Project Proposal

Reservoir quality of Triassic saline aquifers and the sealing capacity of their caprocks, North Sea region and East Irish Sea: tools to identify potential CO_2 storage sites (TriStore)

Prof Quentin Fisher[1,2], Prof Nigel Mountney[1], Dr Adriana del Pino Sanchez[2], Dr Luca Colombera[1,3]

1 – School of Earth and Environment, University of Leeds, UK

2 – PETRIVA Ltd, University of Leeds, UK

3 – Department of Earth and Environmental Sciences, University of Pavia, Italy

Executive Summary

- This document contains a proposal to conduct a study on the reservoir quality of Triassic sandstone successions and the sealing capacity of their caprocks in the North Sea region and East Irish Sea.
- The principal aim of the proposed research project is to identify the most suitable sites for large-volume subsurface CO_2 storage.
- Results from the project will also be of relevance for those planning medium enthalpy geothermal energy in Triassic sandstone successions.
- The principal objective of the project is to integrate existing large-volume data sources (e.g. from core, cuttings, wireline-log and outcrop) to enable lithological characterization and petrophysical property of the reservoir and caprocks at multiple scales: pore scale, facies units, and architectural elements.
- The project will deliver a large relational database that can be used to characterize reservoir quality and top seal capacity. This database will serve to minimize costs for subsurface petrophysical characterization and lithological prediction of Triassic aquifers and their caprocks; it will enable ranking of potential subsurface reservoir targets using a quantitative approach.
- The project will be undertaken by the University of Leeds and PETRIVA Ltd; both have significant experience and long track records in the key areas of research required to make this project a success. In particular, the project will make specific use of skills and facilities in the following areas:
    - Reservoir quality and petrophysics of sandstones generated during the **PETGAS Joint Industry Project (JIP)**, which has been running since 2010 and has developed technology to integrate cuttings and wire-line log analyses to estimate reservoir quality when no core is available.
    - **The Fluvial, Eolian & Shallow-Marine Research Group JIP** has been running since 2008 and has developed the world's largest and most sophisticated databases describing the sedimentary architecture of clastic fluvial, aeolian, lacustrine and shallow-marine successions. These databases are applied to predict multiscale lithological heterogeneity in subsurface successions, and to model connectivity of both reservoir compartments, as well as baffles and barriers to flow, especially in relation to UK Triassic successions.
    - The **Wolfson multiphase flow laboratory** has compiled a large database of the single and multiphase flow properties of both faults and caprocks. It already has significant data on faults within Triassic sandstones of the UK and has unique laboratory facilities for measuring the top seal capacity of shale under reservoir stress conditions.
- The project is divided into 6 work packages (WPs):
    - WP1 – Collation of data on available core, cuttings and wire-line logs.
    - WP2 – Generation of a database of the microstructural and petrophysical properties of Triassic sandstones.
    - WP3 – Generation of a sedimentological database of lithofacies units and architectural elements that comprise Triassic Sandstone successions.
    - WP4 – Cuttings analysis and integration with wire-line log data.
    - WP5 – Fault rock properties
    - WP6 – Caprock properties
- The project will cost £50,000 per sponsor per year and will last for 3 years; a minimum of four sponsors are required for the project to run.

Introduction

Carbon storage in both depleted oil and gas fields, and very large-scale saline aquifers is a potentially important technology that will help the UK meet its reduced GHG emission targets. Depleted oil and gas fields are often considered the most promising storage options since much is already known about their reservoir properties and performance. Depleted gas fields also have a large pore volume available because they have been produced by natural depletion and low compressibility brine has not yet entered the vacant pore space. However, a key problem with using depleted oil and gas fields is that existing production wells are generally not suitable for re-use in CO2 storage due to incompatibility issues associated with high-pressure CO2 injection, as well as the fact that wells and their associated infrastructure are now approaching or beyond their working lifespan and will have experienced significant erosion and corrosion. Drilling new wells is complicated by the fact that low reservoir stresses reduce the total horizontal stress, meaning that the reservoir may fracture under the weight of the drilling fluid or cement column.

Regionally extensive saline aquifers could be used to store very large volumes of CO2 but, because they have not been used as petroleum reservoirs previously, their reservoir quality is poorly understood, the extent of fault-related compartmentalization is unknown, and the top seal capacity is untested. These unknowns mean that characterization of these aquifers to assess their potential for CO2 storage could be time-consuming and expensive. Yet saline aquifers offer the greatest potential as safe, very large-scale, and permanent underground repositories for CO2.

The School of Earth and Environment at the University of Leeds has sector-leading expertise and experience in subsurface lithological and structural reservoir and top seal characterization: we have the capability to apply our predictive database and analytical methodologies to quantitatively characterize reservoir quality, fault compartmentalization and top seal capacity in Triassic sandstone reservoirs of the North Sea region, Irish Sea, and surrounding regions of the UK.

- The PETGAS Joint Industry Project (JIP) has been running since 2010 and has developed technology to integrate cuttings and wire-line log analysis to estimate reservoir quality where no core is available.
- The Fluvial, Eolian & Shallow-Marine Research Group JIP has been running since 2008 and has developed the world's largest and most sophisticated databases describing the sedimentary architecture of clastic fluvial, aeolian, lacustrine and shallow-marine successions. These databases are applied to predict multiscale lithological heterogeneity in subsurface successions, and to model connectivity of both reservoir compartments, as well as baffles and barriers to flow, especially in relation to UK Triassic successions.
- The Wolfson multiphase flow laboratory has compiled a large database of the single and multiphase flow properties of both faults and top seals. It already has significant

data on faults within Triassic sandstones of the UK and has unique laboratory facilities for measuring the top seal capacity of shale under reservoir stress conditions.

Here, we propose to leverage this experience to undertake a large-scale study on reservoir quality, fault and top seal capacity of Triassic sandstones in the North Sea region, Irish Sea and adjoining regions. Results will provide the basis for identifying suitable very large-scale subsurface CO2 storage sites that will be required if the UK is to meet its imminent and long-term future Net Zero targets.

Review of knowledge gaps

To be suitable for CO_2 storage, it is necessary to demonstrate that subsurface structures will have the following attributes:

- **Secure** such that leakage rates back to the surface can be shown to be significantly below 0.01% per year (Hepple and Benson, 2005; Shaffer, 2010).
- **Sufficient pore volume** to allow the storage of CO_2 from the main point sources that they are intended to serve.
- **Sufficiently high permeability** to allow CO_2 to be injected at the rate at which it is being produced from the main point sources that they are intended to serve.
- **Appropriate intra-reservoir migration pathways** to allow injected CO_2 to progressively fill the subsurface storage volume gradually from the site(s) of injection.

It is necessary to carefully characterize individual subsurface prospects to ensure that these criteria are met. Unlike production of energy, CCS is at an early stage of commercialization and few projects are commercially viable in the current climate. Yet, it is essential to keep the costs of subsurface characterization as low as possible. The primary focus of the current proposal is to develop workflows and databases that will allow this to be achieved. The project will use data and samples that are already currently available. Many UK Triassic saline aquifers and their caprocks have been penetrated by a large number of wells and a significant amount of wire-line log data, as well as cuttings samples, are available for analysis. Core of Triassic sandstone is available from numerous boreholes and many outcrops expose Triassic reservoir and caprocks in the UK. This project will characterize the key properties to determine and quantitatively characterize key types of the heterogeneity in the reservoir and sealing elements of proposed storage sites. Additionally, it will develop tools for assessing potential CO_2 storage sites away from known closures.

Aim and objectives

The aim of this proposed research project is to devise a novel and bespoke database-informed approach to identify and rank the most suitable UK Triassic sites for large-volume subsurface CO_2 storage.

Specific research objectives are as follows: (i) to construct a database of available UK core, cuttings and wire-line logs within the Triassic interval; (ii) to generate a database of the microstructural and petrophysical properties of Triassic sandstones; (iii) to generate a sedimentological database of lithofacies units and architectural elements that comprise UK Triassic successions; (iv) to analyse cuttings and to develop a workflow for their effective integration with and relation to wire-line log data; (v) to analyse and characterize mechanisms of fault seal; and (vi) to analyse and characterize mechanisms of caprocks.

Project proposal

This research project comprises 6 interrelated work packages (WP1-WP6), which relate to the stated research objectives.

WP1: Collation of data on available core, cuttings and wire-line logs

Creation of a comprehensive database of wells within the North Sea region and East Irish Sea Basin (EISB) that have penetrated the Triassic sandstone successions. Work will involve the assembly of details relating to core and cuttings availability, and a wire-line log listing, including provision of a data-quality index. This is achievable through the existing national data repository and the open access databases managed and administered by the North Sea Transition Authority (NSTA). Existing core poroperm data, saturation, density, mineralogical, and sedimentological data will be compiled.

WP2: Generation of a database of the microstructural and petrophysical properties of Triassic sandstones

A database of the microstructural and petrophysical properties of Triassic sandstones will be generated that can then be used to estimate reservoir quality from the microstructure of cuttings samples obtained from wells for which core is not available. Special attention will be paid to assessing the diagenetic history of the samples and whether this can be related to factors such as depositional environment. The first stage in this process is to create a database of the microstructural and petrophysical properties of core of Triassic sandstone samples. In the first instance, we will sample core from the BGS core store from directly adjacent to where core plugs used for routine core analysis have already been taken. If necessary, we will also collect new core plugs from core or outcrop and measure their porosity and permeability, as well as their microstructural properties.

Microstructural information will be generated by automatically scanning samples in the backscattered electron mode using our Tescan VEGA 3 scanning electron microscope (SEM). This allows us to collect several thousand SEM images from each sample, which can be combined to create high-resolution panoramas (**Figure 1**). These can be used to manually identify analogues based on the microstructure of cuttings. The large number of images to be generated is also ideally suited to training machine learning algorithms, such as convolutional neural networks (CNNs), which can then be used to automatically analyse SEM images of cuttings samples.

To help create a link between the microstructure of Triassic sandstones and their petrophysical properties, we will load all data into our bespoke data visualization and data mining software package, PETMiner. This software allows the user to visualize up to five properties on a single graph and it allows points on cross-plots to be replaced by images, thereby allowing the user to assess the key controls on properties (Figure 2).

Our previous work on tight gas sandstones has been highly successful at linking the position of points on porosity-permeability cross-plots with specific microstructural features, such as the thickness of illitic grain coats. However, many of the Triassic sandstone successions to be considered will not have experienced significant mesodiagenetic alteration and their properties will be controlled by grain-size and sorting. We therefore intend to obtain data on grain size and sorting from image analysis of the backscattered electron (BSE) images and using a particle sizer to analyse disaggregated sandstones.

The same microstructural and grain-size data can be obtained from cuttings so that we can identify suitable analogues on our database as a basis for estimating poroperm properties of Triassic samples in reservoirs where core is not available.

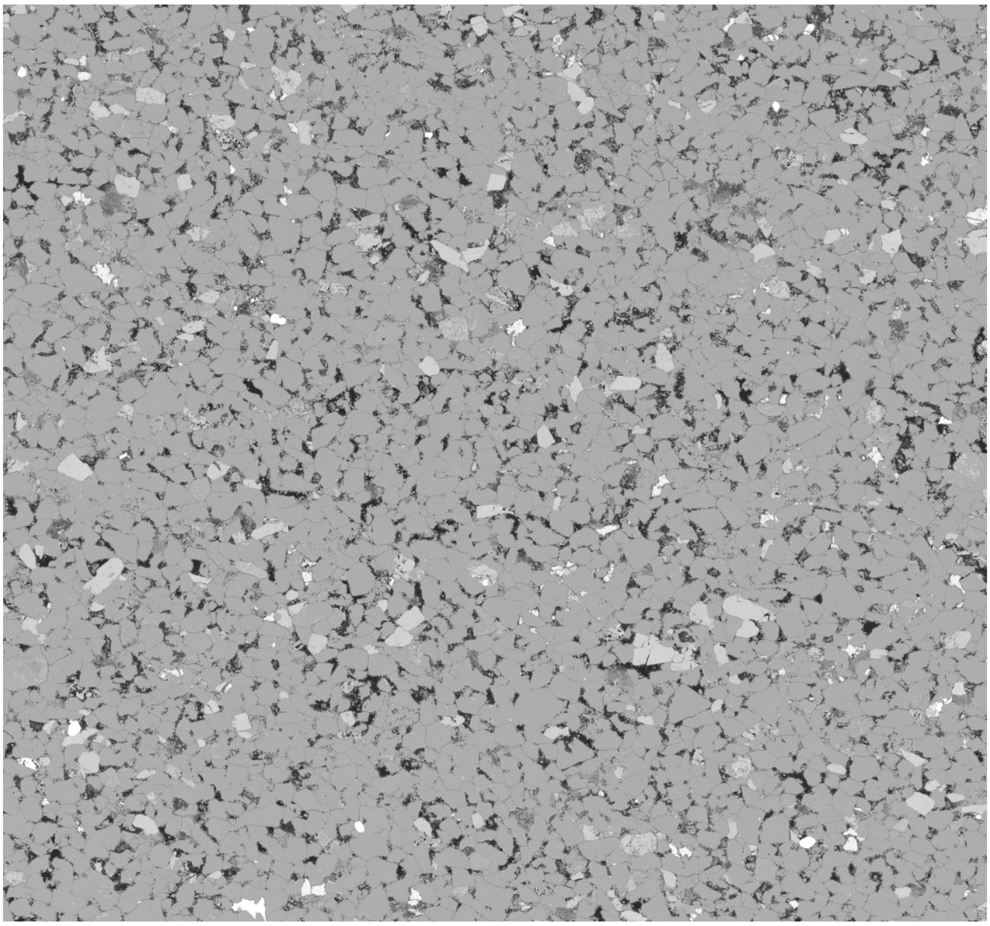


Figure 1 *High-resolution panorama of a sandstone sample created by combining >1000 BSE images; the image is of a 1 cm^2 area of the sample and has a total of ~1 billion pixels.*

