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NATURAL ENVIRONMENT RESEARCH COUNCIL

Primary and Secondary Controls on Reservoir Quality; Relationships Between Lithofacies and the Development of Deformation Bands

Oliver Wakefield[1], Ed Hough[1], Karl Clark[2]
1 - British Geological Survey, Keyworth, Nottingam, NG12 5GG, UK.
2 - University of Liverpool, Earth, Ocean and Ecological Sciences, Liverpool. L69 3GP, UK.

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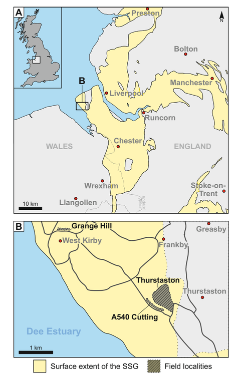
Introduction

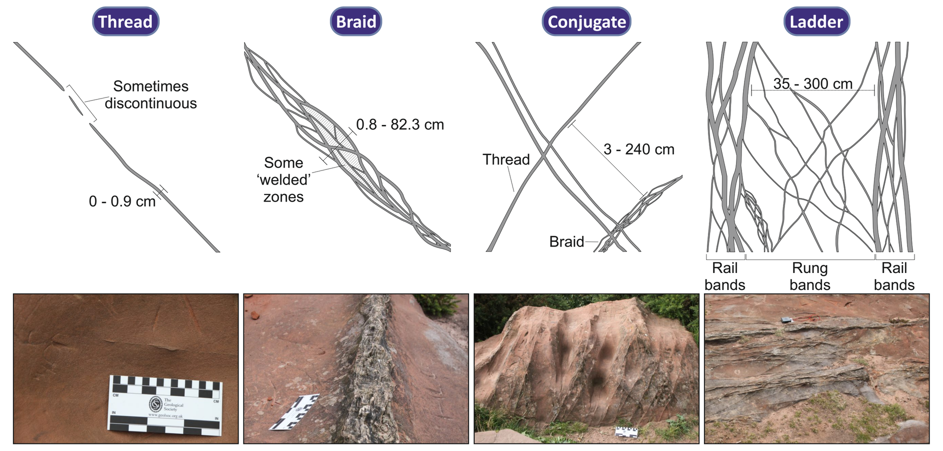
Deformation bands

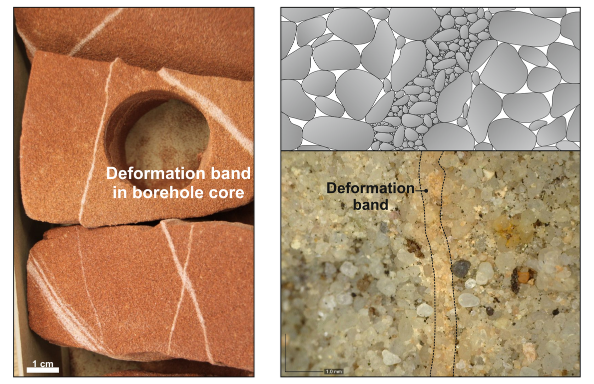
Deformation bands are a diagenetic processes that can create planar features of reduced permeability. From in-situ permeability testing deformation bands are recognised to have values 2-5 orders of magnitude less than the host sandstones. As such, these features represent significant reductions in the ability of the host rock to hold and transmit fluids. Whilst numerous studies have sought to understand the formation of deformation and quantify the geometries that these features have, it is equally important in understanding how they can divide and compartmentalise reservoir rocks. This work suggests a novel new classification scheme based on the deformation band character and geometry, identifying four broad types; thread, braid, conjugate and ladder.



Classification scheme

Four styles of deformation band are recognised and illustrated below (conceptual and photographic example).
Thread: The most frequent deformation band type recognised, often with the thinnest and most laterally restricted type. Can often be discontinuous with small gaps in the deformation band.
Braid: Larger deformation band upto 10's cm wide. Can have lateral extents of 10's m. This type of band is commonly transitional with thread bands which can converge to form braids.
Conjugate: Is more often characterised by thread bands but can equally be a mix of braid and thread deformation bands. These deformation band types are visibly the most ordered and regimented in orientation.
Ladder: An unusal type of deformation band where outer 'rail' bands contain a chaotic mix of other smaller ('rungs') and have orientations not in-keeping with regional trends. Interval 'rung' deformation bands that frequently do not extend beyond the 'rails'.





Study Location

This study uses examples from the Triassic Sherwood Sandstone Group of the UK. The Sherwood Sandstone Group is a continental succession composed of a variable mix of eolian and fluvial facies types. Within western England the Sherwood Sandstone Group is well exposed at outcrop and locally exhibits abundant types of deformation bands. The deformation bands within the Sherwood Sandstone Group are an important feature as the group is hydrocarbon producing in the East Irish Sea Basin. The group is also the second largest aquifer for the UK and its lateral equivalent in the North Sea are also hydrocarbon producing.

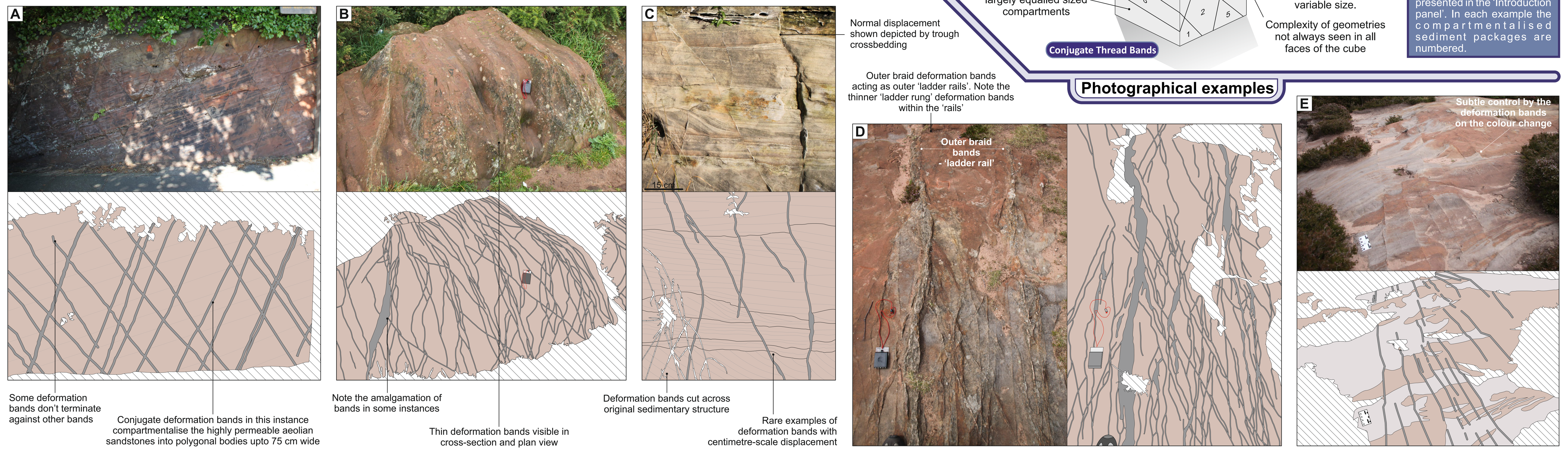
Deformation bands

Photographical and illustrative interpretations of:
A) Conjugate deformation bands within grainfall and grainflow (eolian) facies. Note that the deformation bands are well-ordered and cross-cut the sedimentary structures.
B) Conjugate deformation bands in a smaller example. Note that the deformation bands weather 'proud' and forming small topographic features.
C) Thread deformation bands that show centimetre-scale displacement.
D) Ladder deformation bands with outer 'rail' and inner 'rung' bands. Note that the predominately thread rung bands have orientations oblique to the outer rails.
E) Thread deformation bands that appears to be exerting some control on the regions of modern bleaching within the fluvial sandstone.

