The Rotherham Red Rock: an example of Permian, structurally controlled, deep secondary oxidation

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Abstract: The Rotherham Red Rock forms a distinctive and localized area of secondary oxidation within the Mexborough Rock, a fluvial sandstone within the Pennine Middle Coal Measures Formation in the East Pennine Coalfield. Oxidizing meteoric water percolated downwards through a set of closely-spaced faults during a period of post-Variscan, early-Permian weathering and erosion. A plume-like area of reddened sandstone, partly visible at outcrop and partly recorded at depth on borehole logs, delineates a palaeo-groundwater flow-path as it followed the main fluvial channel axis down-dip, enclosed within unaltered strata.

The Mexborough Rock is a composite, major channel sandstone body of regional extent in the East Pennine Coalfield belonging to the Pennine Middle Coal Measures Formation, of Bolsovian age (Aitken *et al*, 1999; Waters *et al*, 2009). Its surface outcrop in South Yorkshire exceeds 50 km in length (Fig. 2), while in the sub-surface it has been delineated by colliery shafts and boreholes over a wide area underlying parts of South Yorkshire, North Derbyshire, Nottinghamshire and Lincolnshire. Its thickest development occurs close to its surface outcrop in the Rotherham area, where it forms the prominent high ground upon which part of the town is situated, as well as other linear landscape features in the surrounding countryside.

In most respects the Mexborough Rock resembles other Middle to Upper Carboniferous channel-fill sandstone bodies, except for the southern third of its surface outcrop, i.e. from Rotherham to Harthill, which has a distinctive red colour caused by alteration of iron hydroxide grain coatings to hematite. This section has long been called the 'Rotherham Red Rock'.

Several Regionally Important Geological Sites are located along the outcrop of the Mexborough Rock. Most of these are old stone quarries, notably the 19th Century quarried rock face forming the back wall of Boston Park in Rotherham (Fig. 1). Historic workings continue in the adjacent Canklow Woods, and provide exposures of the Rotherham Red Rock.

During recent site monitoring visits, members of the Sheffield Area Geology Trust (SAGT) observed that many of these rock faces are rapidly disappearing behind a cover of dense vegetation. Some of the other sites in the Mexborough Rock are no longer easily accessible, and the owners of two of these even refused permission for photographs to be taken of the geological features. Nevertheless, it was confirmed from these site visits that the Rotherham Red Rock is a local colour variation within a much larger sandstone unit.

Historical observations

For many centuries the distinctive colour of this rock unit has attracted attention in an area where weathered sandstones are usually grey, brown or buff-coloured (Figs 3 & 4). In addition to being quarried for grinding stones, its pleasing appearance made it a desirable material for use in buildings, particularly in local mansion houses and churches (Fig. 5). Throughout the 19th and into the 20th Century its colour and its complicated structural setting caused confusion amongst geologists, who misinterpreted its stratigraphic position and the origin of its pigmentation.

John Farey (1811, p.169) recorded the outcrop of 'salmon-coloured' gritstone at Boston Castle, near Rotherham, as a distinct stratum and suggested that it was probably equivalent to the 16th Grit in his series of strata, i.e. Triassic in age. He traced its outcrop southwards to Harthill where it met the outcrop of the Yellow Lime (Cadeby Formation), against which he thought it was terminated by the 'great zig-zag fault' (his interpretation of the Late Permian escarpment). William Smith correlated the Rotherham Red Rock with the Woolley Edge Rock of Late Duckmantian age, while Smyth and Phillips mapped it as Permian Lower Red Sandstone on the first geological map of the area (Chesterfield, Sheet 82 NW), published in 1852.

***Figure 1**. Outcrop of Rotherham Red Rock in old quarried face that is now within Boston Park (photo: Phil Wolstenholm).*