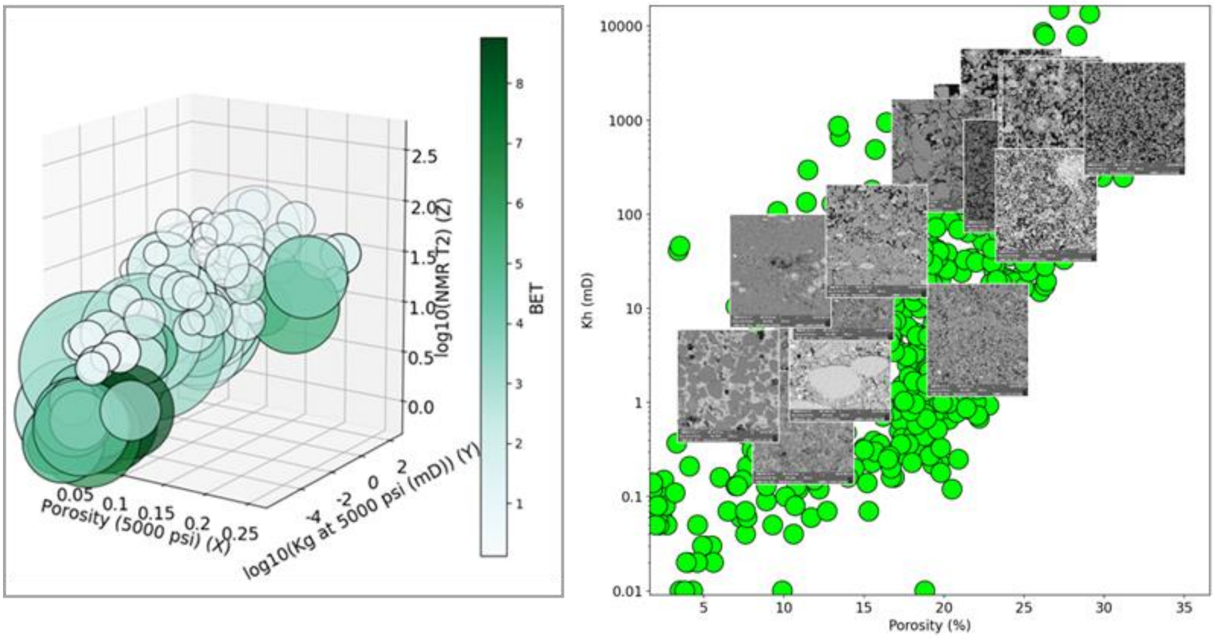


Figure 2 *Left. Plot of porosity vs permeability vs nuclear magnetic resonance (NMR) T2 with the size of points proportional to the illite content and the colour proportional to Brunauer-Emmett-Teller (BET) surface area. Right. Porosity-permeability plot in which selected points have been replaced by BSE images.*

WP3: Generation of a sedimentological database of lithofacies units and architectural elements that comprise Triassic Sandstone successions

United Kingdom Triassic successions chiefly comprise the Bacton and Haisborough groups of the southern North Sea region, and the Sherwood Sandstone, Mercia Mudstone and Penarth groups of the East Irish Sea Basin and onshore regions. Regionally across the North Sea equivalent formations also include the Skagerrak and Lunde formations. Formations of these lithostratigraphic units record sedimentation in a range of channelized and non-channelized fluvial, overbank, aeolian, lacustrine, shoreline, sabkha, and marginal to shallow-marine palaeoenvironmental settings. At times, these related sub-environments developed coevally to accumulate and preserve a highly varied sedimentary architecture. Thus, Triassic successions exhibit considerable lithological heterogeneity at both local (10^0-10^1 m) and regional scales (10^2-10^4 m) scales, resulting in highly variable poroperm distributions, and therefore complicated fluid-flow properties. Moreover, some lithological elements are prone to complex patterns of fracturing and diagenesis.

To date, no systematic and quantitative characterization of the varied lithological architecture of UK Triassic successions has been attempted at the scale of facies units, architectural elements and larger depositional elements, for the purpose of generating quantitative facies models to predict the distribution, extent and continuity of high permeability thief zones, and low-permeability barriers and baffles to flow.

This work package will address this shortcoming by further developing and utilizing the world's largest and most sophisticated relational databases for the characterization of the sedimentary architecture of fluvial and aeolian successions: the Fluvial Architecture Knowledge Transfer System (FAKTS) and the Database of Aeolian Sedimentary Architecture (DASA). These two related databases have been developed at the University of Leeds by the Fluvial, Eolian & Shallow-Marine Research Group (FRG-ERG-SMRG) since 2010.

This project will capture, assemble and incorporate quantitative data (e.g. unit geometries and topological arrangements) and qualitative data (e.g. information on palaeoclimate, basin setting) into the FAKTS and DASA databases. Data detailing the sedimentary architecture of subsurface and outcropping Triassic successions will be acquired from published literature, public-domain reports, core logs, wireline logs and outcrop studies. Sedimentological data from previous core analyses will be integrated into a standardized classification to provide consistency and make legacy data usable. Additional sedimentary logging and repeat logging of selected sections will ensure the creation of a robust database. Data specific to UK Triassic successions will be used to build a series of quantitative sedimentary models applicable to examine and test the impacts of lithological heterogeneity on fluid-flow pathways and behaviour. This will be achieved through application of a well-established, sector-leading database-informed approach, based on the use of bespoke database queries and methodologies (Colombera et al., 2013, 2016). This approach will establish linkages between lithological and petrophysical properties. We will build quantitative facies models based on data on the geometry, proportion, topology (juxtaposition) and lithological heterogeneity of sedimentary geobodies that comprise sedimentary components of identified UK Triassic sandstone-dominated successions. These database-informed models will integrate complementary information drawn from the database of microstructural and petrophysical properties from WP2. We will feed these database outputs to geostatistical algorithms and will apply these to build numerical geological models required for later flow and solute-transport models (as well as heat-flow models relevant to prospects considered suitable for geothermal energy). We will do this by considering scenarios defined on a statistical basis to account for geological uncertainty in our estimates. Figures 3-19, below, demonstrate the FAKTS and DASA databases and illustrate how they can be applied for purposes of quantitative subsurface lithological characterization and prediction.

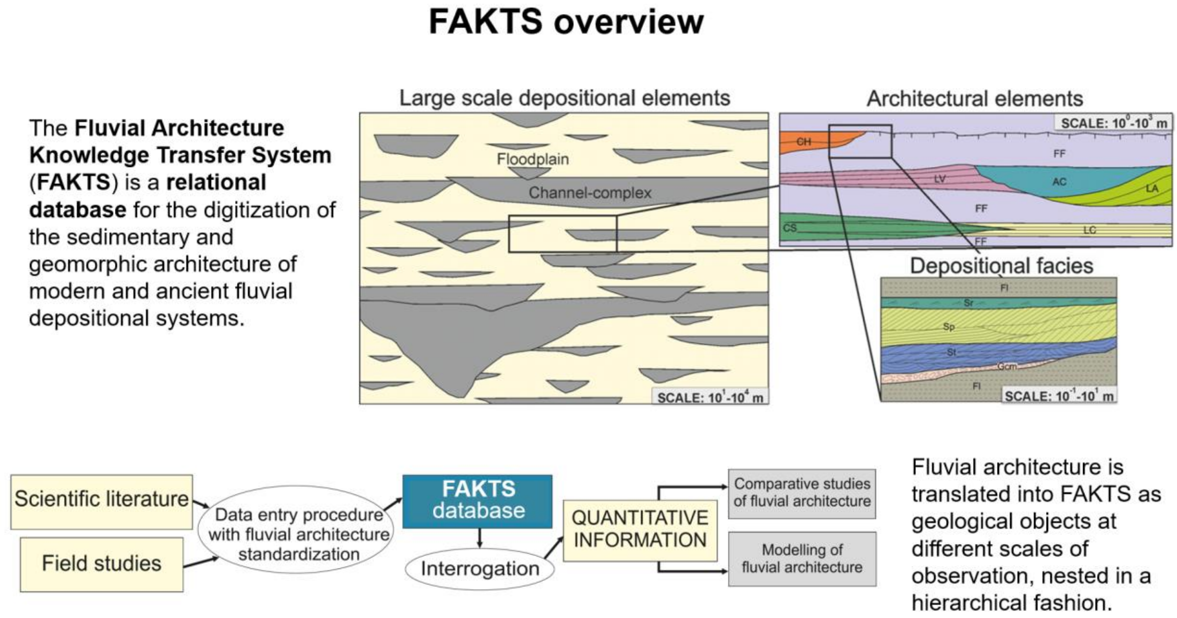


Figure 3 *The Fluvial Architecture Knowledge Transfer System (FAKTS) is the world's largest and most sophisticated relational database on the sedimentology of fluvial systems and their preserved successions. This project will incorporate hard (i.e. quantitative) and soft (i.e. qualitative) data relating to UK subsurface and outcropping Triassic fluvial sedimentary successions into FAKTS. The database will be used integrate multiple datasets on the sedimentology and stratigraphic architecture of Triassic fluvial successions for the purpose of building bespoke quantitative facies models that describe their sedimentary heterogeneity quantitatively and at multiple scales of observation. This project will use FAKTS to characterize Triassic fluvial successions of the UK and to build bespoke facies models.*

FAKTS overview

ARCHITECTURAL ELEMENTS

14 interpretive classes of sub-environments, commonly with geomorphic expression. Modification of scheme by Miall (1996)

Code	Legend	Architectural element type
CH		Aggradational channel fill
DA		Downstream accreting macroform
LA		Laterally accreting macroform
DLA		Downstream + laterally accreting macroform
SG		Sediment gravity-flow body
HO		Scour-hollow fill
AC		Abandoned-channel fill
LV		Levee
FF		Overbank fines
SF		Sandy sheetflood dominated floodplain
CR		Crevasse channel
CS		Crevasse splay
LC		Floodplain Lake
C		Coalbody
		Undefined elements

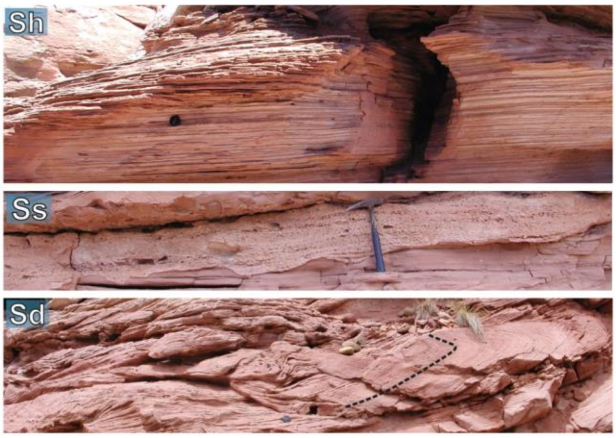
Barform types from dryland fluvial successions.

Figure 4 *FAKTS stores data and information on the geometry and topology (stacking patterns) of fluvial sedimentary architectural elements. This project will assess the proportion, distribution and nature of juxtaposition of fluvial architectural elements of different types present in UK Triassic fluvial successions.*

FAKTS overview

FACIES UNITS

Units bounded by second-order or higher-order bounding surfaces, characterized by given textural and structural properties. 25 textural ± structural classes. Modification of scheme by Miall (1996)



Code	Legend	Lithofacies type
G-		Gravel to boulders - undefined structure
Gmm		Matrix-supported massive gravel
Gmg		Matrix supported graded gravel
Gcm		Clast-supported massive gravel
Gci		Clast-supported inversely-graded gravel
Gh		Horizontally-bedded or imbricated gravel
Gt		Trough cross-stratified gravel
Gp		Planar cross-stratified gravel
S-		Sand - undefined structure
St		Trough cross-stratified sand
Sp		Planar cross-stratified sand
Sr		Asymmetric-ripple cross-laminated sand
Sh		Horizontally-laminated sand
Sl		Low-angle cross-bedded sand
Ss		Scour-fill sand
Sm		Massive or faintly laminated sand
Sw		Symmetric-ripple cross-laminated sand
Sd		Soft-sediment deformed sand
F-		Fines (silt, clay) - undefined structure
Fl		Laminated sand, silt and clay
Fsm		Laminated to massive silt and clay
Fm		Massive clay and silt
Fr		Fine-grained root bed
P		Paleosol carbonate
C		Coal or carbonaceous mud
		Undefined facies

Figure 5 *FAKTS stores data and information on the proportion and distribution of fluvial facies units that represent the constituent internal components of larger architectural elements. This project will assess the proportion, distribution and nature of juxtaposition of fluvial facies units of different types present in UK Triassic fluvial successions.*