Facies Type	Permeability (mD) min	max	mean	Reading count	Number of deformation bands identified
Aeolian crossbeds*	402.87	3033.36	1362.34	27	72
Dry interdune	350.67	632.08	506.28	8	2
Upperplain beds	159.42	401.15	267.56	7	1
Channel Lag deposits	102.45	274.64	192.55	7	2
Fluvial crossbeds	241.27	426.85	328.60	8	1
Fluvial massive	158.45	325.25	255.64	6	0

Facies Permeability

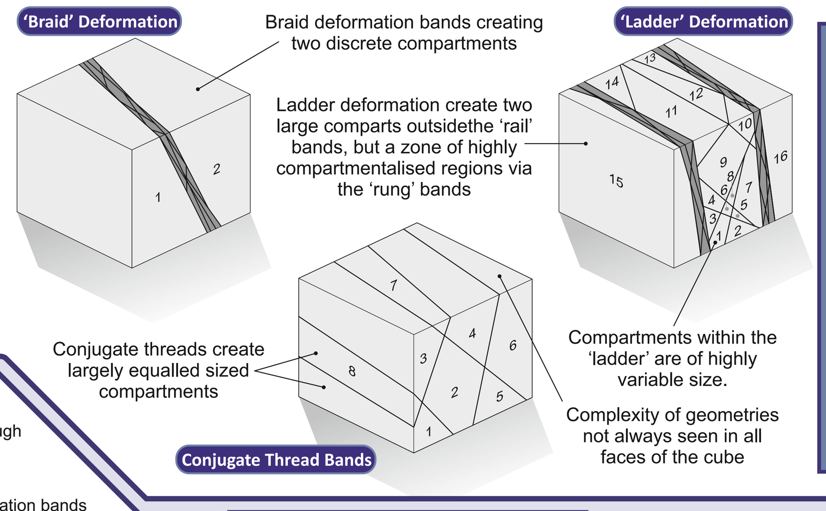
The above table identifies the permeability results using in-situ testing. Note that the aeolian crossbeds (composed of grainfall and grainflow facies) have the highest average and maximum permeability results whilst also being the most frequently hosting deformation bands in the test region. Values from the mini-permeameter are likely to be overestimates but still important for indicating relationships between facies and deformation bands.



Data Collection

Data Collection

Data collection involved the measuring of host rock and deformation permeability using a field-based in-situ minipermeameter. This use of this equipment allowed non-destructive testing in areas where destructive sampling was not allowed. Where deformation bands were identified the thickness, lateral and depth extents were measured (where observable). The orientation (dip and dip azimuth) was also recorded. The 'conclusion panel' provides analysis of some of this data set.



Compartmentalisation

The differing types of deformation band and the differing geometries they exhibit can compartmentalise a body of rock. However, the amount and geometries of these compartments is key in understanding if the potential affects on fluid flow are significant or not.
As such, three conceptual diagrams opposite (left) illustrate three end-member examples using the classification scheme presented in the 'Introduction panel'. In each example the compartmentalised sediment packages are numbered.

Photographical examples

Deformation bands

Photo captions

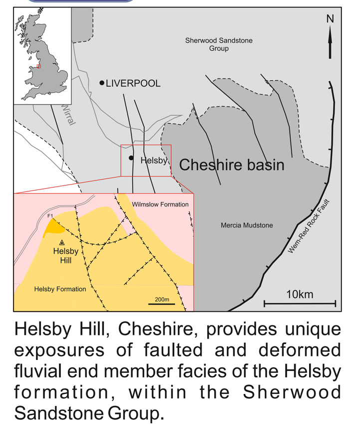
A) Ladder deformation bands with 'rungs' highly oblique to the orientation of the 'rails'.
B) Thread deformation bands in a pseudo-flower structure.
C) Conjugate deformation in 3D.
D) Thin, discontinuous thread deformation band.
E) Braid deformation band with an anastomosing structure.
F) Large braid deformation separating into discrete smaller braid bands.
G) Eolian succession where a large portion of the thread deformation bands terminate at the bounding surface with dry interdune elements. Note that some continue below the same interdunes.

Grain size distribution on deformation band development

Introduction

The effect of porosity, permeability and grain size on the formation and development of deformation bands has been widely studied in predominantly well sorted, clean aeolian sandstones, for which strong controls are for the most part widely recognised and understood. However, little has been done to examine and compare deformation bands within fluvial lithofacies. These units offer insight into the effect of sorting, grain shape, grain angularity, composition and heterolithic bedding on the characteristics of deformation bands and their effect on reservoir quality. This study examines the effect of sorting on deformation bands within a fluvial sandstone member.

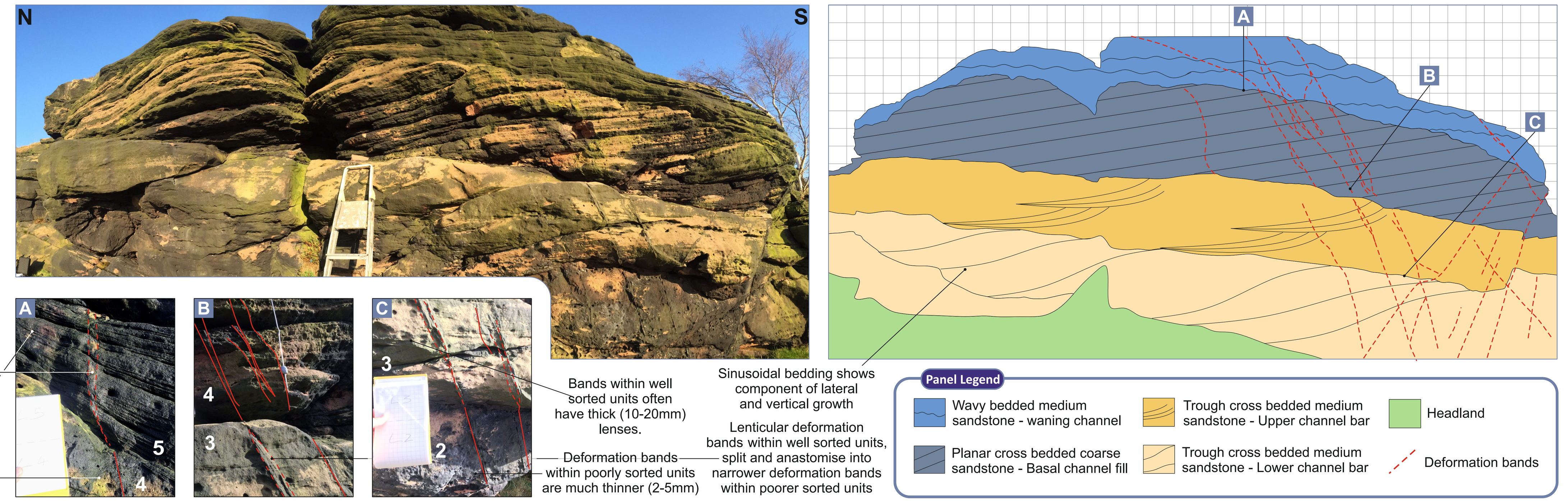
Location Map



Helsby Hill, Cheshire, provides unique exposures of faulted and deformed fluvial end member facies of the Helsby formation, within the Sherwood Sandstone Group.

Methodology

Mean grain size and sorting using the Folk & Ward (1957) classification scheme was obtained using Petrog point counting software, measuring the short and long axis of 250 grains per sample. Porosity reduction by deformation bands was obtained from optical images of both host rock and deformation band using ImageJ analysis using a jPORv1.1 plug in. Back scattered electron images were obtained using both a Phillips XL30 SEM and a Hitachi TM3000 SEM.

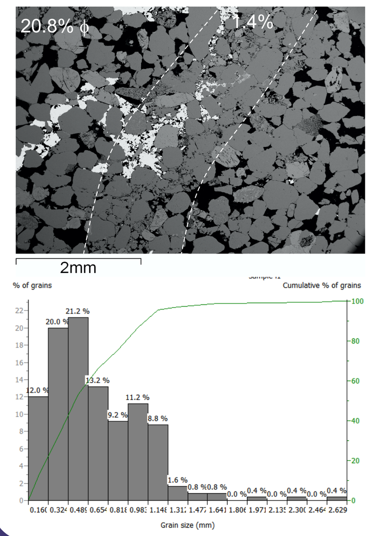


Panel Legend

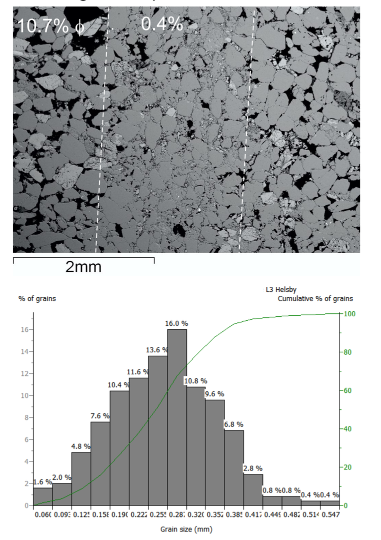
- Wavy bedded medium sandstone - waning channel
- Trough cross bedded medium sandstone - Upper channel bar
- Headland
- Planar cross bedded coarse sandstone - Basal channel fill
- Trough cross bedded medium sandstone - Lower channel bar
- Deformation bands