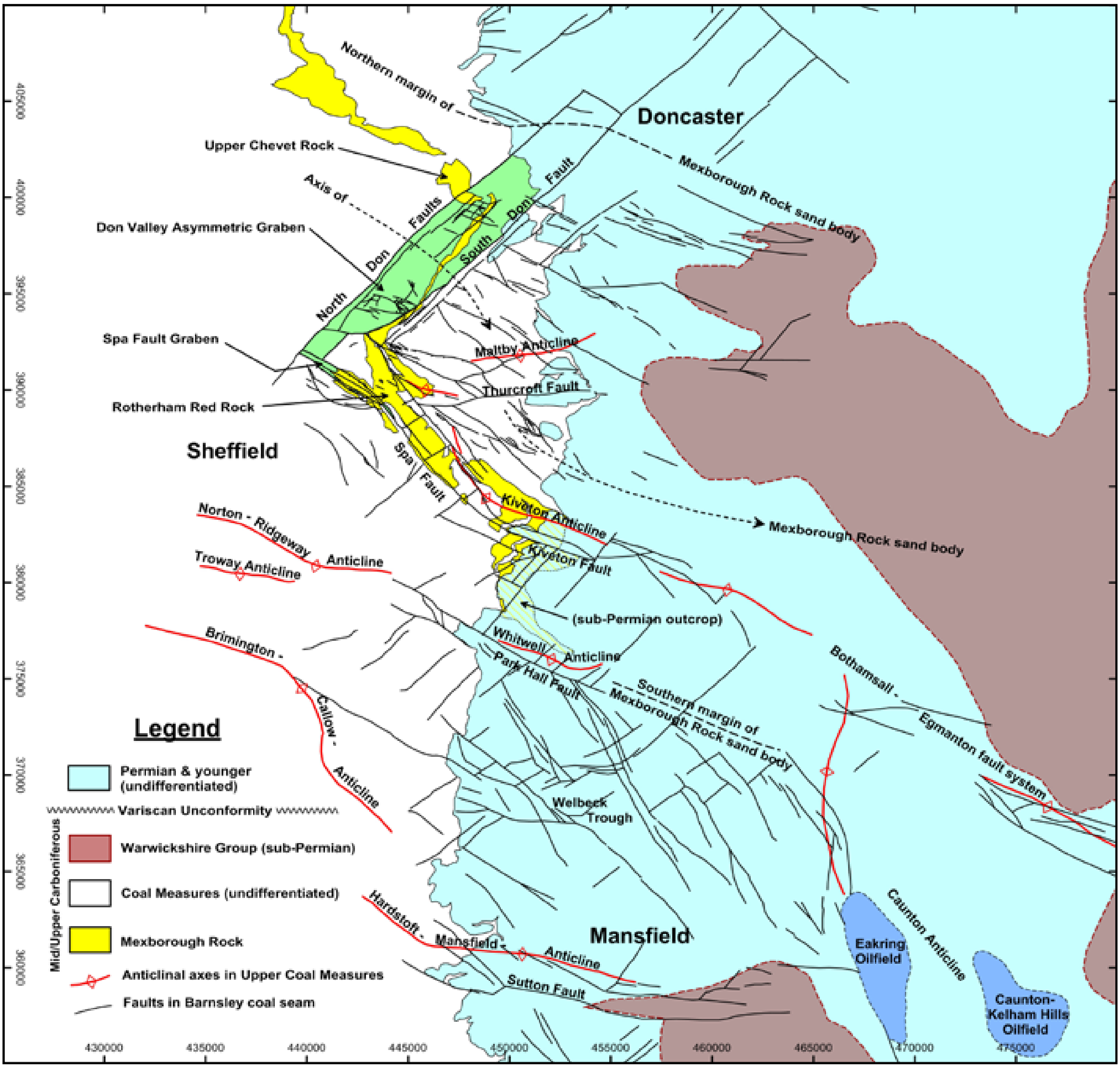

***Figure 2**. Simplified geology of the area around Sheffield and Rotherham, with the outcrop of the Mexborough Rock (largely after British Geological Survey mapping). The Don Valley and Spa Fault grabens are tinted mint-green purely to aid identification.*

***Figure 3**. Outcrop of non-reddened Mexborough Rock at Darfield Quarry (photo: Rick Ramsdale).*

***Figure 4** [far right]. Rotherham Red Rock in a road cutting near Ulley Reservoir.*

Figure 5. *Rotherham Red Rock used to build Ulley chirch.*

In 1850 the Reverend William Thorp, a local amateur geologist, who for many years served as the secretary of the West Riding Geological & Polytechnic Society (a forerunner of the Yorkshire Geological Society), correctly depicted the 'salmon-coloured rock of Rotherham' as a conformable sandstone unit within the Coal Measures in a position above the Newhill (or Clowne) Coal on his schematic vertical sections of the Yorkshire Coalfield (privately published). However, he erroneously thought that it was separate from the 'Upper Chevet Rock' at Hooton Roberts Quarry (Fig. 2), which he placed higher in the sequence.

Green *et al* (1878, p.481), in their exhaustive study of the Yorkshire Coalfield, were not aware of the severity of the faulting that affects the Mexborough Rock southwest of Rotherham, and they misinterpreted the varying thicknesses of measures recorded below it in local colliery workings as evidence for channel incision. They understood that the Rotherham Red Rock is older than the overlying Dalton, Wickersley and Ravenfield Rocks but, lacking the information that became available from later colliery sinkings, they thought that its base was unconformable and therefore indicated localised, syn-depositional tectonics. Like William Thorp, they also regarded it as a separate unit from the buff-coloured sandstone quarried at Hooton Roberts, for which they retained the name of Upper Chevet Rock. The deep, vertical incision they interpreted for the Rotherham Red Rock was depicted schematically in generalised vertical sections shown on the One-inch (Old Series) geological maps for Sheffield (Sheet 82NW) published in 1878 and 1892, although it was not depicted in this way on the Third Edition map, published in 1914.

During the resurvey of the Sheffield-Rotherham-Barnsley area between 1930 and 1952 by R. A. Eden and colleagues, the Rotherham Red Rock and the Upper Chevet Rock, despite their colour differences, were recognised as belonging to the same unit and given the new name of Mexborough Rock. Generalised vertical sections shown on the One-inch (New Series) geological maps published during that time (Sheets 87, Barnsley, and 100, Sheffield) depict it as conformable with adjacent strata. In the accompanying memoir however (Eden *et al*, 1957, p.122), the authors noted the general lack of reddening of other sandstones both above and below it and suggested that its colour may have been a primary depositional feature rather than secondary staining associated with pre-Permian weathering.