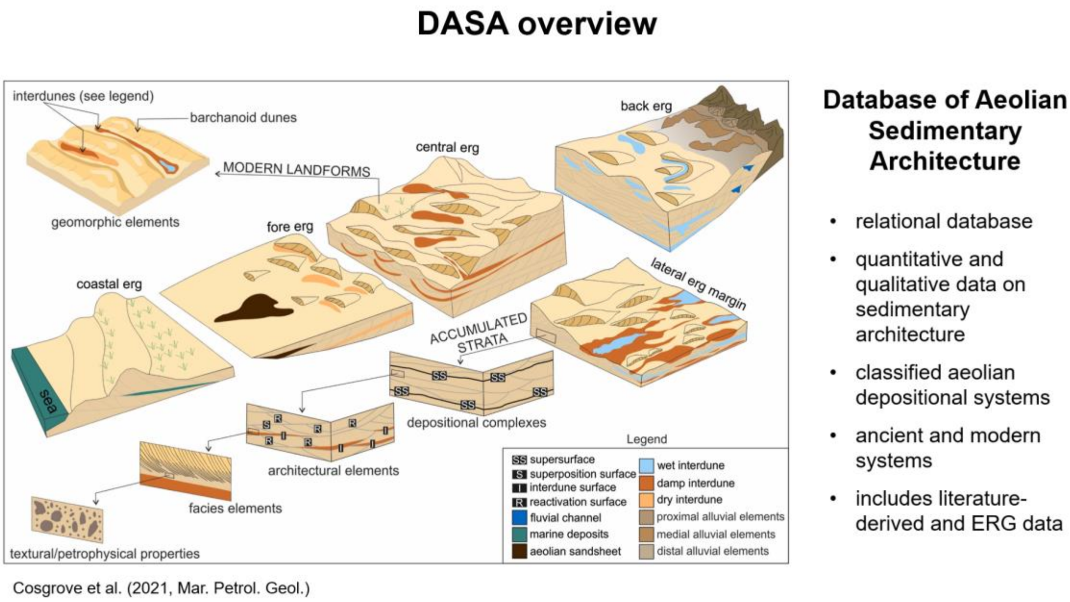


Figure 6 *The Database of Aeolian Sedimentary Architecture (DASA) is the world's largest and most sophisticated relational database on the sedimentology of aeolian systems and their preserved successions. This project will incorporate hard (i.e. quantitative) and soft (i.e. qualitative) data relating to UK subsurface and outcropping Triassic aeolian sedimentary successions into DASA. The database will be used to integrate many datasets on the sedimentology and stratigraphic architecture of Triassic aeolian successions for the purpose of building bespoke quantitative facies models that describe their sedimentary heterogeneity quantitatively and at multiple scales of observation. This project will use DASA to characterize Triassic aeolian successions of the UK and to build bespoke facies models.*

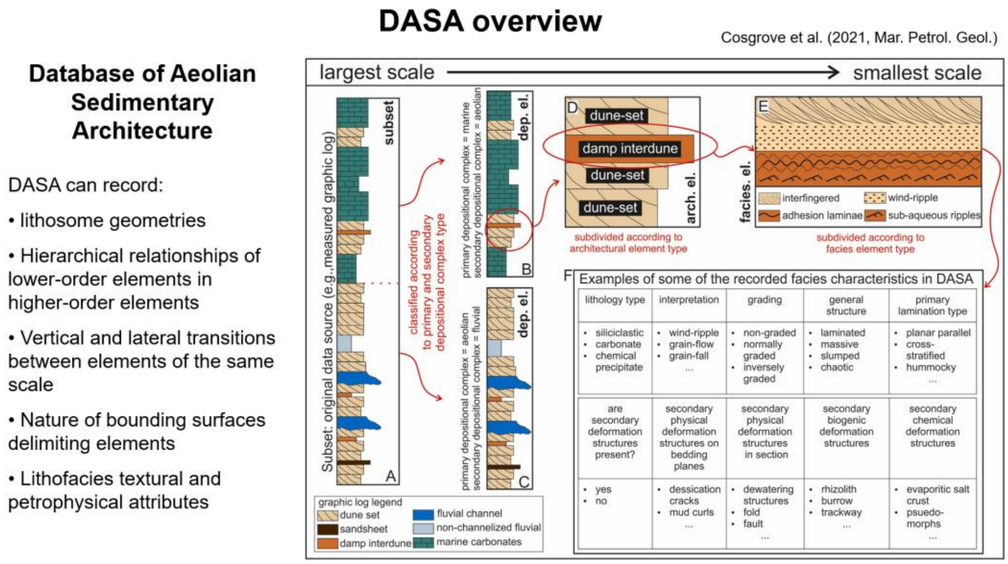


Figure 7 *DASA stores data on lithosome geometries, hierarchical relationships and textural properties, for facies units, architectural elements and larger depositional complexes. This project will assess the proportion, distribution and nature of juxtaposition of aeolian facies, units and architectural elements of different types present in UK Triassic aeolian successions.*

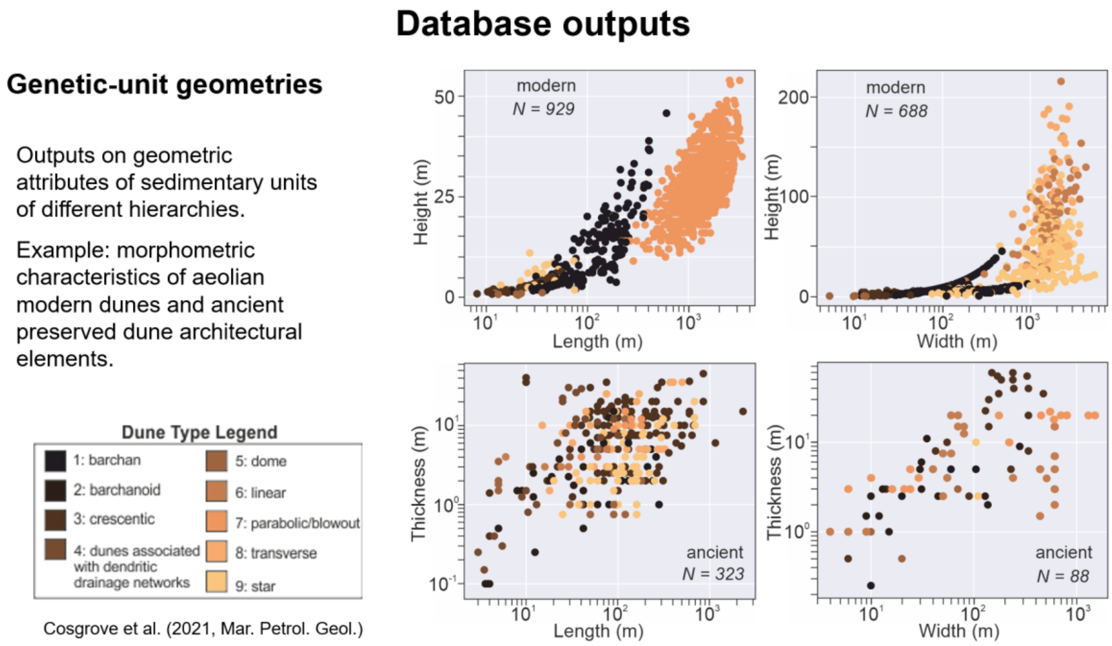


Figure 8 *DASA can be queried to pull back data describing relationships between a range of parameters for both modern aeolian systems and ancient preserved successions. This approach will be used to build bespoke quantitative facies models for different UK Triassic sandstone-dominated successions.*

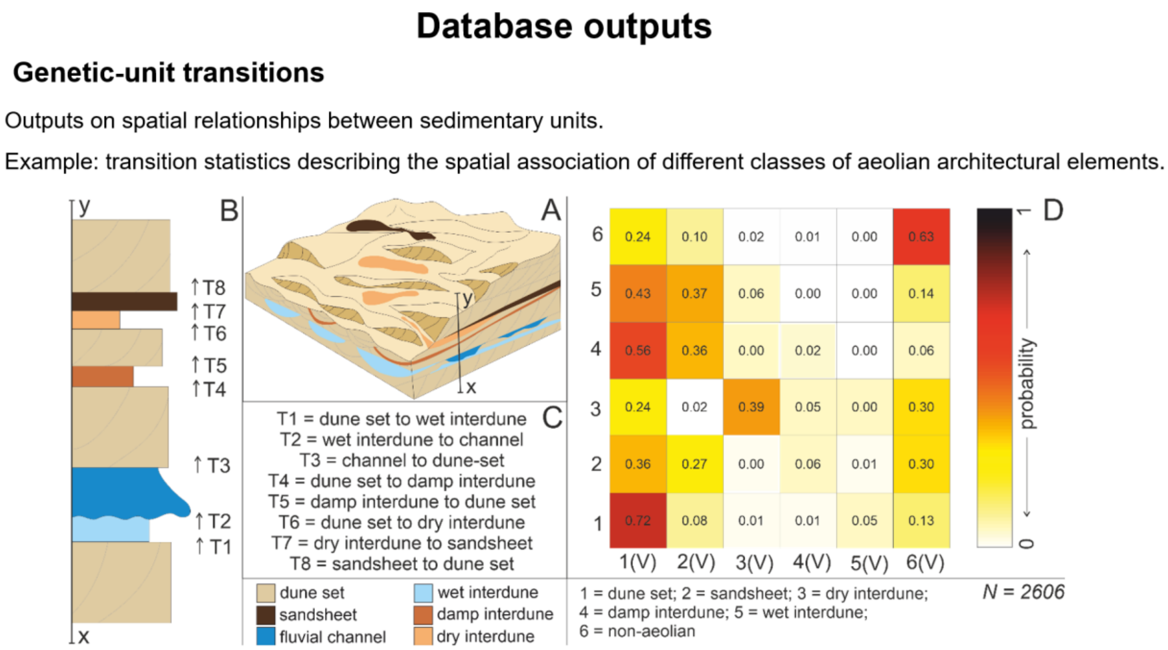


Figure 9 *DASA will be queried to quantify transition statistics (either vertically or laterally) between lithosomes of different types. This is important for establishing how units capable of acting as baffles or barriers to flow might be distributed and juxtaposed adjacent to effective reservoir units within a 3D rock body.*

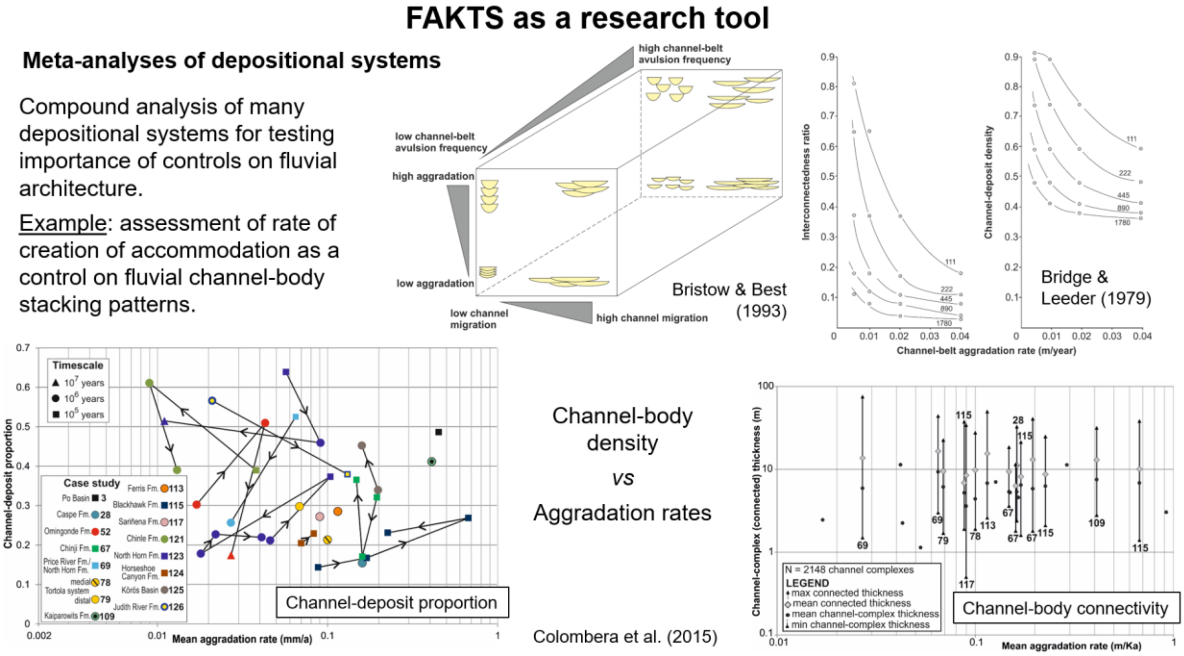


Figure 10 *FAKTS will be employed to consider how allogenic factors such as rates of aggradation, channel avulsion frequency and channel migration likely acted to control the stacking patterns of accumulated and preserved fluvial architectural elements of different types within UK Triassic successions.*