Image analysis

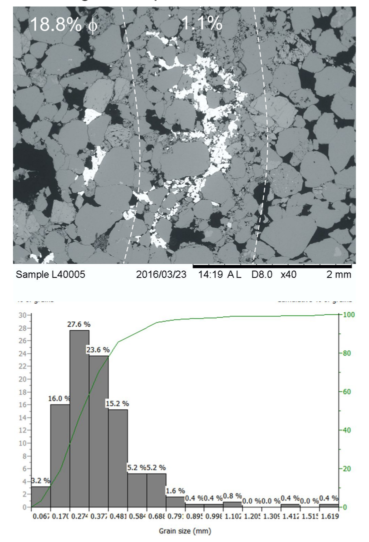
Lithofacies F1
- Mean grain size: 636 μm
- Sorting: 0.918 phi



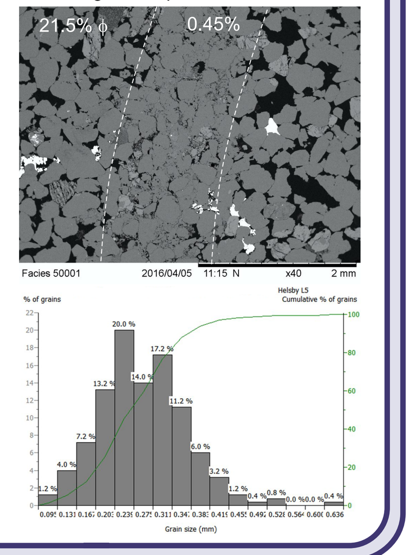
Lithofacies F3
- Mean grain size: 266 μm
- Sorting: 0.530 phi



Lithofacies F4
- Mean grain size: 375 μm
- Sorting: 0.686 phi

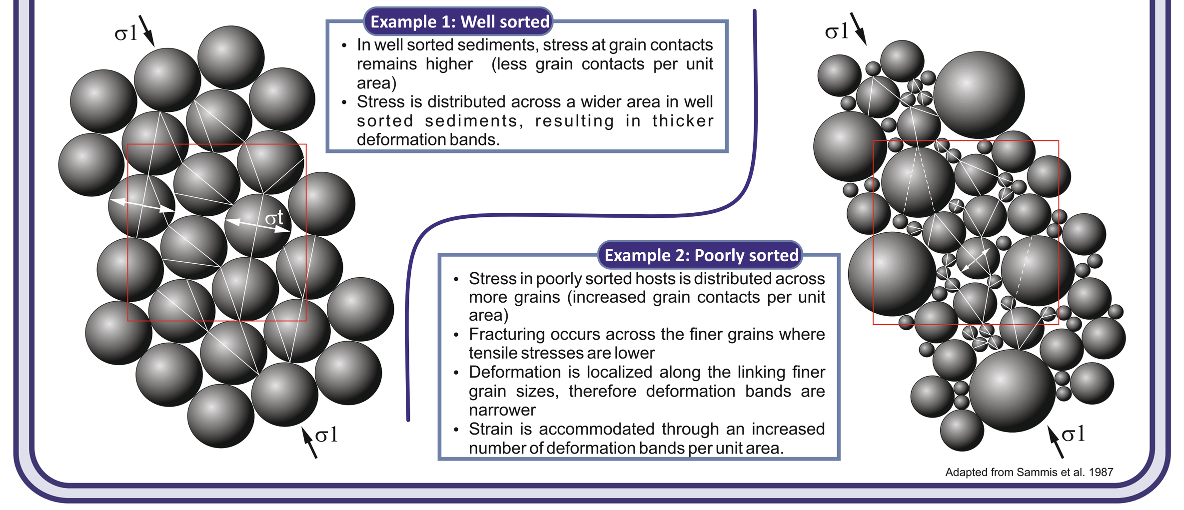


Lithofacies F5
- Mean grain size: 274 μm
- Sorting: 0.443 phi



Deformation Mechanics

Grain sorting can have a considerable control on the formation of deformation bands. In the examples below two different sediment packages are shown to depict well-sorted and poorly sorted end members. In the well sorted example grains are stacked with rhombohedral packing structure. By contrast the poorly sorted grains are randomly packed. Subsequent deformation may be explained by hertzian grain-to-grain fracturing (Wong, 1990).



Example 1: Well sorted
- In well sorted sediments, stress at grain contacts remains higher (less grain contacts per unit area)
- Stress is distributed across a wider area in well sorted sediments, resulting in thicker deformation bands.

Example 2: Poorly sorted
- Stress in poorly sorted hosts is distributed across more grains (increased grain contacts per unit area)
- Fracturing occurs across the finer grains where tensile stresses are lower
- Deformation is localized along the linking finer grain sizes, therefore deformation bands are narrower
- Strain is accommodated through an increased number of deformation bands per unit area.

Adapted from Sammis et al. 1987

Conclusion

Data analysis

The below graphs show preliminary results of the initial field data collection.
A) Deformation band type vs band thickness.
B) Deformation band type vs band length.
C) Deformation band thickness vs permeability. Note that there appears no apparent relationship between the thickness of a band to its permeability.

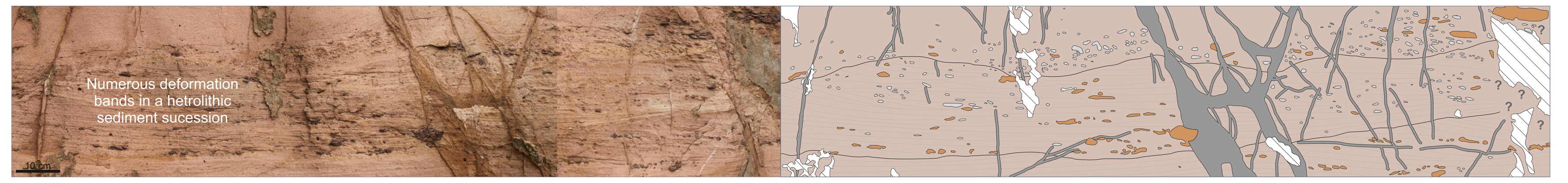
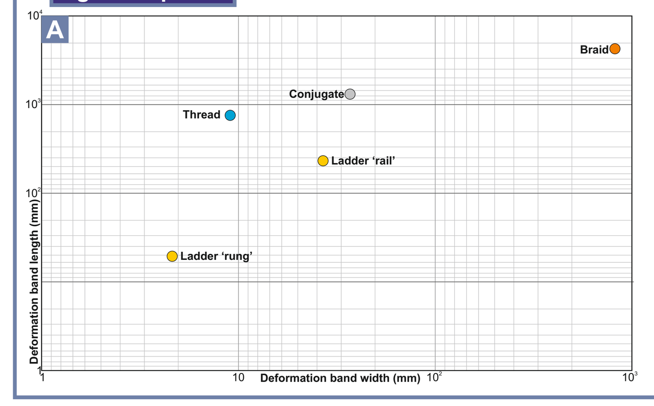
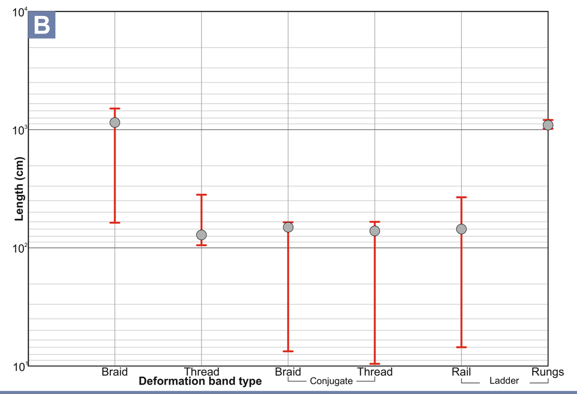
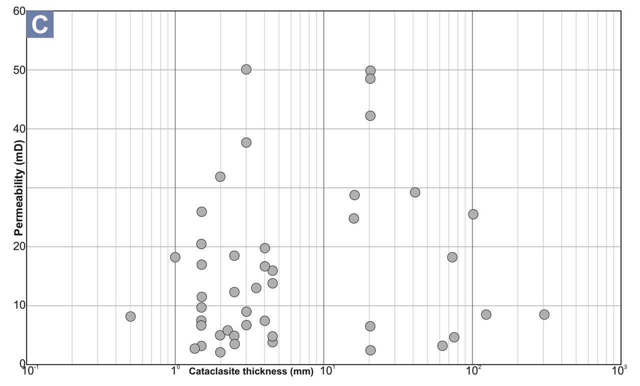


Figure Captions







Conclusion

Deformation bands within fluvial units show greater reduction in porosity when compared to those of eolian lithofacies (Griffiths et al. 2016), due to a high degree of cataclasis within the core of the deformation band. Poorly sorted fluvial sandstones exhibit thinner deformation bands whilst also showing less porosity reduction compared to well sorted examples. Potentially the effect on permeability of the deformation band and the rock as a whole is reduced. However, this is outweighed by an increased deformation band density within poorly sorted units, due to the accommodation of strain by bifurcation, due to grain-grain interaction processes. An increase in density of these very low porosity bands will have a dramatic effect on the bulk transmissivity and connectivity of a reservoir.