Primary red-beds or secondary oxidation

The term 'red beds' is applied to non-marine, mostly-clastic sedimentary strata that are predominantly (i.e. >60% of the succession) red in colour owing to the presence of finely-divided hematite; this typically occurs as coatings around individual grains or as an opaque, cryptocrytalline matrix. Red-coloured soils forming at present are restricted to the tropical climatic zone, and the occurrence of red beds in geological formations is usually interpreted as evidence for their deposition in near-equatorial latitudes under similar climatic conditions.

The oxidation process by which hematite formed is not perfectly understood in all cases, but where the pigment appears to have developed contemporaneously with the deposition of sediments and has been preserved in the consolidated rock, then these strata are described as 'primary red beds'. The same term has also been applied to sediments originally deposited in a non-red state but subjected to early post-depositional reddening under similar climatic conditions. In contrast, non-red sedimentary strata that have become partially reddened by post-depositional alteration processes (unrelated to the original sedimentation, and following a long time interval) are described as 'secondary red beds'.

In the East Pennine Coalfield, reddened Coal Measures were probably first observed below ground when the first colliery shaft was sunk through the Permian cover at Shireoaks, in North Nottinghamshire, in 1859. The shaft log recorded 3 m of reddened mudstone underlying the Permian unconformity. A further 15 m of grey, unoxidized, coal-bearing measures separated this zone from the Rotherham Red Rock, which was intersected at a depth of 83 m. In other sinkings completed during the 19th Century, it was found that the Coal Measures strata immediately beneath the basal Permian beds usually exhibited mottled red staining to varying depths of up to a few tens of metres.

In 1901 a borehole sunk at Thurgarton in Nottinghamshire, south of the Eakring oilfield, intersected about 150 m of 'red measures' of Upper Carboniferous age beneath the Permian unconformity. These strata have no surface outcrop in the East Pennine basin and a description of their character (published in a geological memoir on the concealed coalfield of Yorkshire and Nottinghamshire) was derived from

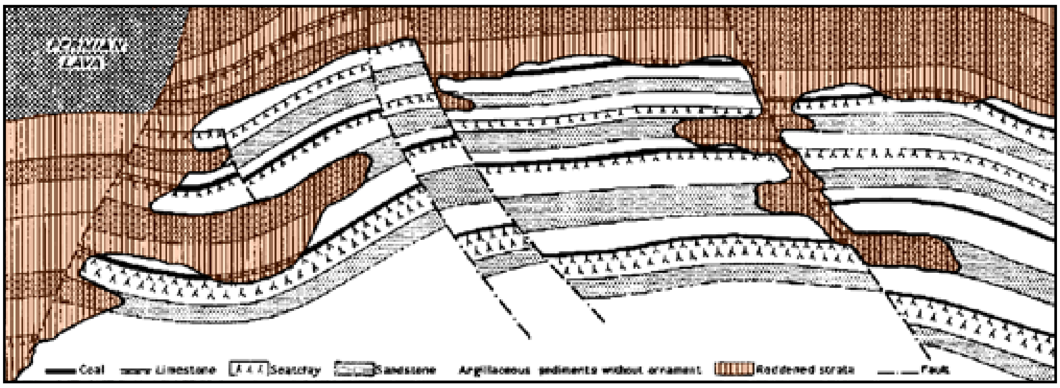

Figure 6. Schematic cross-section of Coal Measures strata in the Ayrshire Coalfield showing partial secondary penetration of oxidation that is associated with the faults (from Mykura, 1960).

limited borehole and shaft data (Gibson, 1913). The red measures, partly intercalated with grey measures, were recognised as resembling the Etruria Marl of the West Midlands. It was proposed that their colour was probably a primary, syn-depositional feature, and thus distinguishable from the irregular secondary staining seen beneath the Permian unconformity.

The third edition of the concealed coalfield memoir (Edwards, 1951), contains an expanded description of both primary and secondary reddened Upper Pennine Coal Measures in the East Midlands, including vertical borehole sections and a map showing the approximate extents of two separate areas of Upper Carboniferous red measures beneath the Permian unconformity. These two areas (Figs 2 & 7) have the appearance of outliers of younger strata preserved in depressions flanking a broad, anticlinal ridge that extends in a northwesterly direction from Grantham towards Sheffield. The memoir notes that the lowermost stratigraphic occurrence of these primary 'red-beds' does not extend below the Cambriense Marine Band, which is slightly higher in the sequence than the Mexborough Rock.

Another useful vertical section is shown in the geological memoir for the Ollerton sheet (Edwards, 1967). It is constructed from six correlated borehole and shaft logs, of which three are interpreted to contain primary red measures whereas the others are considered to exhibit secondary red staining of primary grey measures; all are shown in relationship to the unconformable base of the Permian strata. The upward passage from grey to supposedly primary coloured measures occurs at different stratigraphic levels on three of the logs and implies diachronism in the facies change. However, the horizontal distance between these shafts and boreholes is only a few kilometres and a steep gradient between waterlogged and well-drained alluvial facies would have been required to produce this outcome. Limited evidence for an alternative interpretation is also presented, involving an intra-formational unconformity within the Upper Carboniferous strata caused by localised uplift, erosion and surface oxidation.