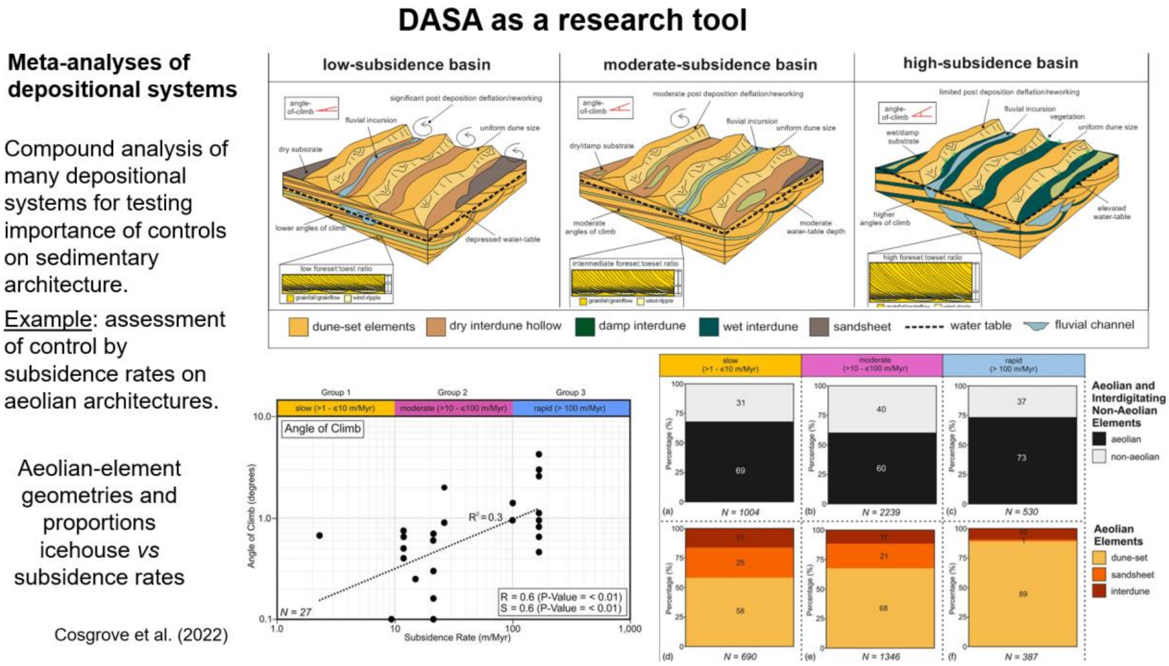


Figure 11 *DASA will be employed to consider how allogenic factors such as rates of basin subsidence likely acted to control the stacking patterns of accumulated and preserved aeolian architectural elements of different types within UK Triassic successions.*

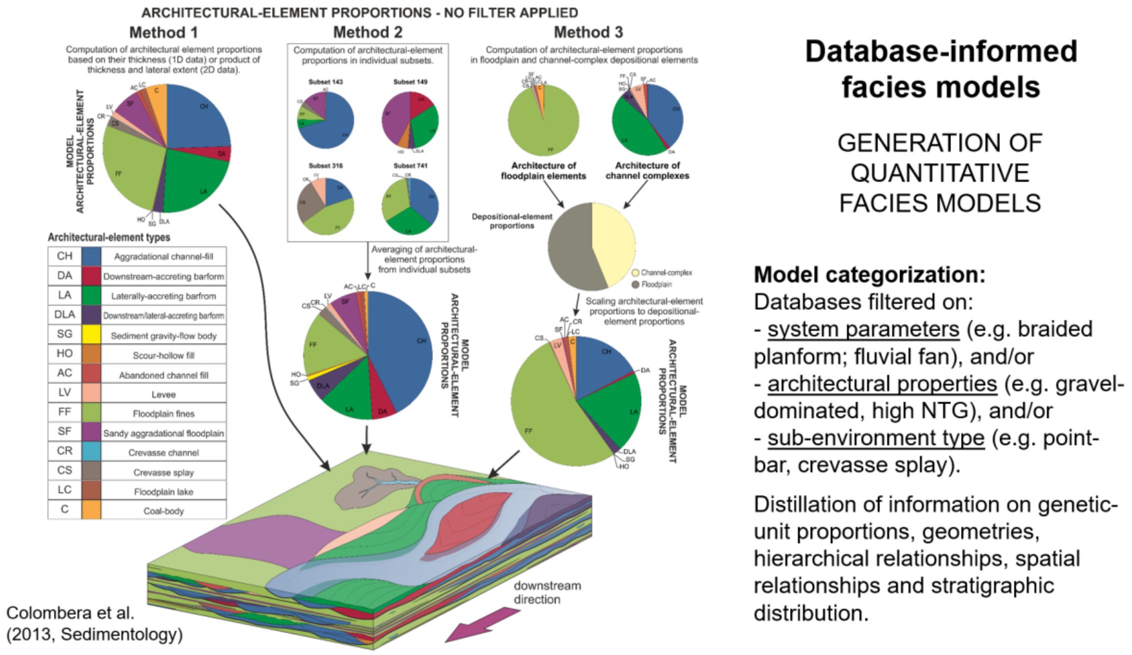


Figure 12 *A database-informed approach will be used to build quantitative facies models that are bespoke to particular UK Triassic successions being considered as sites for CCS, such as those related to existing depleted oil and gas fields with known closures, but also very large Triassic saline aquifer successions more widely.*

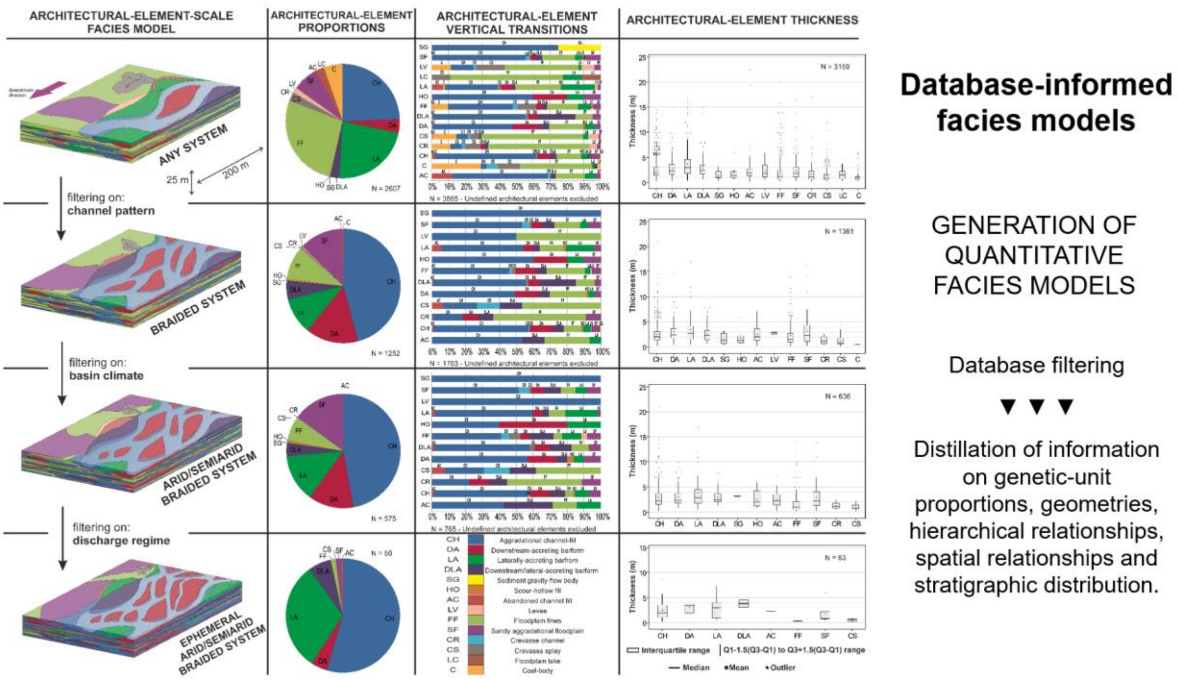


Figure 13 *The large volumes of data captured and stored in FAKTS and DASA means that bespoke quantitative facies models can be highly tailored based on the application of a varied range of database "filters". In the example illustrated, successive filters are applied to tailor a model specifically for ephemeral braided fluvial systems developed under the*

influence of an arid or semi-arid climate regime, as was the case in many UK Triassic fluvial basins.

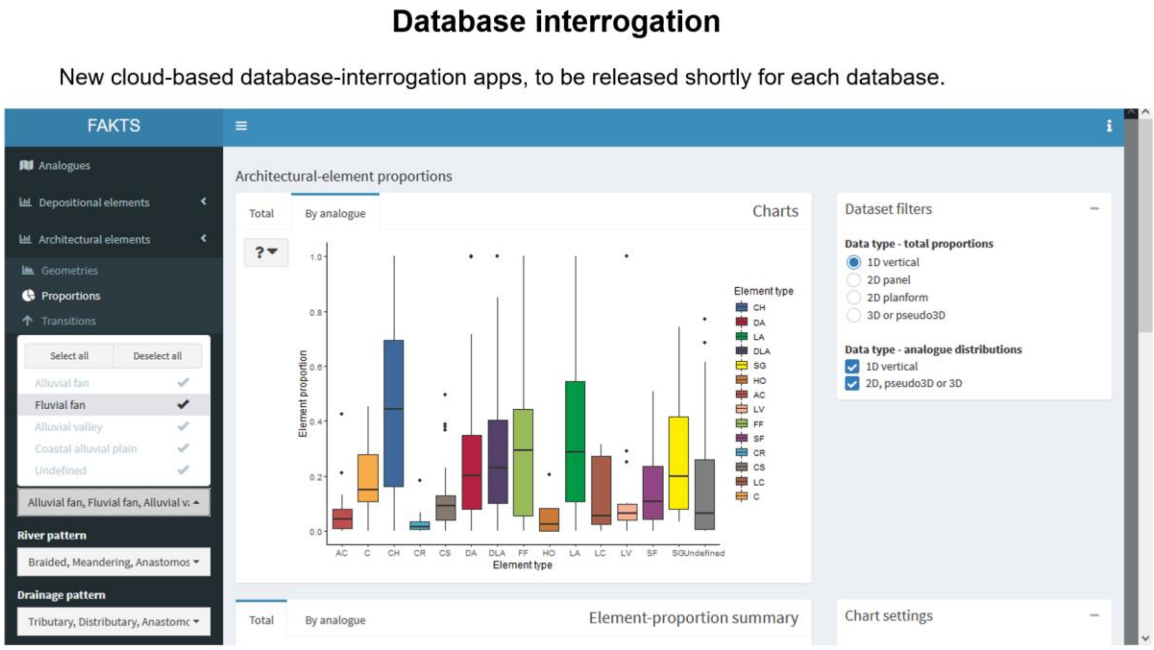


Figure 14 *The FAKTS and DASA databases are supported by a cloud-based database interrogation application that will be accessible to project sponsors. This example page is from the FAKTS database.*

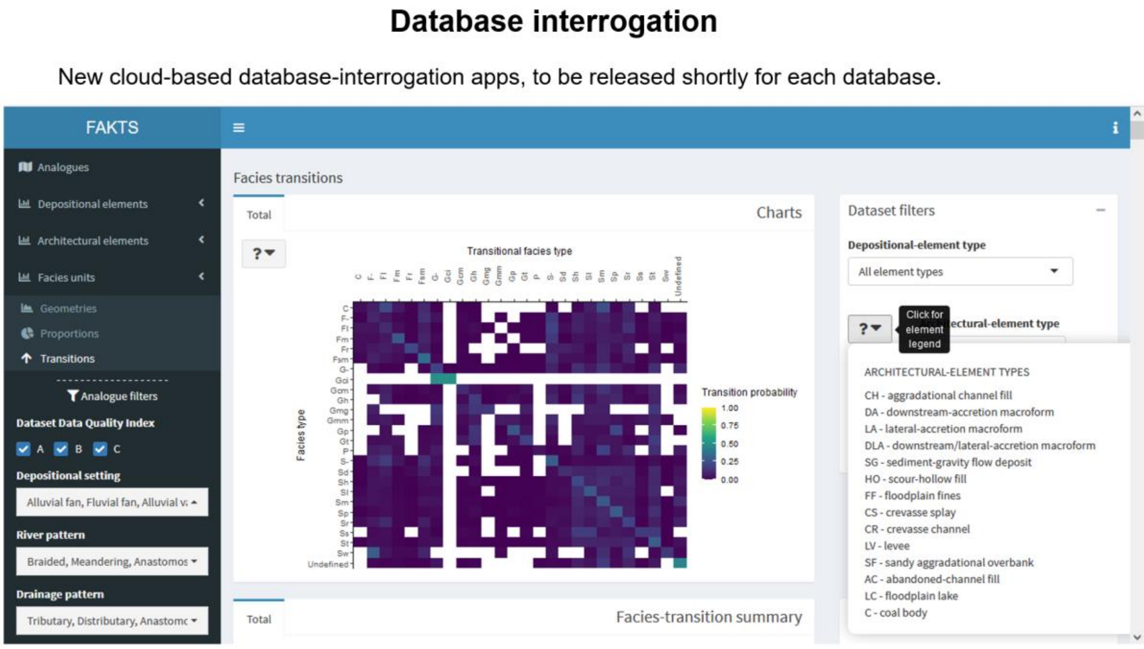


Figure 15 *The FAKTS and DASA databases are supported by a cloud-based database interrogation application that will be accessible to project sponsors. This example page is from the FAKTS database.*