References & Acknowledgements

References
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oliverw@bgs.ac.uk
http://www.bgs.ac.uk
+44 (0) 115 936 3169

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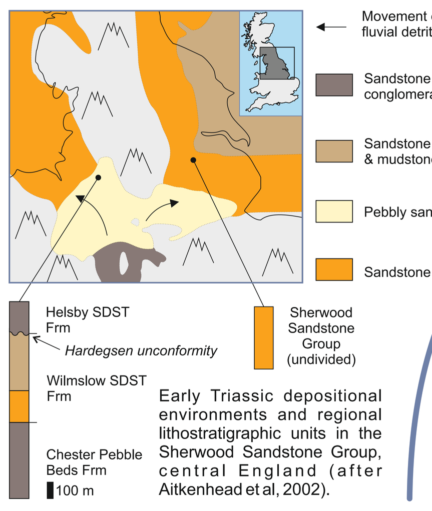
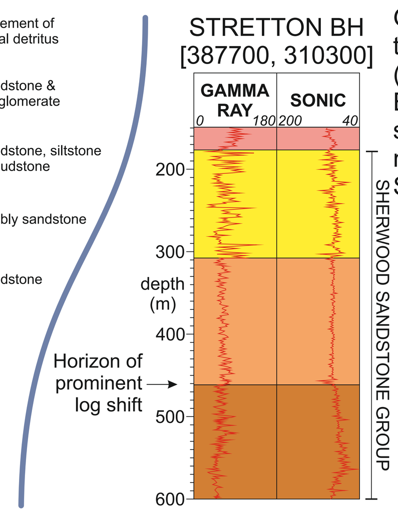
Introduction

Panel legend

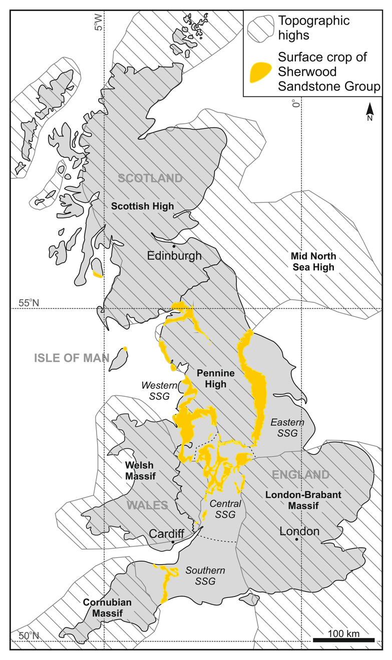
The Sherwood Sandstone Group is late Permian to Mid-Triassic (Ladinian) in age. The Early Triassic in Britain was characterised by rifting and extension, related to the break-up of Pangea, with thick accumulations of arenaceous sediments developing in a series of actively subsiding linked half-graben which fringed the local palaeo-high of the Pennines. Locally, preserved sediments reach over 1000 m in some depocentres, with younger units overlapping inter-basinal highs. Regional-scale depositional models suggest a southerly source in the Variscan foldbelt some few hundreds of kilometres to the south, with northwards draining rivers bifurcated by the Pennine High, diverting sediment westwards towards the Cheshire Basin, Lancashire and Cumbria, and eastwards to the Needwood Bain and East-Midlands Shelf.



Early Triassic depositional environments and regional lithostratigraphic units in the Sherwood Sandstone Group, central England (after Aitkenhead et al, 2002).



Gamma and sonic logs for the Stretton Borehole (Stafford Basin, central England), showing tripartite succession evident across much of the western Sherwood Sandstone.



Context

The Sherwood Sandstone is a critical geological unit in Britain. It is the 2nd most important groundwater aquifer in England, and is a reservoir to hydrocarbon fields both onshore and offshore. Its close spatial relationship with the Coal Measures and proximity to major urban areas including Birmingham and Manchester has led to localised contamination. As such, an understanding of petrophysical properties of the group is relevant to many disciplines.

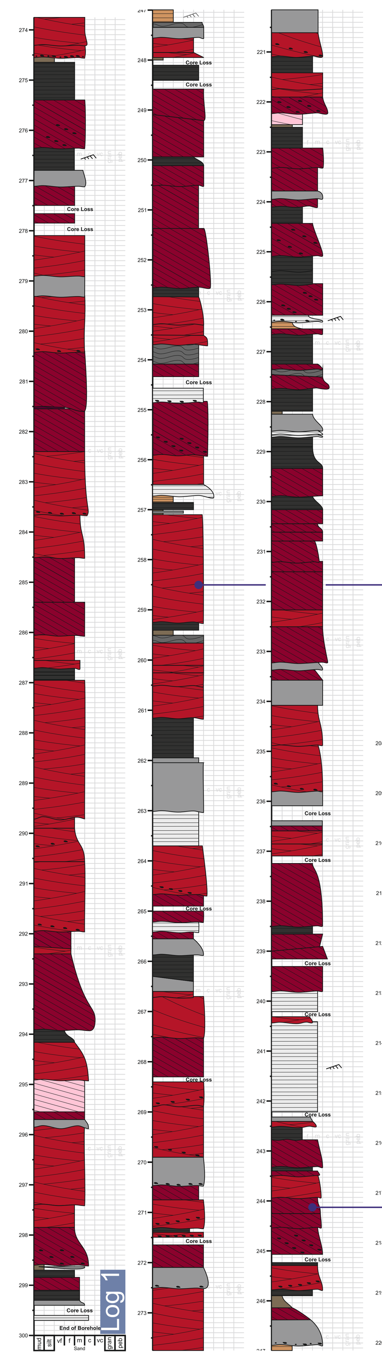
Lithostratigraphy Challenge

The classification of the Sherwood Sandstone is largely based on lithostratigraphy, due to an absence of age-diagnostic fossils. Historically, this succession has been split by using gross differences in composition and character (e.g. pebble content, degree of cementation). However, whilst this approach is successful in areas of lithological variability and good outcrop exposure, and can to some extent be confirmed by borehole cores and logs, it is difficult to apply where variations are more subtle, or outcrop and cores are not available.

The Sherwood Sandstone Group exhibits considerable facies variation to the west of the Pennines (Cheshire and East Irish Sea basins). In many areas, the group can be divided into a tripartite succession comprising a lower fluviatile unit, a middle unit that is predominantly eolian (becoming more so in distal areas), and an upper unit of mixed eolian and fluvial facies which have a complex spatial relationship. In this succession, major erosive bounding surfaces may represent significant time-gaps. Whilst this subdivision is possible across much of central and north-west England, correlations in the north-east (East Midlands Shelf and Cleveland Basin) are difficult to establish and the group remains undivided in the east.