Deep, penetrative oxidation of Coal Measures strata had also been discovered in other coalfields, including Staffordshire and South Lancashire (Trotter, 1954), which was explained in relation to a lowered and fluctuating water table in areas of high topographic relief with a pre-Permian arid climate. A more comprehensive model explaining the development of Upper Carboniferous red beds in terms of four major sedimentary facies associations was proposed by Besly and Fielding (1989). These facies associations were regional in scale, extending across the Pennine Basin, with lateral migration of their transitional boundaries throughout Westphalian time. A well-drained alluvial plain around the margins of the basin with well-developed palaeosols is sufficient to explain the Etruria Formation in this model. In the Stoke on Trent area, beds of red mudstone alternate repeatedly with grey, coal-bearing strata but coalesce laterally to form a continuous, primary red-bed sequence.

In contrast to Besly and Fielding's major contemporaneous facies model, Mykura (1960) described occurrences of extensive secondary reddening of grey strata in the Ayrshire coalfield. This alteration had been caused by the percolation of oxidizing meteoric water down steep fault zones which served as feeders for lateral migration through permeable sandstone beds (Fig. 6). This would have occurred during a period of pre- to early-Permian uplift, subaerial exposure and erosion. The oxidizing waters also caused corrosion of coal seams in contact with sandstone beds and resulted in replacement of coal by massive calcium carbonate and the common development of 'cone-in-cone' textures.

The most recently-published descriptions of red-coloured Upper Carboniferous strata have been prepared from data derived from offshore exploration drilling for gas reservoirs beneath the North Sea, where red-beds of both contemporaneous and secondary alteration origins, similar to the Ayrshire Coalfield, are widely distributed (Besly *et al*, 1993).

In a BGS review of the Upper Carboniferous lithostratigraphy, the primary red-bed strata have been given the formal name of the Warwickshire Group (Powell et al, 2000). The Etruria Marl, now renamed the Etruria Formation, is the lowest formation within the group and its lower boundary with the grey Coal Measures is markedly diachronous across the Pennine Basin. In the southernmost of the two areas in the East Midlands shown on Figure 2, the base of the red-beds is stratigraphically lower than it is in the northern area near Doncaster, although it is still above the Cambriense Marine Band.

Variscan basin tectonics

Deformation of the Variscan orogenic foreland in late Asturian-Stephanian times caused inversion of the Carboniferous strata in the Pennine Basin with widespread uplift, faulting and gentle folding followed by erosion to the level of a low-lying coastal plain (Pharaoh *et al*, 2011). Peneplanation of the folded and tilted Coal Measures placed many truncated fluvial sandstones beneath a low-angle unconformity in contact with the overlying Late Permian marine sediments. Further gentle uplift and tilting of both Carboniferous and Permian strata during the Alpine tectonic event resulted in erosion of the western edge of the Permian, creating the exposed coalfield in Yorkshire and the East Midlands. In the Rotherham area, sufficient Coal Measures have been uncovered to expose an outcrop of part of the Mexborough Rock.

Two intersecting sets of conjugate Variscan faults with mostly normal movement have divided the Coal Measures strata of the East Pennine Coalfield into a mosaic of blocks. The faults are usually steeply inclined, and individual faults intersect the sequence of coal seams at different horizontal positions. Also crossing the coalfield are several north-westerly trending zones of larger faults associated with inversion anticlines. Some of the deeper culminations along these anticlines formed hydrocarbon traps. These major fault zones overlie reactivated older structures in the pre-Westphalian basement.