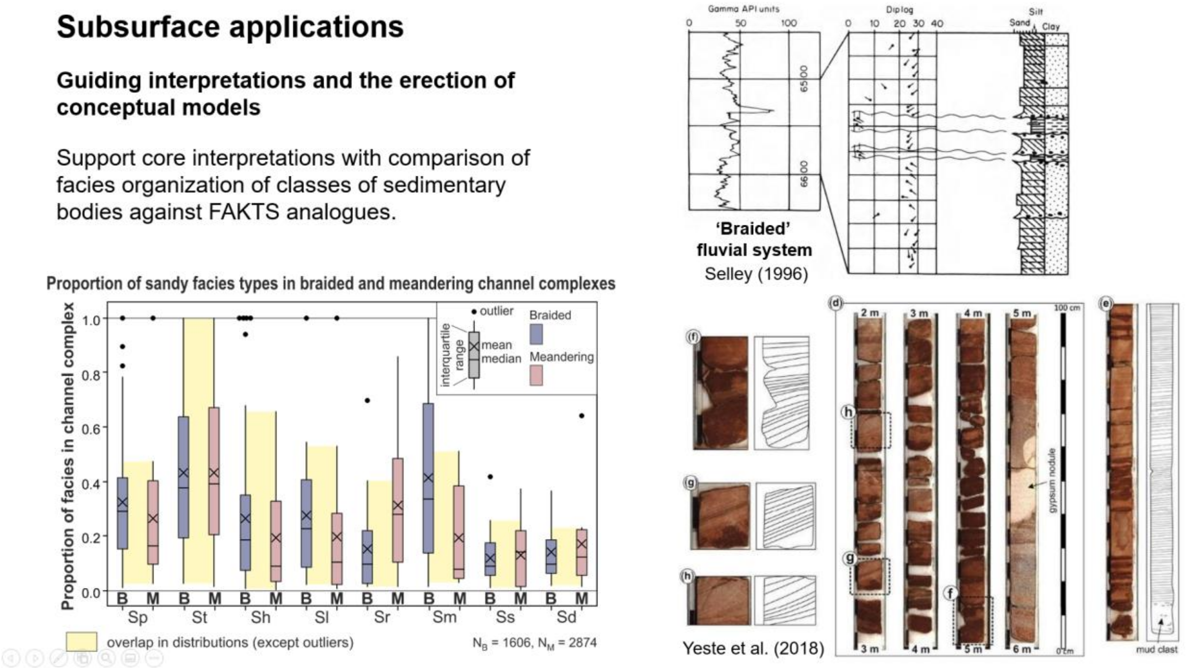


Figure 16 *The databases will be employed to guide subsurface interpretations for a range of UK Triassic successions.*

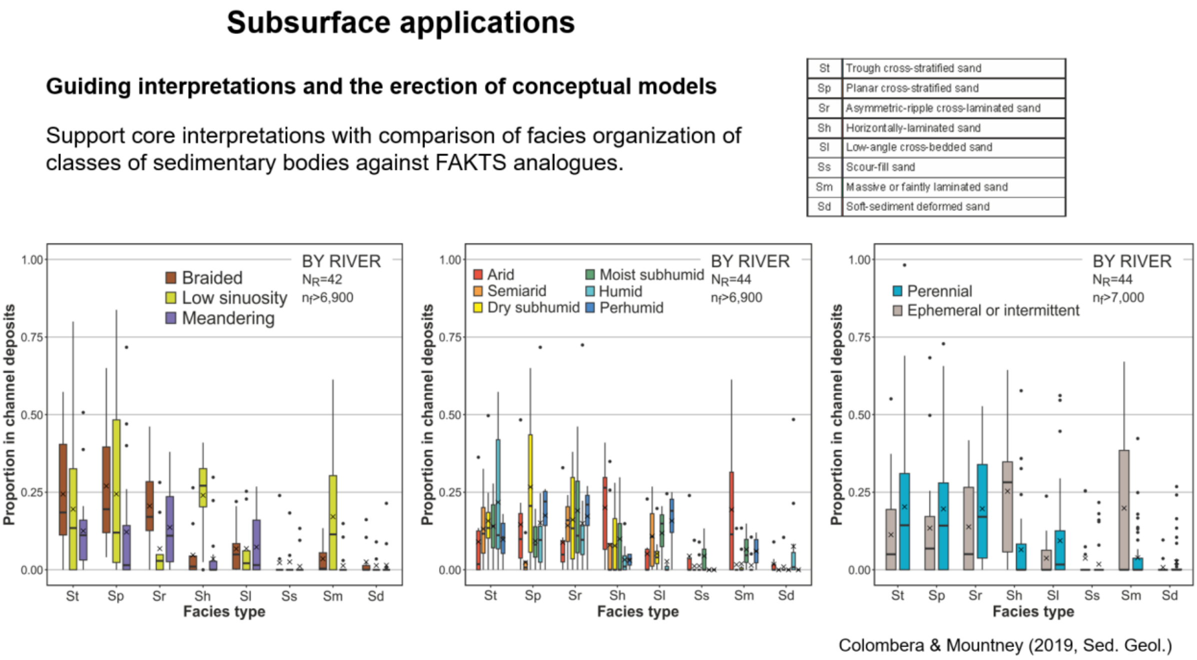


Figure 17 *The databases will be employed to guide subsurface interpretations for a range of UK Triassic successions.*

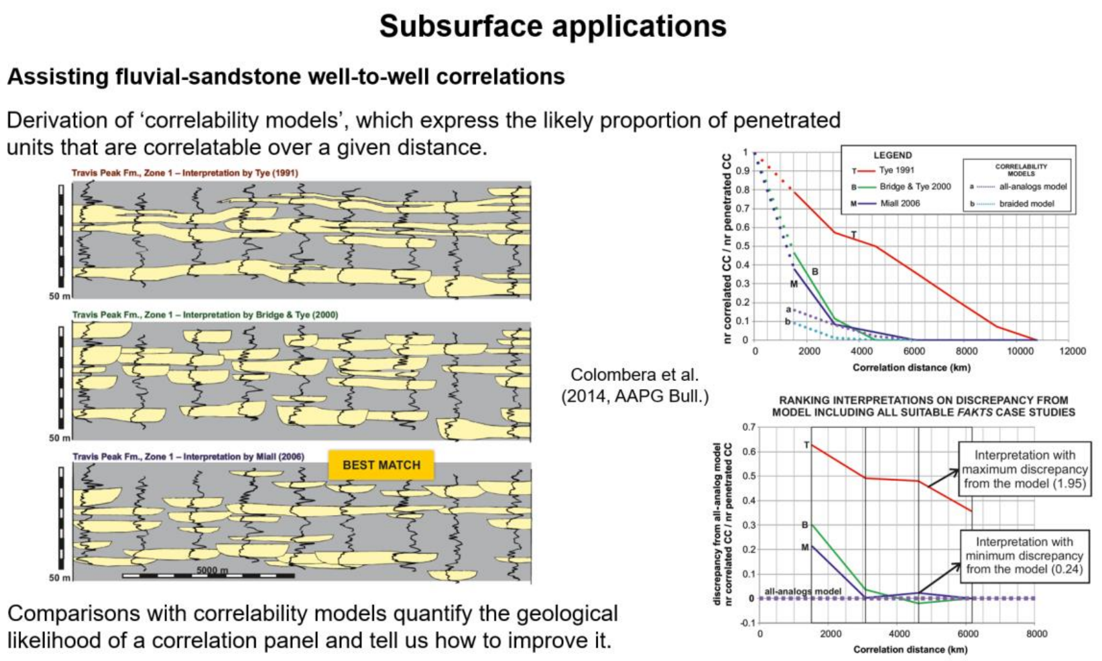


Figure 18 *The databases will be employed to guide subsurface interpretations for a range of UK Triassic successions.*

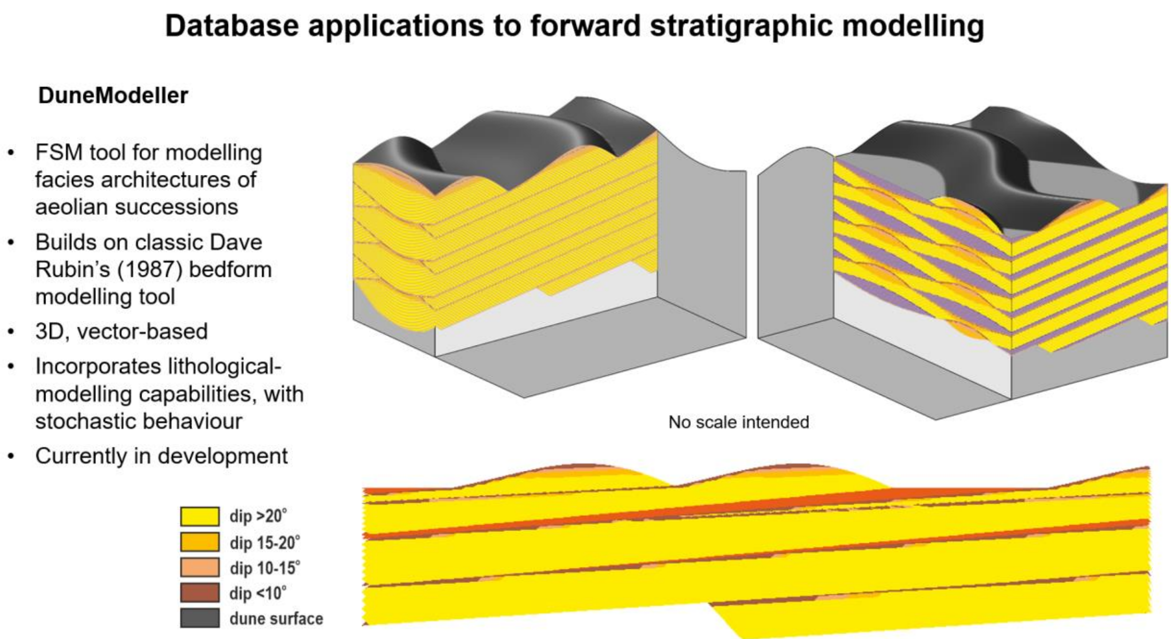


Figure 19 *The databases support advanced forward stratigraphic modelling (FSM) methodologies. The example illustrated shows how the DASA database has been used to constrain an in-house developed FSM, "DuneModeller". This model predicts the 3D geometry, distribution and topology of architectural elements of aeolian dune and interdune origin. This project will build bespoke 3D models to predict reservoir architecture using this approach.*

WP4: Cuttings analysis and integration with wire-line log data

The microstructural data collected on core and outcrop samples during WP2 will be used to develop machine learning techniques, specifically convolutional neural networking (CNN) to automate the interpretation of porosity and permeability relationships. These data, where porosity and permeability are known, will be used to train the convolutional neural network.

The research group behind this convolutional neural networking in core samples have already begun developing these techniques during the well-established PETGAS joint industry project carried out at the University of Leeds, which was initially set up by the Industrial Technology Facilitator (since merged with the Oil and Gas [now NetZero] Technology Centre) and has received ~£2 million of sponsorship from nine companies over the last 12 years. The technology is already at a stage that it can automatically classify microstructures into different rock types, which may then be used to estimate porosity-permeability relationships within approximately 1.5 orders of magnitude of scatter (Figure 20). Although this level of accuracy is already very useful, we aim to continue development of the technology to increase accuracy yet further.

Once the CNN technique has been trained and tested, it will be used to determine porosity and permeability from cuttings samples. This can then be integrated with wireline log data from selected wells. In addition to cuttings available from numerous wells that targeted the Triassic interval, many more cuttings are additionally available from wells that targeted deeper successions (e.g. Carboniferous plays). Utilising these additional cuttings data will expand the database to enable characterization of the Triassic interval in regions where it was not a primary target but was penetrated.

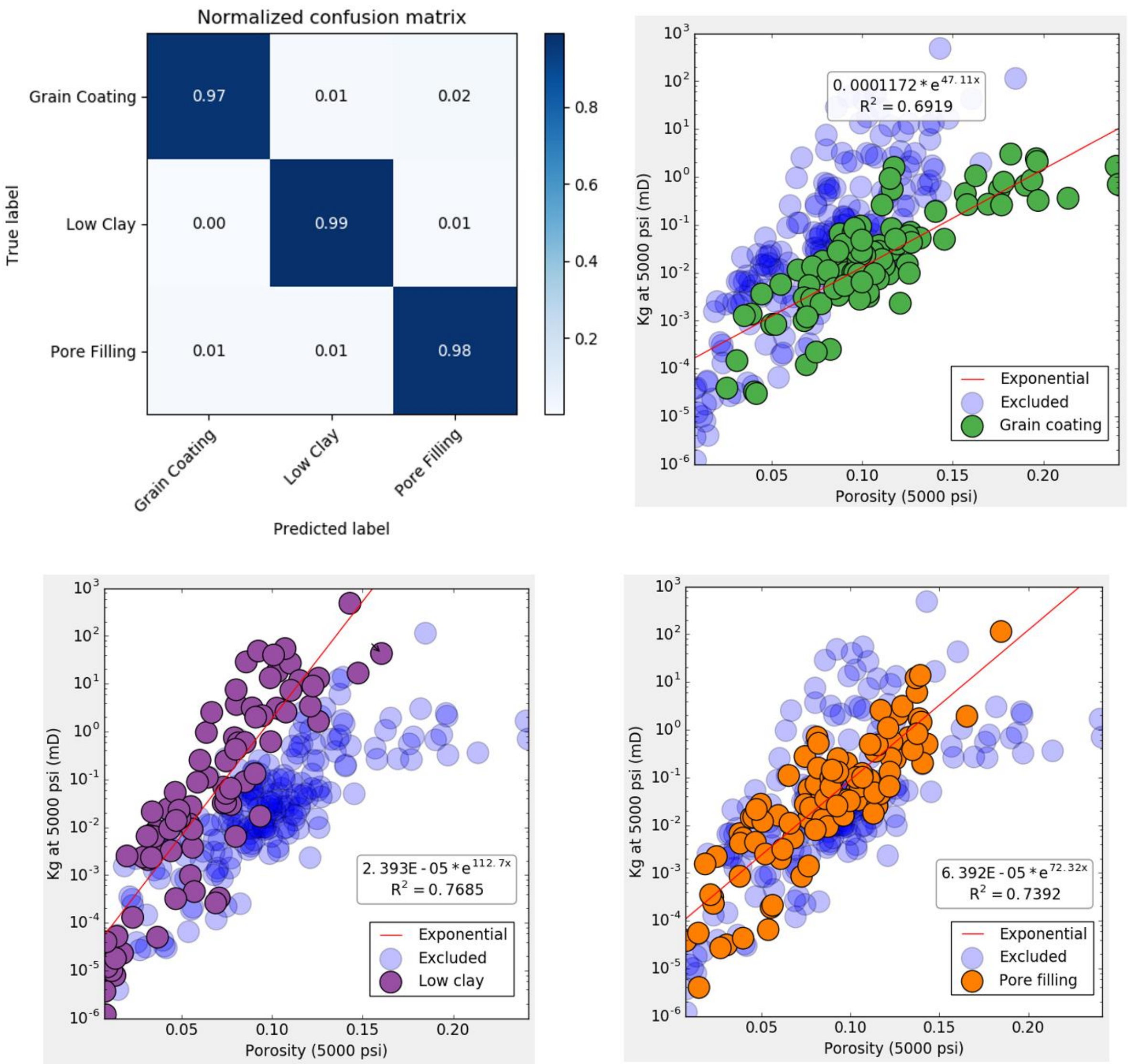


Figure 20 *Top left. Confusion matrix showing the high success rate for automatically classifying rock type using a CNN. The other diagrams show typical porosity-permeability data for different rock types (i.e. those with differing initial compositions and diagenetic histories).*

WP5: Fault rock properties

Many reservoirs are compartmentalized due to the presence of low-permeability fault rocks. Outcrop studies of Triassic sandstones from onshore UK demonstrate that they commonly contain faults dominated by cataclastic fault rocks (Figure 21). Previous work conducted at the University of Leeds demonstrates that these fault rocks can have permeabilities of 1 to 0.0001 mD and Hg-air threshold pressures of up to 1000 psi (~7 MPa). They are therefore capable of providing coherent seals to up to 300 m of CO2.