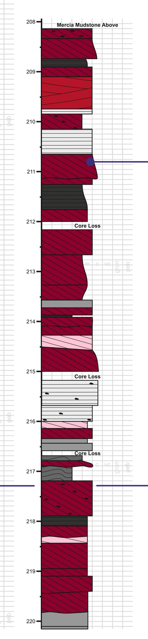
Data sets

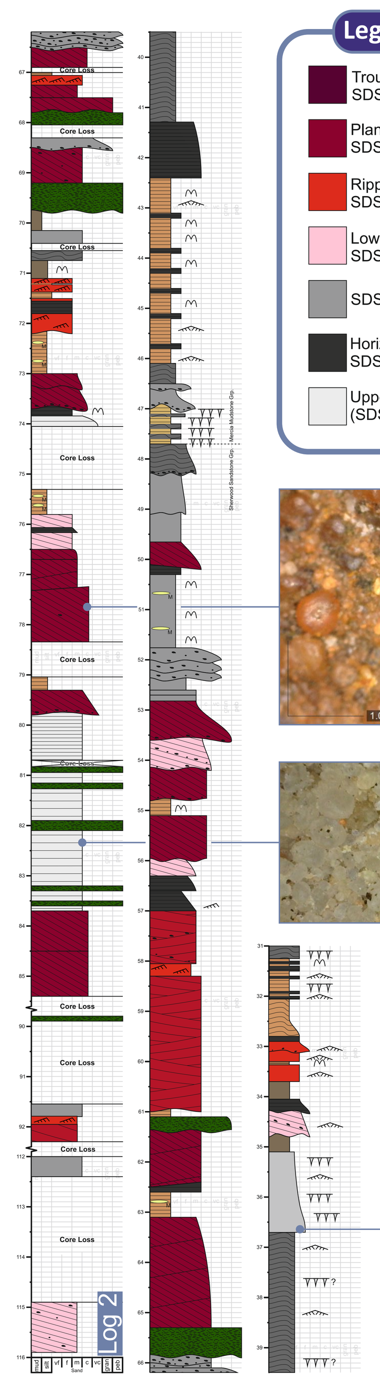
Borehole data

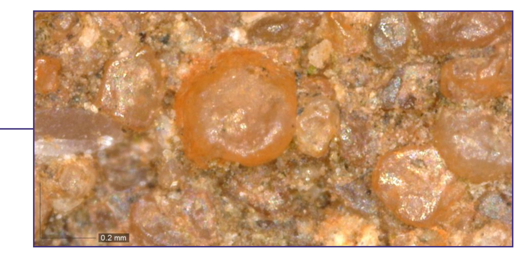


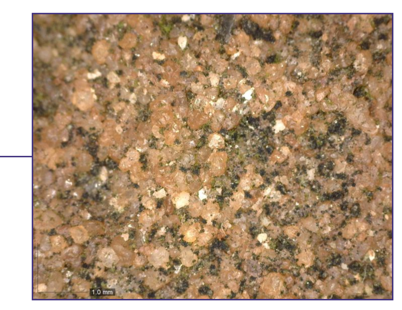
Fluvial vs Eolian

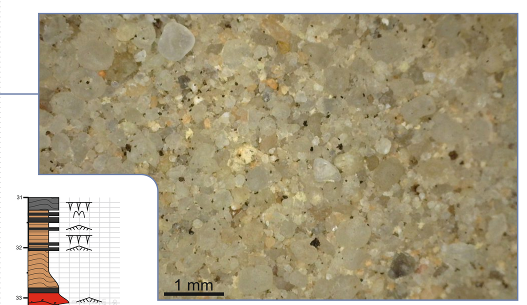
The boreholes detailed here show the general bulk facies assemblages of the Sherwood Sandstone Group. Note the absence of eolian facies types from the boreholes taken from central and eastern England (see map in intro section). Whilst prevailing climatic conditions were conducive to eolian dunefield development across both the east and west of England during the early Triassic the lack of any observed instances in the east is suggestive of a sediment supply or carrying capacity limitation to the wind conditions.









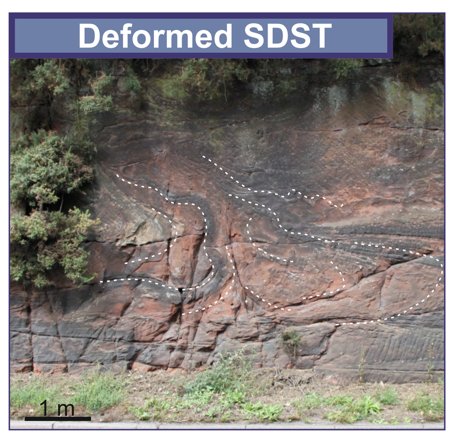


Facies

Eleven principle lithofacies are identified within the Sherwood Sandstone. Indicative photographs of each of the lithofacies is presented below. An understanding of the types and arrangement of lithofacies is important for a number of applied reasons. Crucially the original depositional processes are also responsible for providing the basic initial properties of the lithified material. As such, this is likely to influence any post-depositional diagenetic process which the material is subjected to (e.g. structural or diagenetic etc).
It therefore imperative that a baseline understanding which may impact the arrangement and character of lithofacies is established in order to further an understanding of reservoir conditions

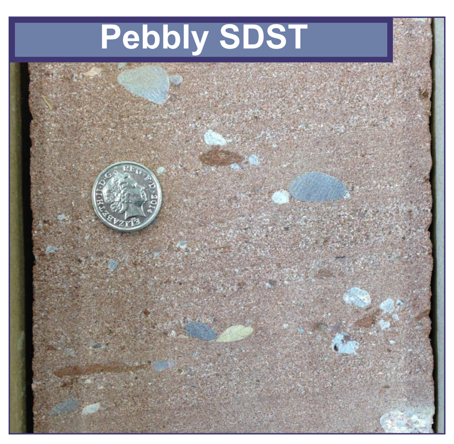
Upper plain beds

Deformed SDST



Muddy SDST

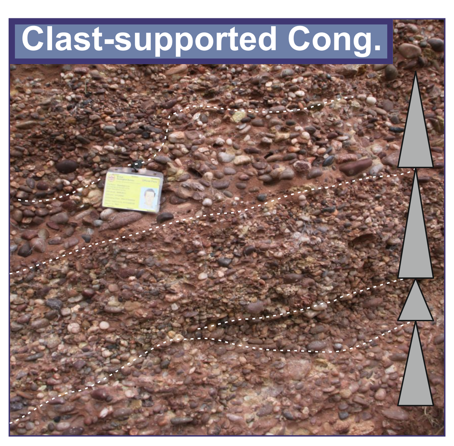
Pebbly SDST



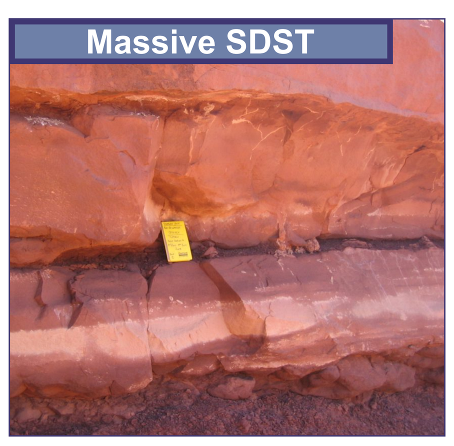
Rippled SDST

Grainflow strata

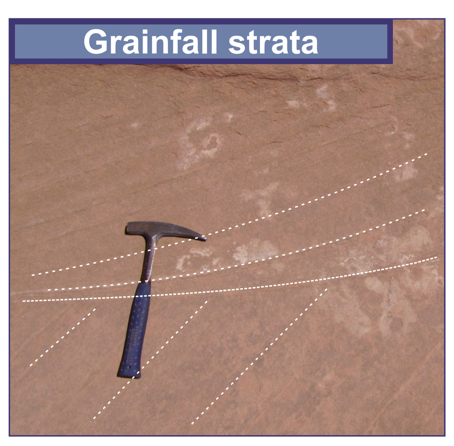
Clast-supported Cong.



Massive SDST

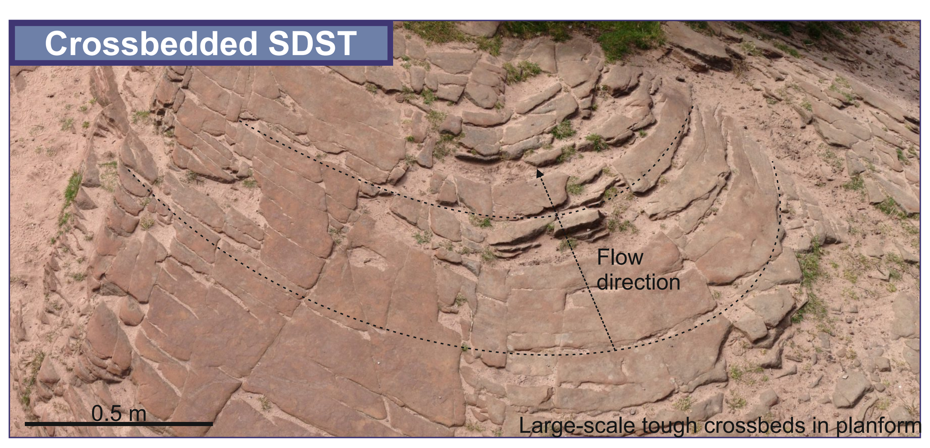


Grainfall strata



Horz. lam. SDST

Crossbedded SDST

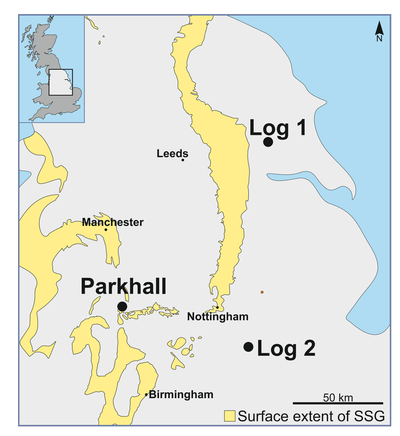


Field and data locations

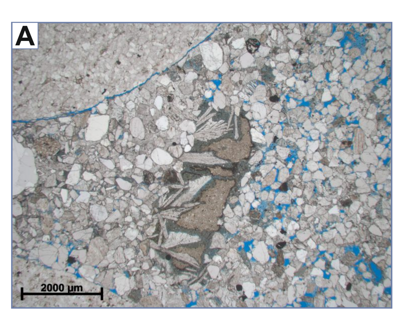
The map opposite indicates the locations of the Sherwood Sandstone Group at the surface.