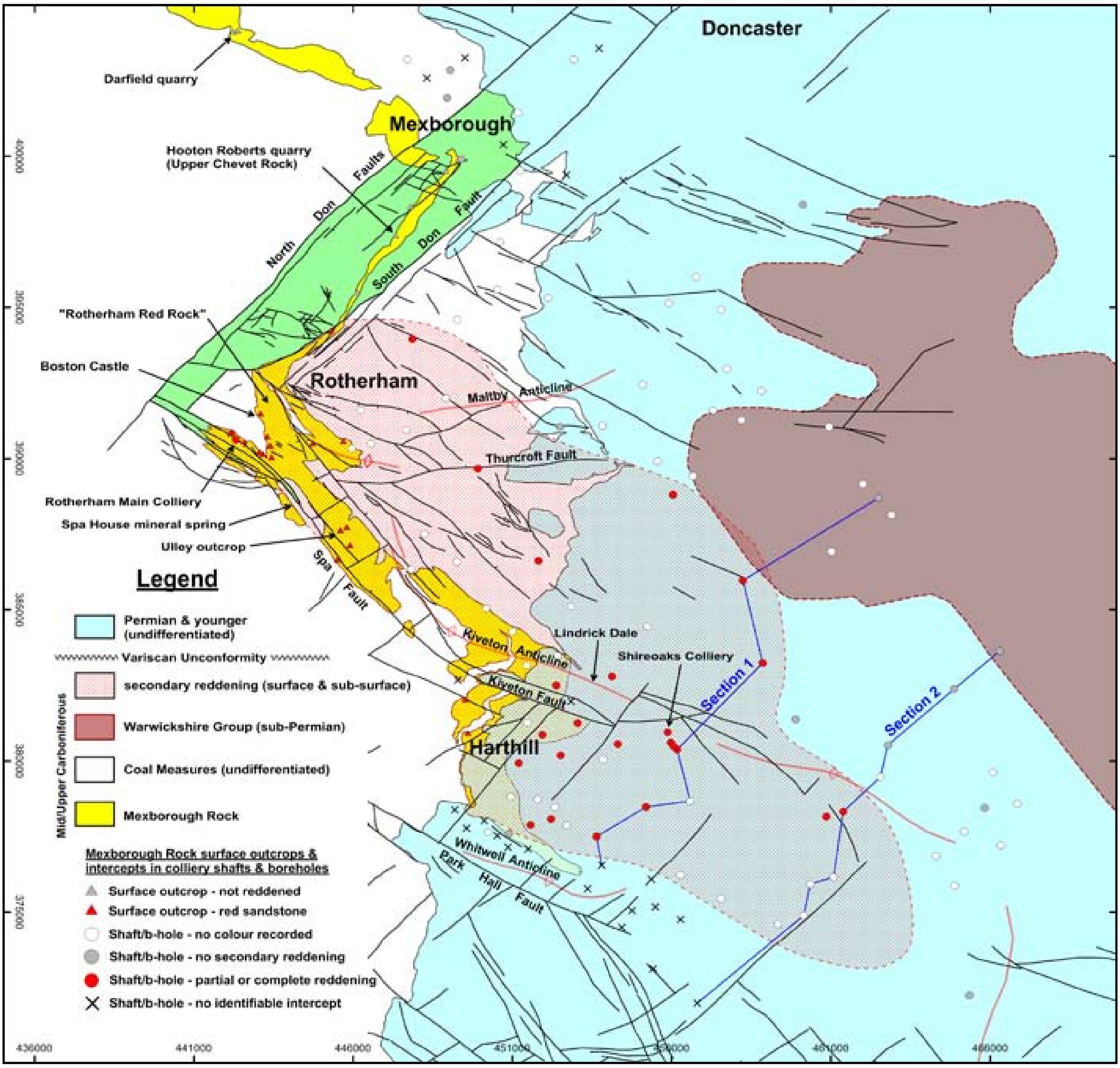

***Figure** 7. Distribution of the reddened Mexborough Rock and the locations of colliery shafts and boreholes from which it was interpreted (sourced from borehole logs by British Geological Survey). The Don Valley and Spa Fault grabens are tinted mint-green purely to aid identification.*