The project will extend the database of fault rock properties with outcrop and core data from Triassic sandstones by measuring the absolute permeability at subsurface stress conditions, their mercury injection threshold pressures and their relative permeability to dense phase CO_2. Results from the analysis will be placed in a PETMiner database (see software description on https://www.petriva.co.uk/en/software-new/) along with other relevant data (e.g. maximum burial depth, fault throw, clay content etc.). Data-mining algorithms will then be used to identify key controls on the fault rock properties.

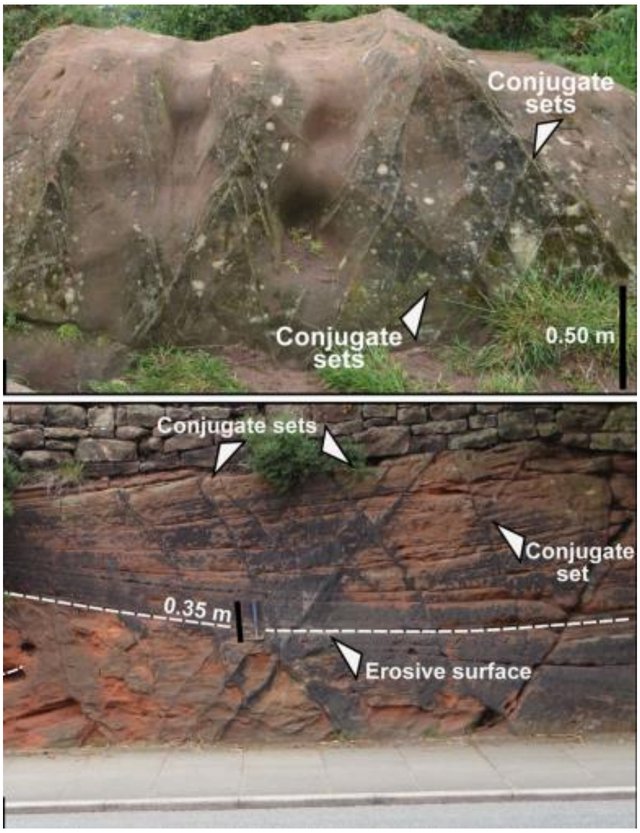


Figure 21 *Low permeability cataclastic faults from the Triassic Sherwood sandstone in Cheshire, UK; the outcrops are 2 to 4 m high.*

WP6: Caprock analysis

Unlike depleted oil and gas reservoirs, saline aquifers in the Triassic of the UK do not contain petroleum and therefore there is no direct evidence to suggest that caprocks can seal significant CO_2 columns. The two most likely ways that CO_2 could leak from structures is by leakage through the caprock matrix or along recently reactivated faults. The ability to leak through the matrix of caprocks can be determined by conducting MICP analysis on laterally continuous shales overlying the Triassic sandstones to assess their membrane sealing capacity. The ability to leak along recently reactivated faults and fractures is strongly determined by their ability to seal-seal. Work packages **WP6a** and **WP6b** described below aim to better understand the membrane sealing and self-sealing of faults and fractures.

WP6a: Capillary pressure

Little information is currently available on the capillary pressure characteristics of shale caprocks to Triassic sandstones within the UK. We will therefore collect samples (mainly outcrop but also core where available) and conduct unconfined and stressed MICP analysis to determine the range of column heights that these shale caprocks can seal. These will be incorporated into a PETMiner database so that the spatial distribution of the properties can be visualized and mapped. We will also measure properties such as the ultrasonic velocities, bulk densities, and clay content to assess whether the membrane sealing capacities can be estimated in places where only wire-line log data are available.

WP6b: Self-sealing potential

Recent work conducted on caprocks to petroleum reservoirs and radioactive waste disposal sites suggest that simple index properties such as clay content, position on cross-plots of dynamic Young's modulus and Poisson's ratio, as well as over-consolidation ratio provide a strong indication of the ability of faults and/or fractures to self-seal. Some recent unpublished studies have also indicated that a brittleness index obtained via the mineralogical analysis (BI_{min}) of caprocks using SEM may provide a valuable indication of the ability to self-seal. It is possible that this BI_{min} could be estimated by analysing cuttings from caprocks using SEM.

This work package aims to firstly conduct a series of laboratory experiments, based broadly on the proppant embedment test to validate that the aforementioned index properties do indeed provide a reliable indication regarding the ability of faults and fractures within shale caprocks to Triassic storage sites to self-seal. The work package will then collate wireline log and publicly available seismic data to create maps of these simple index properties to risk caprock leakage along recently active faults and fractures.

Deliverables, timing, and knowledge transfer

Deliverables

1) Determine the key criteria that control injection and storage and map these properties across the aquifer.
2) Mapping of the aquifer and top seal using selected criteria will enable high grading of specific areas which present a lower risk for CO_2 storage targets.
3) Develop an adapted play fairway analysis used in traditional oil and gas industry, reworked for CCS storage.
4) The project outputs will be made available via a dedicated webpage and via bespoke software (PETMiner - https://www.petriva.co.uk/en/software-new/).

WP1: Collation of existing data: Deliverables

Creation of a comprehensive database of wells within the North Sea region and East Irish Sea Basin (EISB) where Triassic sandstones have been penetrated. The database will comprise details relating to core, cuttings, and a wire-line log listings, including provision of a data-quality index. Existing core poroperm data, saturation, density, mineralogical, and sedimentological data will also be compiled.

WP2 Database of microstructural and petrophysical properties: Deliverables

1) Creation of a database of the microstructural and petrophysical properties of Triassic sandstone successions in the UK. The data will have been collected alongside intervals of legacy core analysis with additional sampling where necessary to create a more robust dataset.
2) A library of SEM images with microstructural information and derived data (e.g. grain size, sorting) will be available for the samples. These will be used to manually identify analogues based on the microstructure of cuttings.
3) The database and linked images will be uploaded into our bespoke data visualization and data mining software package, PETMiner, to visualise and determine the key controls on aquifer reservoir properties.
4) All data will also be made available in standard electronic format so that sponsors can easily upload it into their own data management systems.

WP3 Sedimentology: Deliverables

1) Generation of a database record of the sedimentology and sedimentary architecture of all major UK Triassic fluvial and aeolian successions from outcrops and subsurface succession. Data (e.g. arrangements of lithofacies units and architectural elements, their geometries proportions and topology) will be systematically extracted from published papers and reports, from subsurface datasets core and well-log datasets, and from outcrop studies conducted by members of the project team.

2) Coding and storage of the record of the sedimentology and sedimentary architecture of all major UK Triassic fluvial and aeolian successions in the Fluvial Architecture Knowledge Transfer system (FAKTS) database and the Database of Aeolian Sedimentary Architecture (DASA), the world's two largest and most sophisticated relational databases storing data and information on the sedimentology.
3) Access to FAKTS and DASA trough a graphical user interface to allow sponsors to generate their own bespoke queries relating to UK Triassic sedimentology and stratigraphy, including statistical summaries and models.
4) Generation of a suite of 3D quantitative facies models to demonstrate the variability in sedimentary heterogeneity present in major UK Triassic Sandstone formations currently being considered as potential sites for CCS. For example, models will be created for the relevant formations within the Bacton, Haisborough, Sherwood, Skagerrak and Lunde Groups.
5) Generation of summary statistical tables describing the expected range sedimentological properties for key UK Triassic successions.
6) Generation of numerical geological models that can be used as training images, for example in multipoint statistical modelling (MPS) workflows.

WP4 Reservoir quality from cuttings: Deliverables

1) Database of SEM images of the microstructure of cuttings from each well.
2) Database of the grain-size distribution of cuttings samples.
3) A workflow for the integration of petrophysical properties derived from cuttings with wireline logs, specifically, the development of porosity-permeability transforms based on cuttings analysis and training of the data using convolutional neural networking workflows.
4) Estimates of the reservoir quality of wells where cuttings and wire-line log data are available but not core.

WP5 Fault rock properties: Deliverables

1) A database of fault rock properties observed within the Triassic reservoir successions derived from core and outcrop. Key parameters will include absolute permeability at subsurface stress conditions, mercury injection threshold pressures and relative permeability to dense phase CO_2. Results from the analysis will reside in a PETMiner database along with other relevant parameters (e.g. maximum burial depth, fault throw, clay content etc.).
2) Electronic versions of all analyses so that they can be loading into sponsors own data management tools.
3) A report on the implications of the results for CO_2 injection into Triassic storage sites.

WP6 Caprock analysis: Deliverables

1) Generation of a capillary pressure database comprising measurements of unconfined and stressed MICP analysis in shale caprocks (comprising mainly outcrop but also core where available). This database will demonstrate the range of column heights that these shale caprocks can seal.
2) Integration of additional measured properties (ultrasonic velocities, bulk densities, and clay content) to determine membrane sealing capacity and integration with wireline logs data.
3) Generation of database of the self-sealing qualities of the candidate top seal comprising clay content, position on cross-plots of dynamic Young's modulus and Poisson's ratio, and overconsolidation ratio.
4) Maps of the spatial distribution and leakage risk of the above index properties using the results generated and integration with publicly available wireline log and seismic data.

Project timing

The project team has already started collecting data (e.g. WP1, WP3). We plan to officially commence the project in January 2023 and it will run for 3 years, to complete end-December 2025.

Knowledge transfer

The project team have a long track record of delivering applied research results to industrial partners and sponsors. Historically, the PETGAS webpage (www.petgas3.leeds.ac.uk) has been a primary portal for sponsors to access the deliverables from that project. Knowledge transfer has been a continuous process throughout the project via six-month sponsors meetings and visits to individual companies to present results.

The Fluvial, Eolian & Shallow-Marine Research Group (FRG-ERG-SMRG) has a dedicated website that is dedicated to knowledge transfer to disseminate cutting-edge research into the application of fluvial, aeolian and shallow-marine sedimentology for developing a better understanding of issues relating to subsurface resource exploration, appraisal, development and production/injection: https://frg.leeds.ac.uk/

The group has developed a state-of-the-art knowledge transfer programme to distil current thinking and trends in applied sedimentology research. Summary results and models are presented in a format suitable for direct use by industrial sponsors, including front-end interfaces for our FAKTS and DASA sedimentary databases.

For this project, we will develop a bespoke website accessible only to sponsors that combines aspects of these two current portals into a dedicated site for this project. This will be the main repository for knowledge transfer, databases and research results. In addition, webinars or self-learning guides specific to the project will be accessible here.

In addition to a dedicated site, sponsors meetings will be held on a 6 monthly basis with one meeting per year being field-based.

Creating impact is central to this proposal so we will provide bespoke presentations to sponsors throughout the project, as appropriate, to help with planning future CCS projects. We have the capacity to offer company visits, informal presentations, lunch and learns, online and in-person workshops and field visits. We also offer specialist consultancy services.

Project costs

The project will cost £50,000 per sponsor per year and will last for 3 years; a minimum of four sponsors are required for the project to run.

Project team

Day-to-day project management will be conducted by Dr Adriana del Pino Sanchez (ADPS). The leaders of individual work packages are shown in the figure below: Prof Quentin Fisher (QJF), Prof Nigel Mountney (NM) and Dr Luca Colombera (LC).

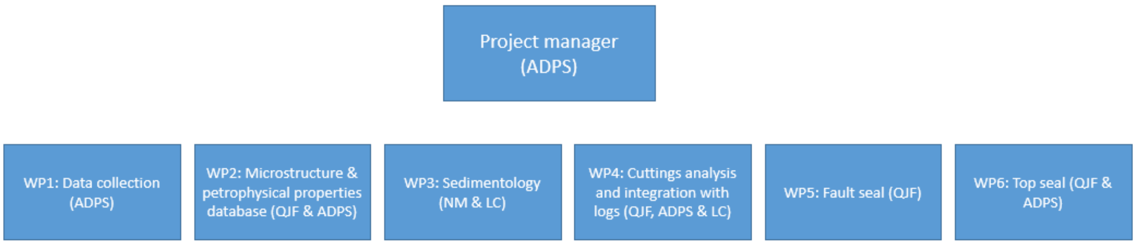


Figure 22 *Management structure of the TriStore project.*

Prof. Quentin Fisher (QJF)

Fisher is currently Professor of Petroleum Geoengineering at the University of Leeds and CEO of Petriva Ltd. He is a multidisciplinary geoscientist with expertise in structural geology, petroleum engineering, multi-phase fluid flow in porous media, rock physics, geomechanics, geophysics. He is particularly well known for his work on fault sealing, which started while working for a Rock Deformation Research Limited. Fisher has written >120 proprietary reports for the petroleum industry mainly on faulting and fault seal analysis. He has worked/consulted on fault and top seal problems in >300 petroleum reservoirs.