Data sets includes outcrop and borehole records. Two borehole records are highlighted and shown in the 'Borehole Data' panel above.

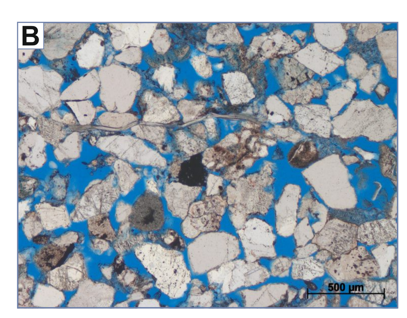
An outcrop example from Parhall Country Park is also presented below. Interestingly this outcrop includes a high proportion of conglomerates, likely derived from nearby topographic highs.



A



B

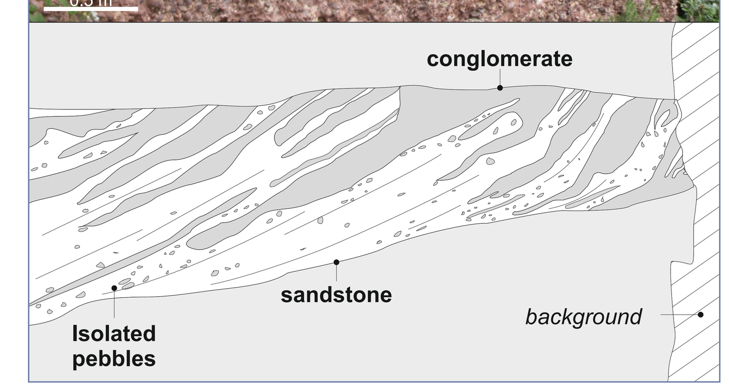


C

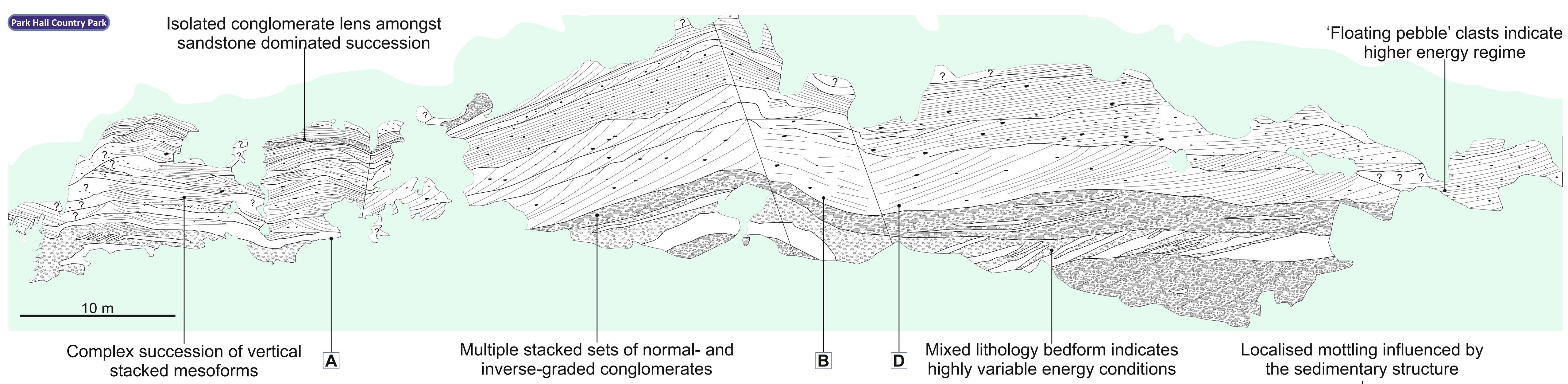
D

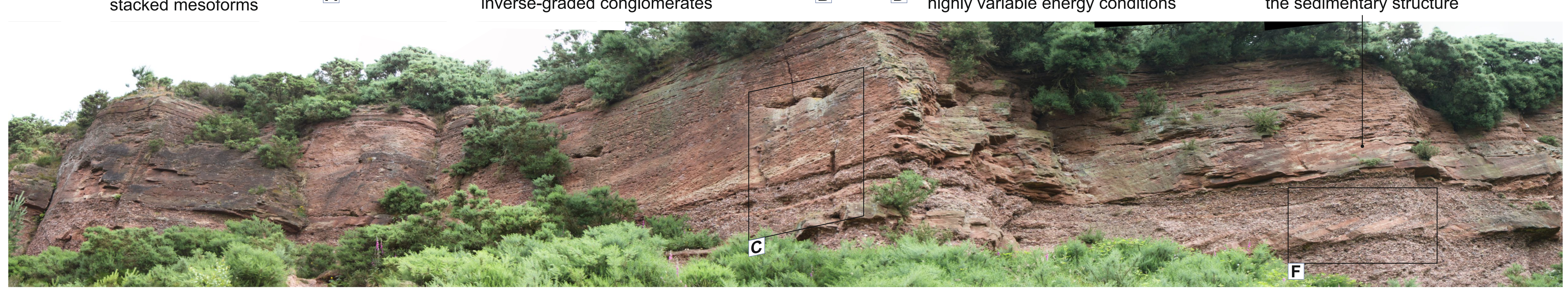
E

F



Park Hall Country Park





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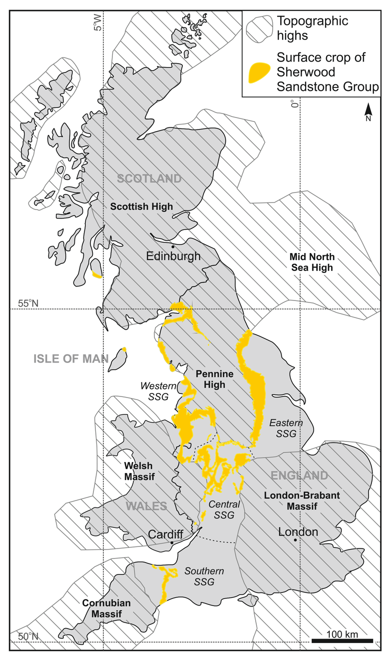
Sherwood Sandstone

The Sherwood Sandstone Group is a critical volume of rock in the UK; it is a commercial hydrocarbon reservoir in both the East Irish and North seas as well as smaller onshore fields. It also represents a potential geological host that is being evaluated for Carbon Capture and Storage (CCS) schemes in north-west Europe. The sandstone is also the second most important groundwater aquifer in the UK, supplying water for potable and industrial use. Stratigraphically, the Sherwood Sandstone lies above productive Coal Measures rocks in many sedimentary basins, including the Stafford, Needwood and Cheshire basins, in addition to the East Midlands Shelf. This close spatial relationship to coalfields, along with the development of large urban conurbations on the Triassic crop (including the cities of Birmingham, Liverpool and Manchester) has left the Sherwood Sandstone vulnerable to pollution by a wide range of contaminants. Of particular note are nitrates from agricultural processes, dense and light non-aqueous phase liquids (D- and L-NAPL) from industry, in addition to a legacy of pollution associated with the closure of coal mines (Hough et al., 2003). Understanding controls to flow through this sandstone is relevant therefore to:

- Pollution studies regarding contamination derived from the Coal Measures
- Contaminant models concerning flow of contaminants directly to the aquifer, from agricultural practices or from the major urban areas
- Modelling hydrocarbon reservoirs (North Sea; East Irish Sea)
- Development of aquifer management plans



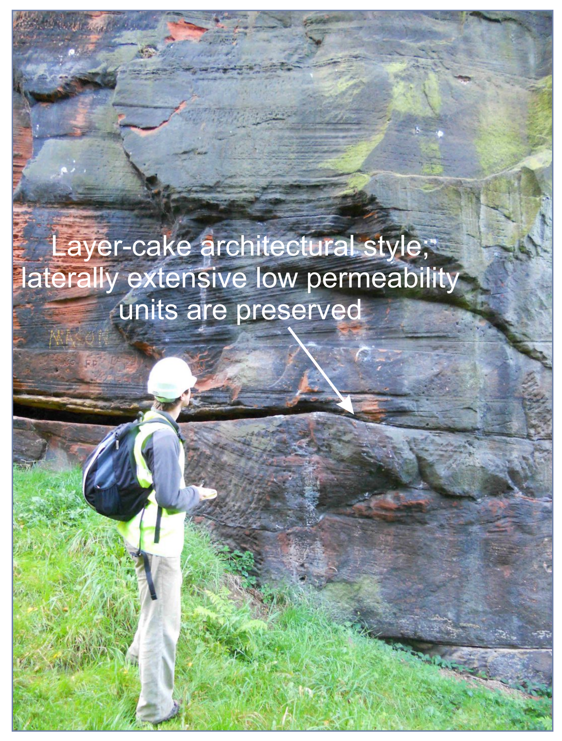
The unit was reappraised by Ambrose et al (2014) who simplified the stratigraphic framework so the unit can be represented seamlessly on 2D maps and by 3D structural geological visulaisations and 4D process-based models. The Sherwood Sandstone Group is present at outcrop beneath over 7500 km2, predominantly in northern England but it also crops out on the Devonshire coast to the south-east of Exeter. At subcrop, however, it is present over a significantly larger area and concealed beneath younger rocks under much of central, southern and eastern England.