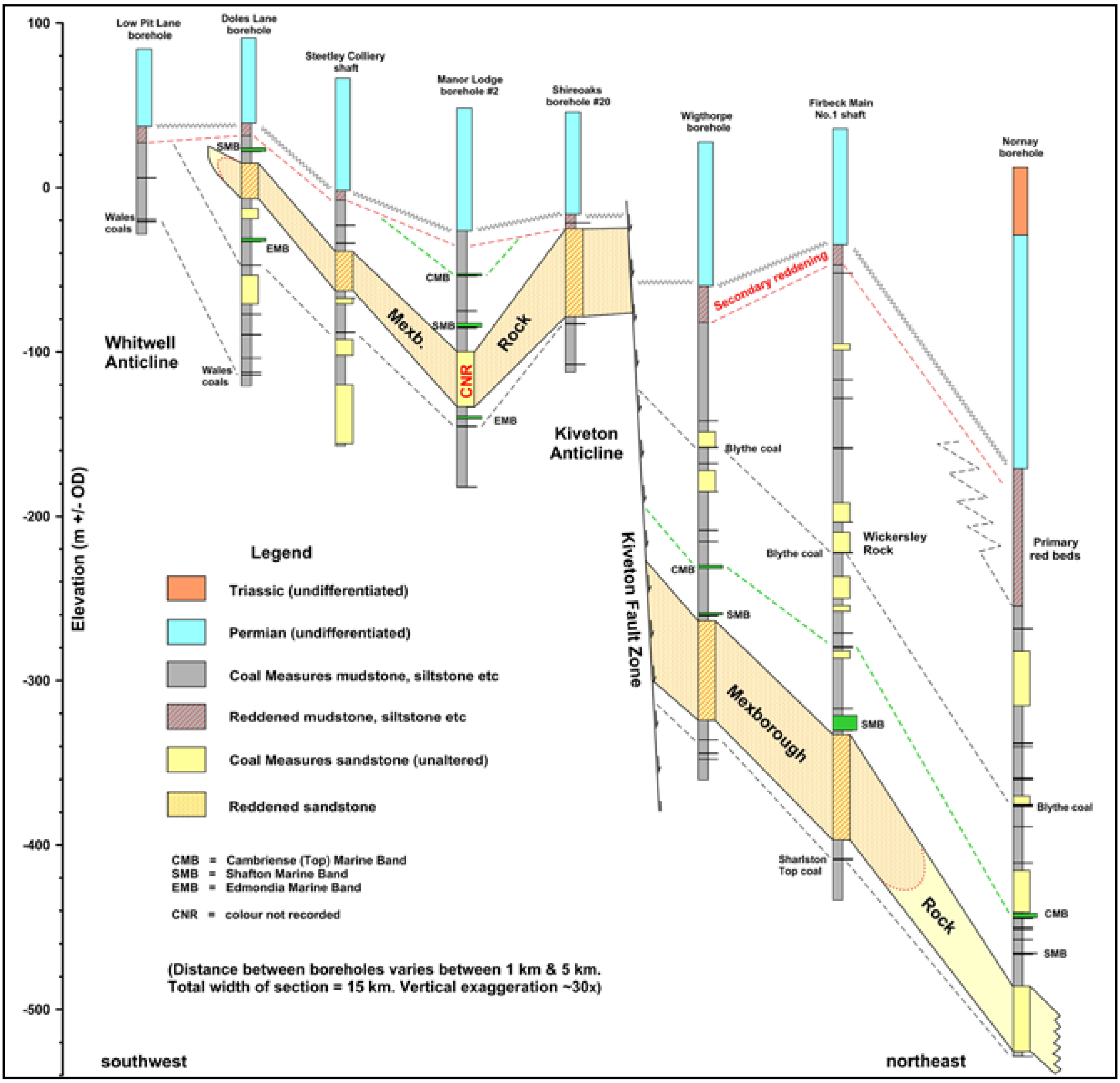

Figure 8. *Simplified correlated borehole and shaft log Section 1, located on Figure 7.*

Figure 2 shows a number of faults that affect the Barnsley (Top Hard) Coal along the outcrop edge of the Permian sequence between Mansfield and Doncaster, i.e. the line separating the exposed and the concealed coalfields. Selective use of fault information from only the Barnsley Coal provides a consistent data set from a single stratigraphic horizon. The faults are shown in their seam intersection positions rather than at their surface locations, and therefore appear offset from the surface outcrop of the Mexborough Rock. In the lower half of the figure these data have been derived principally from Edwards (1951, 1967), while in the area between Sheffield and Doncaster they have been transferred from plans of colliery workings. Also shown on Figure 1 are the axes of the most prominent inversion anticlines affecting the Upper Carboniferous strata. They extend from the concealed coalfield beneath the Permian cover into the exposed coalfield and, where truncated at the base of the Permian, are partly responsible for the more accentuated unconformity in the Rotherham area.

Evidence for an earlier, intra-Carboniferous unconformity at the base of the Warwickshire Group can be seen on logs from some deep boreholes on the south side of the Eakring oilfield (Pharaoh *et al*, 2011). Called the Symon Unconformity, it indicates that an early phase of Variscan deformation of the Pennine Coal Measures Group occurred in this area prior to deposition of the Etruria Formation. It could explain the steepness of the local diachronous transition between the grey and red measures.

Structural setting

Variscan faulting of the Mexborough Rock in the Rotherham area created a confusing arrangement of outcrops which 19th-Century geologists struggled to interpret. The most significant of these is the Spa Fault system which, in the Rotherham area, is a narrow graben.