Fisher has extensive experience building and managing large, industry sponsored, multi-disciplinary research projects. He is Director of the Wolfson multi-phase flow laboratory at the University of Leeds and co-founder and Research Director of Centre for integrated Petroleum Engineering and Geoscience (cipeg.leeds.ac.uk). Fisher has developed cross-institution research groups (e.g. Integrated Petroleum Engineering – Geomechanics and

Geophysics involving the University of Leeds, Bristol and Rockfield Software Limited) aimed at creating software and workflows to integrate the petroleum geoscience disciplines (i.e. petroleum engineering, geophysics, geomechanics and geology). He has extensive knowledge transfer activities, including websites, regular industrial seminars etc. that eventually resulted in persuading oil companies to incorporate realistic fault rock properties into production simulation models. Fisher has published ~60 papers on subjects including geochemistry, geomicrobiology, structural geology, petroleum engineering, geomechanics and geophysics.

Prof. Nigel Mountney (NM)

Mountney is currently Professor in Sedimentology, Director of the Institute of Applied Geoscience, and Director and Principal Investigator of the Fluvial, Eolian & Shallow-Marine Research Group at the University of Leeds.

Mountney has >26 years' experience working on the development of novel approaches to gaining improved understanding of subsurface sedimentary successions. He specialises in developing quantitative models for the prediction of sedimentary architecture; such models are used to constrain and quantify rates of environmental change but also find application in predicting the characteristics of subsurface groundwater aquifers and hydrocarbon reservoirs (e.g. modelling fluid-flow rates and pathways through different types of sedimentary rocks). He develops models to predict how best to inject carbon dioxide in liquid form into subsurface reservoirs for long-term storage solutions that are essential to help reduce greenhouse gas emissions to the atmosphere.

He is the Founder, Director and Principal Investigator of the Fluvial & Eolian Research Group (FRG-ERG), and co-Founder and co-Director of the Shallow-Marine Research Group (SMRG) at Leeds, both major Joint Industry Projects (JIPs) that have attracted sponsorship from 17 international companies and research Councils (e.g. NERC). These ventures have enabled the successful funding and supervision of over 40 postgraduate research studentship projects.

He undertakes numerical modelling work to predict sedimentary system response to changing environmental conditions. From an applied standpoint, forward stratigraphic models have been developed for predicting the impact of lithological heterogeneities at a range of scales. Such models help predict fluid-flow behaviour in groundwater aquifers and hydrocarbon reservoirs. One branch of my research has developed a series of databases for the characterization of sedimentary deposits. Sedimentary architectural databases find application in quantifying rates of environmental change but are also used to predict the arrangement of subsurface deposits that form reservoir hosts for oil, gas, ore minerals, water, carbon dioxide, subsurface hydrogen storage. Such database-driven subsurface characterization is also used to guide geothermal energy solutions. These databases are the largest and most sophisticated of their type yet created; research results arising from this research are fundamentally changing how we understand the development of fluvial successions.

He has published more than 150 research manuscripts in peer-reviewed journals and special publications. His publications are primarily focussed on the science of sedimentology, stratigraphy and basin analysis. He publishes on topics whereby sedimentological concepts and thinking are applied widely to research problems more generally. He has published in a wide range of leading international journals in the fields of sedimentology, stratigraphy, basin analysis, petroleum geology, carbon capture and storage, numerical modelling, geomorphology, hydrology, hydrogeology, palaeoclimatology and palaeoecology. Thus, his research is both multidisciplinary and interdisciplinary. Many of his papers provide research outputs of commercial value in that they find application to better predicting hydrocarbon reservoirs, groundwater aquifers, and for identifying possible sites for long-term underground storage (sequestering) of carbon (CCS schemes), shorter-term storage of hydrogen to be used as a clean fuel source, and subsurface sites of potential geothermal energy. The database concepts are used widely in industry for characterization of fluvial and aeolian reservoirs.

Dr Adriana del Pino Sanchez (ADPS)

del Pino Sanchez has a PhD in the use of structural geology techniques for understanding soft sediment deformation in deepwater clastics. ADPS has 10+ years industry experience working for BG Group and Shell, which has been particularly focused on exploration for, and appraisal of conventional and unconventional petroleum reservoirs. ADPS is experienced in building databases from legacy data and working on large-scale regional studies, play fairway evaluation, as well as developing criteria for assessing and risking petroleum reservoirs. ADPS will be responsible for the construction of the initial database of core, cuttings and wire-line logs from the Triassic within the study area. She will also work with QF on the collection of microstructural image data, integration with wire-line log analysis and commercialization of the results.

Dr Luca Colombera

Colombera is a Senior Research Fellow at the University of Leeds. He is a sedimentary geologist with expertise in clastic sedimentology & stratigraphy and subsurface characterization & modelling. He has pioneered database-driven approaches to the description, interpretation and prediction of sedimentary architectures at multiple scales, and has contributed to the development of novel methods for the application of geological analogues and reservoir modelling.

Colombera is co-director and Chief Investigator of the Fluvial, Eolian & Shallow-Marine Research Group. In this role, he develops the research programme, conducts the research, and supervises researchers; he leads strands of research on analogue quantification & application and meta-analyses, and undertakes related knowledge-transfer activities through interaction with industrial sponsors. Colombera has published ~60 papers in the fields of pure and applied sedimentary geology.

Facilities

The project will make extensive use of the equipment within the Wolfson Multiphase Flow laboratory, the Leeds Electron Microscopy and Spectroscopy Centre (LEMAS), and the Sorby Environmental Fluid Dynamics laboratory. Key equipment that will be used is described below.

Wolfson multiphase flow laboratory

The Wolfson multiphase flow laboratory was initially established to measure the petrophysical properties of low and ultralow permeability rocks such as fault rocks, top seals, tight gas sandstones and shale resource plays. It is, however, equality capable of characterizing the single and multiphase flow properties of conventional (i.e. medium to high porosity-permeability) reservoirs.

Our research facilities include a CT scanner, flow systems for relative permeability and capillary pressure determinations, an ultracentrifuge, pulse-decay permeameter, NMR, as well as equipment for investigating the electrical and ultrasonic properties of rocks. The laboratory has two temperature controlled laboratories that are specifically designed for measuring the multiphase flow properties of low permeability rocks.

The laboratory is one of the only facilities in the world that has experience measuring the single and multiphase flow properties of fault rocks. It also has a unique mercury injection porosimeter that is capable of conducting measurements at ultrahigh confining pressures (up to 55,000 psi) and measuring the threshold pressure using electrical conductivity measurements. This instrument is ideally suited to measuring the threshold pressure of top seals and fault rocks.

A list of key equipment that may be used during the project is provided below.

- CT Scanner
- State-of-the-art two-phase flow system
- Steady-state gas permeameter
- Steady-state liquid permeameter
- Pulse-decay gas permeameter
- Ultracentrifuge
- He porosimeter
- Hg-injection porosimetry

- Porous plate
- Humidity chambers
- Capillary pressure and formation resistivity apparatus
- Minipermeameter
- Water-shut of equipment
- Gas-brine relative permeameter
- NMR spectrometer
- Triaxial cell and loading frame for Vp, Vs and rock deformation experiments

Leeds electron microscopy and spectrometry centre

Leeds Electron Microscopy and Spectroscopy Centre (LEMAS) is internationally renowned as a leading research centre in microscopic and spectroscopic characterization of solid materials. LEMAS has a huge range of state-of-the-art instruments that allow imaging of samples from the atomic to the core plug scale. In this project we intend to make particular use of the **Tescan VEGA3 XM scanning electron microscope** with large chamber and high sample throughput, equipped with X-max 150 SDD EDS and Aztec 3.3 software, also RGB filtered CL system. This instrument allows images to be rapidly taken of an entire thin section to assess sample heterogeneity. It can also be set up to automatically collect a large number of images (>20,000 overnight) that are ideal for training machine learning algorithms such as convolutional neural networks.

Sorby environmental fluid dynamics laboratory

Our facilities enable a wide interdisciplinary community to experiment upon a range of simulated natural processes, from flow-sediment transport links in alluvial channels, through the dispersal of sediment in the deep oceans, to particulate transport through pipes and rig vessels. The current application will make use of the particle size analysis equipment to determine the grain-size distribution of disaggregated cuttings and core samples. It will also make use of the FAKTS and DASA sedimentary databases and bespoke numerical modelling software tools developed by the research group that operates the Sorby laboratory.

Project team: curriculum vitae

Prof. Quentin Fisher (QJF)

EDUCATION

1984-1987	University of Sheffield, Honours in Geology (2.1)
1989-1992	University of Leeds, PhD in Geology
	"Geochemical and isotopic investigations of diagenesis in the Hepworth sequence (Westphalian) Northern England."

WORK EXPERIENCE

1993 – 1994	Microstructural Geologist, Rock Deformation Research, University of Leeds
1994-1998	Project Manager, Rock Deformation Research,
1998-2008	Group Manager, Rock Deformation Research,
	Lecturer, School of Earth Sciences, University of Leeds
2003-2007	Principal Research Fellow, School of Earth and Environment, University of Leeds.
2004-present	Director, Wolfson Multiphase flow laboratory, University of Leeds.
2007-present	Research Director for the Centre for Integrated Petroleum Geosciences, University of Leeds
2008-Present	Professor of Petroleum Geoengineering, University of Leeds
2017-Present	CEO, Petriva Ltd

RESEARCH GRANTS

- Co-PI - Diagenesis of mudrocks (£80,000 NERC grant to Liverpool, Leeds and Newcastle).
- Co-PI - Controls of reservoir quality in the Corrib Field, Ireland (£50, 000 PhD studentship to Liverpool and Leeds).
- Co-PI - Seismic Anisotropy as an indicator of lithology and fluid properties (£350, 000 ITF Grant to Leeds and Manchester).
- PI - Integrated Petroleum Engineering, Geophysics and Geomechanics (£600, 000 project sponsored by BG, BP, ENI, Statoil)
- Co-investigator - Carbon Capture and Storage UK – (£140,000 of a £2 million TSEC consortium)
- Co-PI – GESER: Geophysics and Geomechanics of Tight Gas Sandstone Reservoirs (£620,000 sponsored by Chevron, ConocoPhilips, UK Department of Energy and Climate Change, Shell)
- PI – PETGAS: Petrophysics of tight gas sands (£2,000,000 project sponsored by Aurelian BG, BP, EBN, Shell, Wintershall)
- PI – Multiphase flow properties of fault rocks (£300,000 consortium project sponsored by 12 major oil companies)
- Co-I: Leeds Low Carbon Technologies Doctoral Training Centre (£6.4 million EPSRC grant to train 50 PhD students in low carbon technologies)

- Co-I – BUMPS (Bristol University microseismicity consortium) – (£400,000 research consortium)
- PI - Royal Society Laboratory Refurbishment (£600, 000 grant to extend multiphase flow laboratory for measuring the properties of caprocks to CO2 storage sites)
- PI – SHAPE (Shale permeability measurement) – (£400,000 project sponsored by Chevron, EBN, Nexen)
- CO-I – FRACGAS (Hydraulic fracture development in shales) – (£1 million JIP in partnership with Rockfield Software Ltd and Bristol University)
- CO-SHAPE UK - £2 million UKRI funded project to investigate potential for seismicity and overburden leakage from shale resource plays.

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- Fisher et al., (2009) Integrated petroleum engineering, geomechanics and geophysics (IPEGG) Sponsored by BG, BP, ENI, Statoil.
- Fisher et al., (2012) Petrophysical properties of tight gas sandstones (PETGAS) sponsored by Aurelian, BG, BP, EBN, Shell and Wintershall.
- Dutko et al., (2012) Integrated geomechanical and geophysical analysis of tight gas sandstone reservoirs. Sponsored by Chevron, ConocoPhillips, DECC, Shell

- Fisher et al. (2015) Petrophysics of fault rocks (FAULTPROP). Sponsored by BHP, ConocoPhillips, Shell, Statoil, Wintershall.
- Fisher et al. (2015) Shale permeability analysis. Sponsored by Chevron, EBN, Nexen.
- Fisher et al., (2016) Petrophysical properties of tight gas sandstones (PETGAS) sponsored by BG, BP, EBN, GDF Suez, Shell and Wintershall.
- Fisher et al. (2016) Impact of faults on fluid flow in Carbonates (CARBFAULT) sponsored by ADCO, ENI, OMV, Petrobras and Wintershall.
- Fisher et al., (2016) Petrophysical properties of tight gas sandstones (PETGAS) sponsored by EBN, Nexen, PDO and Wintershall.

INDIVIDUAL STUDIES

Fisher has conducted over 150 consultancy projects for industry around the areas of faulting and fault seal analysis, top seal analysis, reservoir characterization. He has worked throughout the world but has most experience working on offshore assets in the UK, Norway and the Netherlands.