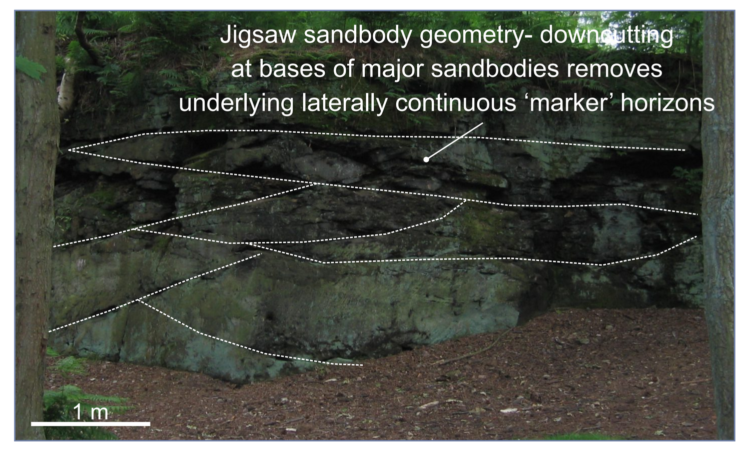
Outcrop

Originally deposited in a number of linked half graben, the Sherwood Sandstone is present in broadly north-trending crops, split by the Pennine Hills into the East Midlands Shelf and a series of smaller basins to the west.

The Sherwood Sandstone was formalised as a Group by Warrington et al (1980), however, nomenclature has evolved since into a confusing array of local terms applicable to a particular sub-basin.

Outcrop Studies I

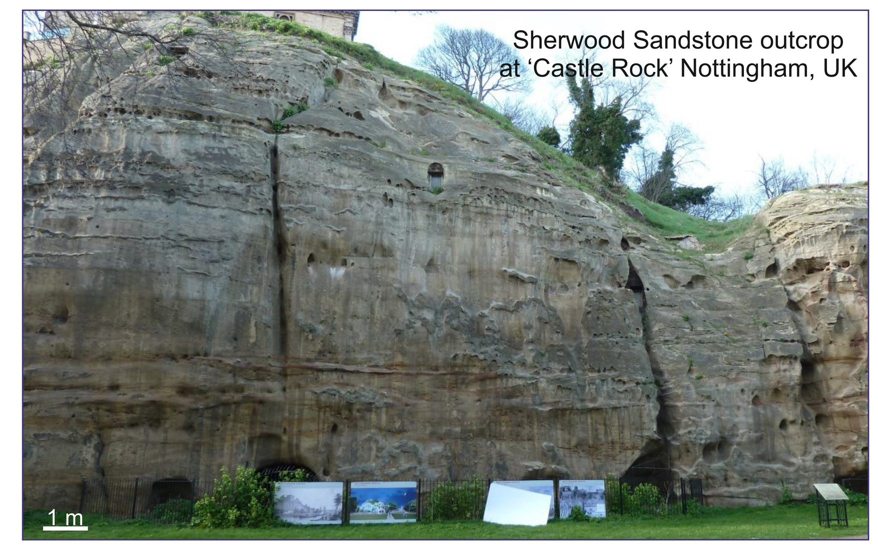




Lawrence et al (2006) outlined two architectural models for the Helby Sandstone (upper Sherwood Sandstone): layer cake and jigsaw-type. The former has a lateral continuity to units, including subordinate mudstone beds, which may provide baffles to flow, whereas the latter jigsaw-type is typified by erosive-based sandbodies that down-cut through underlying mudstone beds and does not typically preserve laterally extensive low-permeability units. The distinction between layercake and jigsaw architectural styles is relevant when considering that in some instances, lateral dispersion of contaminants is fracture controlled (Chen et al., 2012) so maybe more relevant in layercake architectural styles. Contaminant migration in the unsaturated zone is particularly relevant to predicting pollution pathways in urban and peri-urban settings due to the concentration of industry in those areas.

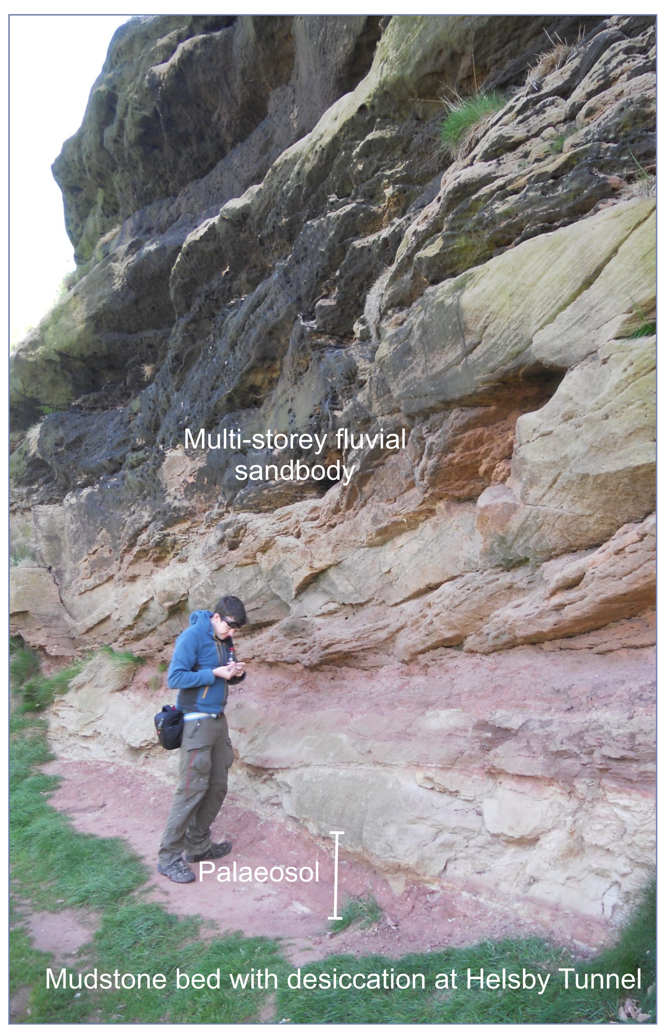
Quantifying lateral extents

Fluid flow through sandstone reservoirs has been described as being influenced by the geometry of depositional units, and the distribution of high porosity-permeability zones (Fraser & Davies, 1998). Data describing the sedimentary architecture and reservoir properties are important variables required to obtain a representative model of a reservoir. Whereas cored sections can provide information concerning the vertical thickness variation of sandbodies and vertical sedimentological relationships, outcrop studies are required to confirm lateral compositional and structural heterogentity and the scales of variability (seismic data is often compromised as many relevant features are below the typical seismic scale, or of insufficient contrast to be imaged).



Sherwood Sandstone outcrop at 'Castle Rock' Nottingham, UK

Understanding the subsurface



Mudstone bed with desiccation at Helsby Tunnel

There are currently several subsurface survey and monitoring projects under development in the UK. These are designed to monitor changes that occur in response to human activities such as hydraulic fracturing, the development of geothermal schemes, or Carbon Capture and Storage (CCS). The Energy Security and Innovation Observing System for the Subsurface (ESIOS; http://www.bgs.ac.uk/research/energy/ESIOS/home.html), is a scheme that is planned to incorporate a group of research facilities, the first of which is likely to be based in north Cheshire, in the north-western part of the UK.

At this site, there is a significant thickness (200 – over 1000 m) of Sherwood Sandstone at rockhead that is fractured and faulted, and in common with the sandstone regionally, comprises both eolian- and fluvial-dominated depositional units, including fluvial channel (lateral accretion), eolian dune, interdune and poorly developed colonized (palaeosol) surfaces (see image to left). Although cored intervals of sandstone are available to quantify the deposition and vertical variations present, questions remain regarding the lateral extent and compositional variability of sandbodies, and their impact on flow, and the monitoring of flow, through the sandstone. Understanding the role of fractures and faults will also be critical to gaining an appreciation of how human activity in the subsurface may impact a principal aquifer in linked half-graben settings. Detailed outcrop studies describing the relationship between depositional events and facies from localities close to the proposed facility will be an important piece of baseline input data from which detailed flow and models of seismicity can be generated.