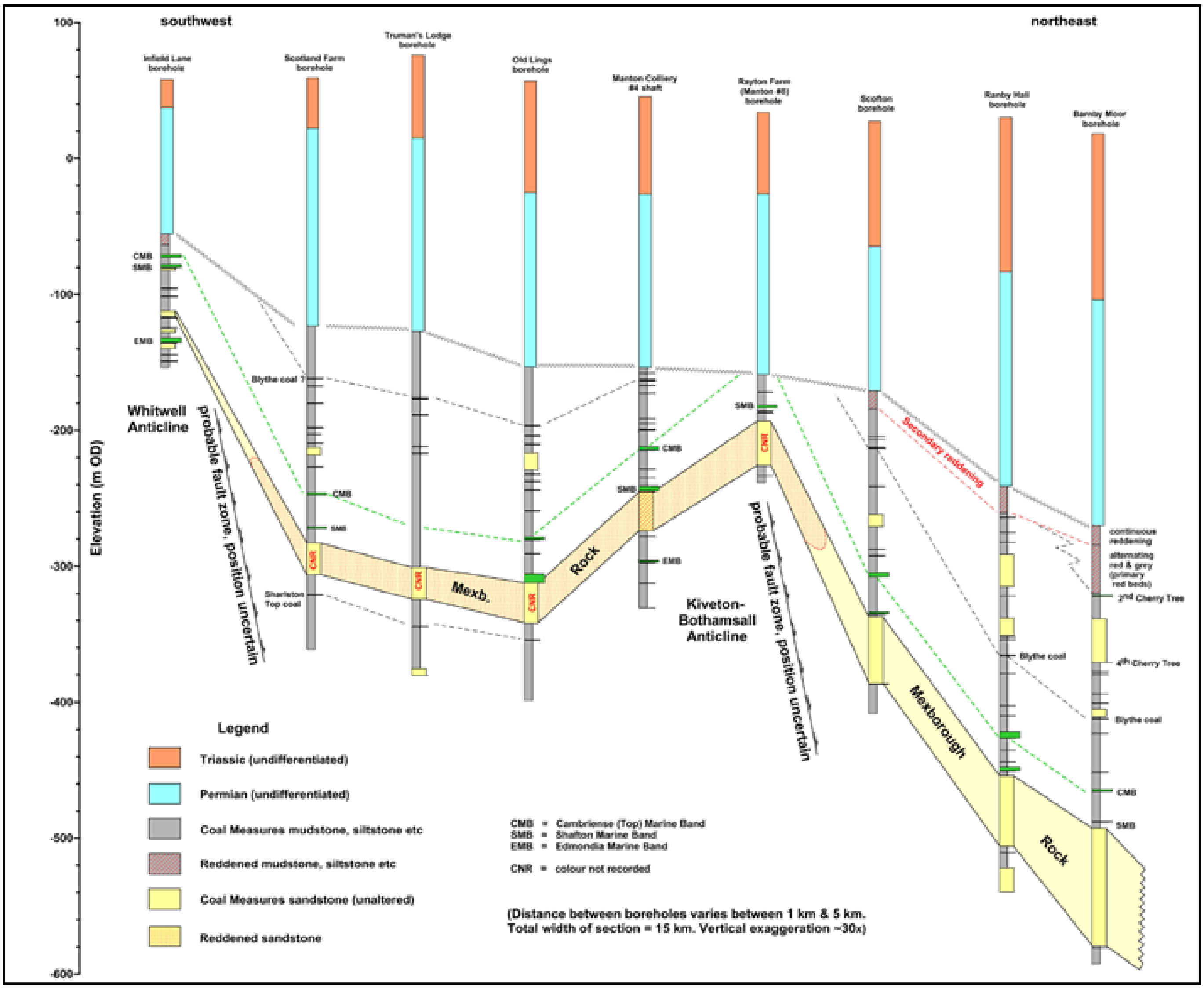

Figure 9*. Simplified correlated borehole and shaft log Section 2, located on Figure 7.*

The northwest-trending Spa Faults terminate against the northeast-trending Don Fault system near Boston Park where, coincidentally, the Mexborough Rock reaches its greatest thickness. The Spa Fault system, together with the Kiveton Fault and the Kiveton Anticline are an extension of the Bothamsall–Egmanton inversion anticline where it emerges from beneath the Permian cover in the Rotherham area.

The Don Faults are the principal components of a major structure called the Don Monocline (Eden *et al*, 1957), which has caused a gross vertical downthrow across it (from northwest to southeast) of up to 500 m. Information shown on plans of colliery workings in the Barnsley Coal along the Don valley suggests that the structure can be characterised more accurately as an asymmetric graben, with a lens-shaped block of ground trapped between the North and South Don faults, which dips steeply towards the southeast.

The larger faults affecting the Barnsley Coal in the Rotherham area have substantial vertical displacements, sometimes exceeding 100 m, and these structures often formed the underground boundaries between different colliery workings. Some blank areas on colliery plans represent barriers of unworked coal left intentionally to control water leakage but can also indicate areas of coal unworked where the ground was badly disturbed.

Oxidation of the Mexborough Rock

Pervasive reddening of the Mexborough Rock at outcrop is restricted to an area between Rotherham and Harthill (Fig. 7). The reddened rock can be observed at a cluster of surface exposures and, where not directly visible, its presence can be interpreted from soil colour in freshly-ploughed fields. The lack of reddening of the Mexborough Rock at the town of Mexborough itself, which is closer to the outcrop edge of the overlying Permian beds than is Rotherham, indicates that the alteration process was not spatially related to that unconformity.

Intersections of Mexborough Rock have been recorded on lithological logs from many of the colliery shafts and exploration boreholes. Descriptive lithology logs from 118 shafts and boreholes nearest to the outcrop have been examined (Fig. 7). The resolution of and level of detail contained in the logs is very variable. Of the 118 logs studied, almost half (58) had no colour recorded for the Mexborough Rock intercept, usually because the relevant interval had not been cored and lithologies were interpreted from open-hole electrical logs. Of the remainder, 24 logs recorded reddened Mexborough Rock intercepts, 13 recorded grey intercepts and 23 had no recognisable intercept. The shaft and borehole symbols plotted on Figure 7 are differentiated by this classification scheme.

The 37 logs with records of colour are sufficient to delineate a large area of reddened Mexborough Rock extending beneath overlying Coal Measures, down-dip from the outcrop. The altered area, which extends for a distance of at least 10 km and reaches a depth below the Permian unconformity of at least 360 m, follows the axis of the Variscan inversion anticline structure comprising the Spa Faults, the Kiveton Fault and the Kiveton Anticline. Between Rotherham and Harthill the western limb of the anticline has been eroded away; the alteration zone occupies the eastern limb and also follows the axis of maximum thickness of the sandstone. Southeast of Harthill the alteration zone gradually becomes confined to the western limb of the Kiveton anticline, filling the synclinal area separating it from the Whitwell anticline and penetrating the thinner margins of the sandstone.

The structural disturbance caused to the Upper Coal Measures, and to the Mexborough Rock in particular, by the faulted Kiveton Anticline is illustrated by two sections constructed across the altered area (Figs 8 & 9). The Mexborough Rock is relatively easy to identify on borehole logs from the Edmondia Marine Band or the Sharlston Coal beneath it and from the Shafton Coal and Shafton Marine Band above it. The Kiveton Fault was reactivated in post-Permian times, possibly during Alpine tectonism, as shown by the offset in the basal Permian unconformity (Fig. 7). The same reactivation event caused gentle flexing of the overlying Permian strata and the fold axis can been seen at outcrop in the sides of a railway cutting near Lindrick Dale [SK 536822].

