfield, Matlock and Mansfield. *Mem. Geol. Surv. G.B.,* Sheet 112.

Spears, D. A., 2015. The geochemistry and mineralogy of high-S coals, with examples mainly from the East Pennines Coalfield in Yorkshire and Nottinghamshire, UK: an overview. *Proc. Yorks. Geol. Soc.*, **60**, 204–226.

Tucker, M. E., Gallagher, J. & Leng, M. J., 2009. Are beds in shelf carbonates millennial-scale cycles? An example from the mid-Carboniferous of northern England. *Sedimentary Geology*, **214**, 19–34.

Waters, C. N. & Condon, D. J., 2012. Nature and timing of Late Mississippian to Mid Pennsylvanian glacio-eustatic sea-level changes of the Pennine Basin, UK. *J. Geol. Soc.*, **169**, 37–51.

Waters, C. N. & Davies, S. J., 2006. Carboniferous: extensional basins, advancing deltas and coal swamps. In: Brenchley, P. J. & Rawson, P. F. (eds), *The geology of England and Wales*, Geological Society: London, 173–223.

Waters, C. N., Waters, R. A., Barclay, W. J. & Davies, J. R., 2009. A lithostratigraphical framework for the Carboniferous successions of southern Great Britain (Onshore). *Brit. Geol. Surv. Research Report*, RR/09/01.

Wilcockson, W. H., 1947. Some variations in the coal measures of Yorkshire. *Proc. Yorks. Geol. Soc.*, **27**, 58–81.

John Hunter
miner@aditlevel.co.uk
Sheffield Area Geology Trust,
c/o Department of Civil and Structural Engineering,
University of Sheffield, S1 3JD