Depositional physical properties

The Sherwood Sandstone is relatively well-exposed throughout its crop. Zones of better-cemented strata commonly form positive topographical features, such as the prominent range of hills extending southwards from Frodsham and Helsby in Cheshire, NW England, and Cannock Chase in the English Midlands. These better-cemented intervals are commonly fluvial in origin and have been extensively quarried, giving excellent exposures with faces that are often perpendicular to one another, giving an impression of 3D structure. However, eolian units are typically poorer cemented and were not as widely quarried. This gives a bias of outcrop in favour of fluvial units.
Links between primary deposition in the Sherwood Sandstone and present-day petrophysical and hydrogeological characteristics have been the subject of several studies (e.g., Bouch et al., 2006; Beach et al., 1997; Griffiths et al., 2016).
It has been recognised that facies associated grainsize variations were a principal controlling influence on reservoir properties (along with compaction) (Grant et al. 2014).
Due to bed-plane discontinuities, Hitchmough et al (2006) reported development of significant anisotropic permeability, being 23 times greater in the horizontal than the vertical, justifying the need to inform reservoir and aquifer models with data derived from outcrop in addition to vertically cores sections.

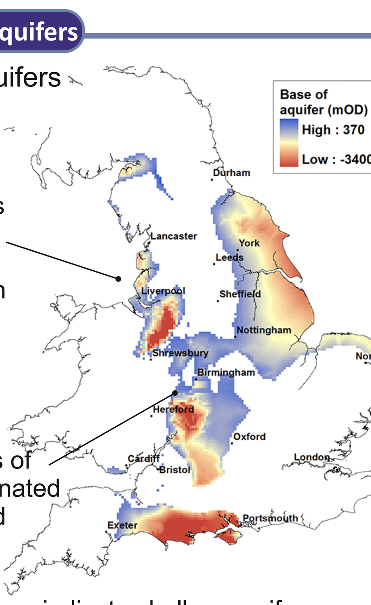
Bimodal coarse and fine sandstone

Inter-laminations of mudstone, siltstone and sandstone

Flowpaths with the Sherwood Sandstone

The Sherwood Sandstone is a dual porosity aquifer that primarily accommodates flow by matrix (intergranular) flow and to a lesser extent fracture flow (Allen et al., 1997; Lawrence et al., 2006). The amount of fracture flow remains largely unknown (Bloomfield et al., 2006), although may be important in certain settings (e.g., where non-aqueous phase liquids are travelling through an aquifer; Lawrence et al., 2006). Allen et al (1997) reported matrix intergranular permeability and porosity values as 0.1 – 10 md-1, and 15 – 30%; Lawrence et al (2006) quote 35% as the maximum porosity. Fracture flow proceeds via bedding (lamination, bounding surfaces), joints and faults (Allen, 1998), with deformation bands impeding flow. Bloomfield et al (2006) called for a better understanding of sedimentary architecture and how this influences the hydraulic conductivity of different sandstone lithofacies.

Triassic Aquifers



Blue areas indicate shallow aquifers
Red indicate deeper aquifer bodies.

Aquifer properties

Regional scale geological models may be appropriate as a first pass tool in understanding and predicting flow through aquifers. However, studies have concluded that assumptions are required due to the lack of information describing even the most basic data such as fracture density in Triassic sandstones (e.g., Hitchmough et al., 2006). Studies of outcrop can contribute to closing this knowledge gap, but outcrop itself can be subject to a natural bias in distribution.

Hornung & Aigner (2002) recognised the potential to relate lithofacies types to petrophysical rock types, as a way of classifying Triassic strata based on depositional energy (clay mineralogy and abundance).

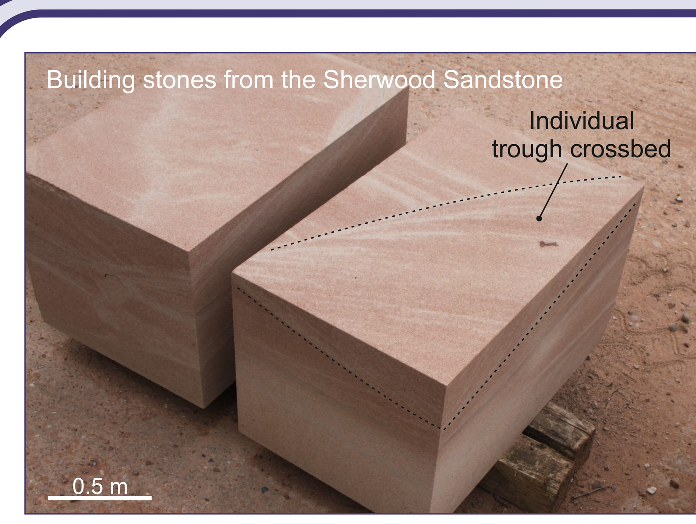
Outcrop Studies II

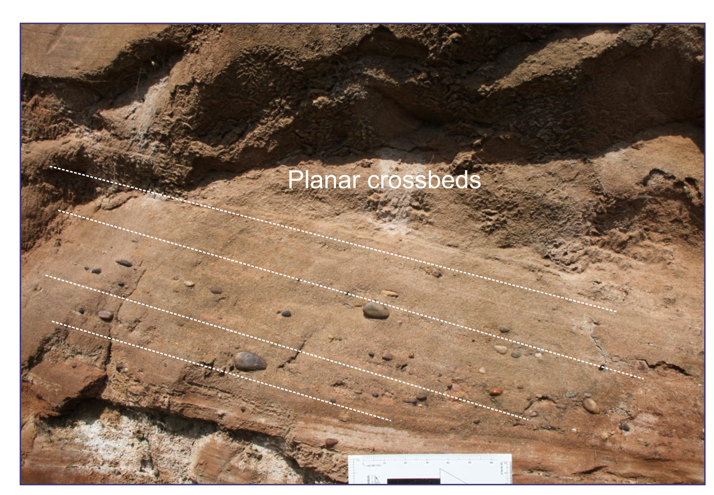
Depostional heterogeneity

Characterisation of sandstone reservoirs can proceed with the identification and mapping of features identifiable on the seismic scale (typically 10-20 m). However, there is significant and marked variation in lithology and petrophysical properties at the sub-seismic scale due to changes in depositional setting that give rise to marked lithological variability; this is clearly seen at an exposure from the upper part of the Sherwood Sandstone at Frogsmouth Quarry, Runcorn, Cheshire, NW England. Here, dune beds are exposed with damp and rare wet interdune units, preserved due to the interaction with a shallow, fluctuating water table (Mountney & Thompson, 2002).

The recognition that lithological variation can influence the development of diagenetic cements and the style, occurrence and amount of fractures has been discussed by many authors (e.g., Shipton & Cowie, 2003; Hough et al., 2006; Griffiths et al., 2016). This is of particular relevance to the identification and understanding of features relevant to reservoir quality at the sub-seismic scale, as the scale of individual element-bounding surfaces in the Sherwood Sandstone (a mixed Aeolian-fluvial sandstone that accumulated in a terrestrial setting) often less than 2 m, with many published examples of depositional heterogeneity at a similar scale (e.g., Wakefield et al., 2015; Bouch et al., 2006; Newell, 2006; Hornung & Aigner, 2002).

Primary depositional influence on flow





Bedrock heterogeneity in terms of bed character, composition and lateral and vertical extents in terrestrial sedimentary environments is partly influenced by changes in depositional facies, which can be significant on scales as little as 20 cm (Hitchmough et al., 2006). As groundwater flow (and that of constituent contaminants, if present) will preferentially concentrate along zones of higher permeability, and may indeed pond, resting on top of units of lower permeability (Lawrence et al., 2006), an understanding of depositional processes and hierarchy is relevant to contaminant management strategies. This natural variability is often beyond the resolution of many models which often consider the aquifer as isotropic at the scale of the modelled volume. In many settings, primary deposition influences the permeability and hydraulic conductivity of the reservoir, therefore having a direct impact on fluid flow, with all 'large bedding plane discontinuities' in the Sherwood Sandstone from Cheshire in one study being considered transmissive to flow (Hitchmough et al., 2006). The influence of depositional environment has an obvious effect on intergranular flow, but it is also a factor in the development of certain styles of fracture that impede flow. The relationship in 3D of this heterogeneity (controlled by the interplay between different depositional environments) is a key input parameter to groundwater conceptual models, where an understanding of groundwater flow, and the controls on the rate and direction of flow are relevant to aquifer management strategies, the mitigation of pollution (Allen et al., 2013) and the modelling strategy itself (Chen et al., 2012).

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