Each drawn section (Figs 8 & 9) includes a borehole through the northern area of primary red beds belonging to the Warwickshire Group, and on these boreholes the red beds extend to a lower stratigraphic level than in the adjacent boreholes. The lithological records of these red beds describe them as a zone of alternating red and grey measures, but insufficient information is available to determine whether this is an interdigitised diachronous transition or evidence for the Symon Unconformity in the vicinity of Rotherham and Doncaster.

Also shown on the sections is the interpreted lateral extent of the reddened zone within the Mexborough Rock. The alteration is shown in simplified form as affecting the entire thickness of the sandstone but in detail its vertical penetration is variable, with different shades of red, brown and purple colour locally alternating with zones of apparently unaltered grey rock. Within the reddened rock, pebbles of reworked sideritic clay-ironstone have been converted into hematite.

Causes of the oxidation

The restriction of the pervasive reddening of the Mexborough Rock to a limited part of the sandstone on the south side of the Don Fault system in the Rotherham area suggests a localised origin by secondary alteration, although the process by which this occurred is not obvious from an examination of the currently accessible outcrops.

It is possible that oxidizing water may have percolated into the Mexborough Rock at the same time as the deposition of the overlying primary Warwickshire Group red-beds, in Late Carboniferous time. However, this would only be the case if the Mexborough Rock had been unroofed by local uplift and then eroded along the axis of the Spa Fault and the Kiveton Anticline, making it potentially part of the same event that apparently caused the Symon Unconformity. The westerly limit of the Warwickshire Group strata in the subsurface south of Doncaster is currently about 10 km from the outcrop of the Mexborough Rock at Rotherham, and although the original distribution of these primary red beds was probably wider, their extent cannot be determined, nor can a prior local uplift in this area be confirmed. Moreover, any window of Mexborough Rock exposed by local uplift would have been very limited in area and could not have included the up-thrown continuation of the sandstone across the Don Faults, which is unaltered.

Another explanation for the oxidation of the Mexborough Rock could be that it occurred during or after the main phase of Variscan basin inversion, or during the period of regional erosion prior to the Late-Permian marine transgression, when the entire land surface was oxidized to a shallow depth. Even with this model, it is necessary to account for the restriction of the oxidizing percolation to almost a single sandstone in only the Rotherham area. Most of the other Coal Measures sandstones in the immediate vicinity do not show significant reddening. The principal exceptions are part of the Wickersley Rock, along the crest of the Maltby Anticline, and a minor, unnamed sandstone at Hooton Roberts village. Unlike the Mexborough Rock, the alteration of the Wickersley Rock does not persist beneath younger strata at depth.

The close spatial association between the reddened Mexborough Rock, the Spa Fault system and the Kiveton faulted anticline makes it reasonably certain that the latter structures were an essential component of the alteration event. The alteration process probably involved downward percolation of oxidizing meteoric water during a period of lateritic weathering and the style and setting is equivalent to the examples previously described from the Ayrshire Coalfield and from beneath the North Sea. In the Ayrshire Coalfield, the lower limits of the alteration zone in underground mine workings, i.e. the redox fronts, were usually associated with pervasive deposition of calcite and dolomite within and around the coal seams. Writers who were able to observe these details at first hand thought that the percolating water had introduced the minerals

in solution (Dron, 1904). There are no equivalent underground observations for the Mexborough Rock, and it is not known if similar carbonate precipitation occurred in association with its alteration at depth.

The Spa Faults therefore, unlike the Don Faults, appear to have been major open conduits for groundwater flow in the Early Permian. The smaller area of reddened Wickersley Rock may also have resulted from oxidizing waters entering this sandstone via an intersection with the Spa Fault system, thereby at a level above the Mexborough Rock that has since been removed by erosion. It is noteworthy that the Spa Faults also have similar properties at the present time. The name is derived from the Spa House mineral spring near Guilthwaite Farm, which was developed into a therapeutic bathing centre in 1664 by the landowner, George Westby (Hunter, 1819, p.293). A local doctor sent his patients there for treatment, probably in a convenient arrangement with Westby, and the facility was eventually abandoned after both men died. In 1890 the shafts for Rotherham Main Colliery were sunk through the Mexborough Rock, with both passing through one of the Spa Faults and a number of subsidiary faults. Groundwater feeders encountered by the sinkers were as high as 120,000 gallons per hour and required as many as nine pumps in each shaft to control the flow before linings could be installed (Anon., 1892).

It is concluded that the localised alteration of ubiquitous and finely dispersed brown iron hydroxides in the Mexborough Rock to a red, hematitic stain represents a permanent record of a palaeo-groundwater flow down the gently dipping channel axis of a major Carboniferous fluvial sandbody. In this respect it resembles the better-known alteration zones associated with uranium-bearing redox 'roll-fronts' in Palaeogene continental sedimentary basins in Wyoming, USA (Hunter, 1999). Clearance of vegetation from the extensive surface outcrops of Mexborough Rock in Boston Park (Fig. 10) and Canklow Woods near Rotherham would reveal more exposures of reddened rock to be examined for possible evidence in support of this hypothesis.

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***Figure 10**. Panoramic view of the entire rock face at Boston Park showing the extent of vegetation cover (photo: Phil Wolstenholm).*

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