Prof. Nigel Mountney (NM)

EDUCATION

Birmingham University, PhD Interaction between tectonics & sedimentation at convergent plate margins, 1995

Keele University, MSc Computing in Earth Sciences, Pass with Distinction, 1992

University of Nottingham BSc II(i) Honours Geology and Geography, 1990

WORK EXPERIENCE

2018 - present: Professor of Sedimentology, Earth & Environment, University of Leeds, UK

2008 – 2017: Senior Lecturer in Sedimentology, Earth & Environment, University of Leeds, UK

1998 – 2007: Senior Lecturer in Sedimentology and Basin Studies, Earth Sciences, Keele University, UK

1996 – 1998: Postdoctoral Researcher, Stratigraphy Group, Earth Sciences, University of Liverpool, UK

RESEARCH AWARDS

- May 2018 Gabriel Dengo Award of the AAPG for excellence in research.
- Jan 2006: Nomination: Charles Lyell fund, Geological Society of London for excellence in research.
- Dec 2005: British Sedimentological Research Group award for "outstanding contribution to published research in any field of sedimentology".

PROFESSIONAL ASSOCIATIONS

American Association of Petroleum Geologists (AAPG)

International Association of Sedimentologists (IAS)

Society for Sedimentary Geology (SEPM)

British Sedimentological Research Group (BSRG)

SENIOR EDITORIAL AND COMMITTEE MEMBERSHIP

Director, Institute of Applied Geoscience, School of Earth and Environment, University of Leeds (2018-present).

Chief Editor for the journal *Sedimentology* (2014-2018).

Bureau Member of the International Association of Sedimentologists (2014-2018).

Mountney, N.P., September 2011-present. Nomination Committee member for the Society for Sedimentary Geology (SEPM).

Mountney, N.P., April 2011-present. Associate Editor for the journal *Sedimentology*.

PHD RESEARCH STUDENTS AND POSTDOCTORAL RESEARCHERS SUPERVISED

44 PhD research students supervised: 40 successfully completed; 4 on-going.

4 PDRA researchers (Luca Colombera, Na Yan and Grace Cosgrove, Roman Soltan) specialising in development of novel approaches to the characterization of sedimentary architecture.

2 Research Assistants.

SELECTED FUNDED RESEARCH PROJECTS WITH INDUSTRIAL PARTNERS

2021-present: Fluvial, Eolian & Shallow-Marine Research Group Phase 5 JIP, University of Leeds; 3 sponsors (with Colombera, L.). £300.000

2018-2020: Fluvial & Eolian Research Group Phase 4 JIP, University of Leeds; 11 sponsors (with Colombera, L.). £1,000,000

2016-2019: Shallow-Marine Research Group Phase 2 JIP, University of Leeds; 3 sponsors (with Colombera, L., Hodgson, D & McCaffrey, W) £300,000

2016. Database technology for deep marine clastic characterisation: upscaling for impact. NERC Innovation Scheme: Follow-on Fund Award. NE/P01691X/1 (with McCaffrey, W.D.). £125,000.

2016. Database technology for geological modelling of hydrocarbon reservoirs. NERC Innovation Scheme: Follow-on Fund Award. NE/N017218/1 (with McCaffrey, W.D. and Colombera, L.). £122,648.

2015-2017: Fluvial & Eolian Research Group Phase 3 JIP, University of Leeds; 8 sponsors. £800,000

2014. NERC Research Grant. Knowledge to application: meta data approaches to improved geological model conditioning in petroleum industry workflows. NERC Knowledge Exchange Scheme. NE/M007324/1 (with McCaffrey, W.D., Hodgson, D.M.). £85,000.

2013-2015: Shallow-Marine Research Group Phase 1 JIP, University of Leeds; 3 sponsors (with Colombera, L., Hodgson, D & McCaffrey, W). £100,000

2013 Analysis of sedimentary controls on flow heterogeneity in the Sherwood Sandstone, Triassic, UK. Total (with Odling, N & West, J.). £125,000

2012-2014: Fluvial & Eolian Research Group Phase 2 JIP, University of Leeds; 8 sponsors. £700,000

2009-2011: Fluvial & Eolian Research Group Phase 1 JIP, University of Leeds; 7 sponsors. £600,000

OTHER COLLABORATIVE FUNDED RESEARCH PROJECTS WITH INDUSTRIAL PARTNERS

2008. Sedimentology of the Permian Bridgnorth Sandstone and the Triassic Helsby Sandstone formations, West Midlands, UK: implications for reservoir geology. Centrica Energy Ltd.

2008. Sedimentological work to support static reservoir modelling; Rotliegend 2 reservoir, Auk Field, Central North Sea; 2007-2008. Talisman (UK) Ltd and Ichron Ltd (with Besly, B.)

2007. Aeolian sedimentology of the Permian Bridgnorth Sandstone, Shropshire, UK. Petroleum and Exploration Society of Great Britain.

2007. Sedimentology and stratigraphy of the Permian Bridgnorth Sandstone: Implications for reservoir geology in aeolian successions.

2006. Sequence stratigraphy, sediment architecture and correlation in red-bed systems, Paradox basin, Utah: Implications for hydrocarbon exploration in marginal aeolian-fluvial reservoirs. A field trip run for Statoil ASA and RWE.

2006. Carboniferous and Permo-Triassic facies and reservoir geology of Staffordshire, Cheshire and Shropshire, UK as analogues for the southern North Sea. A field trip run for E.On Ruhrgas UK

2003. Dynamic models for arid fluvial and erg margin successions. Shell Petroleum Ltd.

2003. Southern North Sea burial history and basin modelling analysis blocks 48/18, 48/19. Gaz de France.

2002. Aeolian sedimentology of the cored intervals from the Kudu Field, offshore Namibia. Shell.

2002. Aeolian sedimentology of the Huab Basin (NW Namibia) with implications for hydrocarbon exploration. Shell Petroleum Ltd.

2001. Predicting 3D aeolian set geometries and reservoir quality from 1D core in the V-Fields of the SNS. Funded by Conoco UK Ltd.

1998-1999. Mobil North Sea Ltd Chlorite Project burial history and basin modelling – blocks 48/11, 48/12.

1996-1988. Aeolian sequence stratigraphy & reservoir architecture, Etjo Sandstone, Namibia. Conoco & BG.

SELECTED PUBLICATIONS

Cosgrove, G.I.E., Colombera, L. and **Mountney, N.P.** (2022) Eolian stratigraphic record of environmental change through geological time. Geology, 50, 289-294. https://doi.org/10.1130/G49474.1

Cosgrove, G.I.E., Colombera, L. and **Mountney, N.P.** (2022) The role of subsidence and accommodation generation in controlling the nature of the aeolian stratigraphic record. Journal of the Geological Society, 179, jgs2021-042. https://doi.org/10.1144/jgs2021-042

Cosgrove, G.I.E., Colombera, L. and **Mountney, N.P.** (2021) Quantitative analysis of the sedimentary architecture of eolian successions developed under icehouse and greenhouse climatic conditions. *Geological Society of America, Bulletin*, **133**, 2625-2644. https://doi.org/10.1130/B35918.1

Yan, N., Colombera, L. and **Mountney, N.P.** (2021) Evaluation of Morphodynamic Controls on the Preservation of Fluvial Meander-Belt Deposits. *Geophysical Research Letters*, **48**, e2021GL094622. https://doi.org/ 10.1029/2021GL094622

Yan, N., Colombera, L. and **Mountney, N.P.** (2021) Controls on fluvial meander-belt thickness and sand distribution: insights from forward stratigraphic modelling. *Sedimentology*, **68**, 1831-1860. https://doi.org/10.1111/sed.12830

Colombera, L. and **Mountney, N.P.** (2021) Influence of fluvial crevasse-splay deposits on sandbody connectivity: lessons from geological analogues and stochastic modelling. *Marine and Petroleum Geology*, **128**, 105060. https://doi.org/10.1016/j.marpetgeo.2021.105060

Cosgrove, G.I.E., Colombera, L. and **Mountney, N.P.** (2021) A Database of Aeolian Sedimentary Architecture for the characterization of modern and ancient sedimentary systems. *Marine and Petroleum Geology*, **127**, 104983. https://doi.org/10.1016/j.marpetgeo.2021.104983

Montero, J.M., Colombera, L, Yan, N and **Mountney, N.P.** (2020) Predicting heterogeneity in fluvial meander-belt successions using a combined forward stratigraphic modelling and multi-point geostatistical approach. *Journal of Petroleum Science and Engineering*, **108411**. https://doi.org/10.1016/j.petrol.2021.108411

Somerville, D.J.P., **Mountney, N.P.**, Colombera, L and Collier, R.E.L. (2020) Role of rift-basin evolution in controlling alluvial fan development: an example from the Gulf of Corinth, Greece. *Basin Research*, **32**, 764-788. https://doi.org/10.1111/bre.12396.

Colombera, L. and **Mountney, N.P.** (2020) Accommodation and sediment-supply controls on clastic parasequences: a meta-analysis. *Sedimentology*, **67**, 1667-1709. https://doi.org/10.1111/sed.12728

Coronel, M.D., Isla, M.F., Veiga, G.D., **Mountney, N.P.** and Colombera, L. (2020) Anatomy and facies distribution of terminal lobes in ephemeral fluvial successions: Jurassic Tordillo Formation, Neuquén Basin, Argentina. *Sedimentology*, **67**, 2596-2624. https://doi.org/10.1111/sed.12712.

Li, W., Yue, D., Colombera, L., **Mountney, N.P.** and Wu, S. (2020) A novel method for estimating sandbody compaction in fluvial successions. *Sedimentary Geology*, **105625**. https://doi.org/10.1016/j.sedgeo.2020.105675

Parquer, M., Yan, N., Colombera, L., **Mountney, N.P.**, Collon, P. and Caumon, G. (2020) Combined inverse and forward numerical modelling for reconstruction of channel evolution and facies distributions in fluvial meander-belt deposits. *Journal of Marine and Petroleum Geology*, **104409**. https://doi.org/10.1016/j.marpetgeo.2020.104409

Yan, N., Colombera, L. and **Mountney, N.P.** (2020) Three-Dimensional Forward Stratigraphic Modelling of the Sedimentary Architecture of Meandering-River Successions in Evolving Half-Graben Rift Basins, *Basin Research*, **32**, 68-90. doi: 10.1111/bre.12367.

Wang, R., Colombera, L. and **Mountney, N.P.** (2020) Database-Driven Quantitative Analysis of the Stratigraphic Architecture of Incised-Valley Fills. *Earth Science Reviews*, **102988**, 1-25.

Medici, G., West, L.J., **Mountney, N.P.** and Welch, M. (2019) Review: permeability development in the Triassic Sherwood Sandstone Group (UK), insights for management of fluvio-aeolian aquifers worldwide. *Hydrogeology Journal*, **27**, 2835-2855. https://doi.org/10.1007/s10040-019-02035-7

Burns, C.E., **Mountney, N.P.**, Hodgson, D.M. and Colombera, L. (2019) Stratigraphic architecture and hierarchy of fluvial overbank crevasse-splay deposits. *Journal of the Geological Society of London*, **176**, 629-649. doi: 10.1144/jgs2019-001.

Santos, M.G.M., Hartley, A.J., **Mountney, N.P.**, Peakall, J., Owen, A., Merino, E.R. and Assine, M.L. (2019) Meandering rivers in modern desert basins: Implications for channel planform controls and prevegetation rivers. *Sedimentary Geology*, **385**, 1-14. doi: 10.1016/j.sedgeo.2019.03.011.

Colombera, L., **Mountney, N.P.**, Medici, G. and West, L.J. (2019) The geometry of fluvial channel bodies: empirical characterization and implications for object-based models of the subsurface. *AAPG Bulletin*, **103**, 905-929. doi: 10.1306/10031817417.

Colombera, L. and **Mountney, N.P.** (2019) The lithofacies organization of fluvial channel deposits: a meta-analysis of modern rivers. *Sedimentary Geology*, **383**, 16-40. doi: 10.1016/j.sedgeo.2019.01.011

Medici, G., West, L.J. and **Mountney, N.P.** (2019) Flow heterogeneities and permeability development in the Triassic UK Sherwood Sandstone Group; insights for reservoir quality. *Geological Journal*, **54**, 1361-1378. doi: 10.1002/gj.3233

Yan, N., Colombera, L., **Mountney, N.P.**, Dorrell, D.M. (2019) Three-dimensional modelling of fluvial point-bar architecture and facies heterogeneity using analogue data and associated analysis of intra-bar static connectivity: application to humid coastal-plain and dryland fluvial systems. *In: Ghinassi, M., Colombera, L., Mountney, N.P. and Reesink, A.J. (Eds.), Fluvial Meanders and their Sedimentary Products in the Rock Record*. International Association of Sedimentologists Special Publication, **48**, 475-508.

Colombera, L., Yan, N., McCormick-Cox, T., **Mountney, N.P.** (2018) Seismic-driven geocellular modelling of fluvial meander-belt reservoirs using a rule-based method. *Marine and Petroleum Geology*, **93**, 553-569. doi: 10.1016/j.marpetgeo.2018.03.042

Medici, G., West, L.J. and **Mountney, N.P.** (2018) Characterization of a fluvial aquifer at a range of depths and scales: the Triassic St Bees Sandstone Formation, Cumbria, UK. *Hydrogeology Journal*, **26**, 565-591. doi: 10.1007/s10040-017-1676-z

Besly, B., Romain, H.G. and **Mountney, N.P.** (2018) Reconstruction of linear dunes from ancient aeolian successions using subsurface data: Permian Auk Formation, Central North Sea, UK. *Marine and Petroleum Geology*, **91**, 1-18. doi: 10.1016/j.marpetgeo.2017.12.021

Yan, N., **Mountney, N.P.**, Colombera, L. and Dorrell, R.M. (2017) A 3D forward stratigraphic model of fluvial meander-bend evolution for prediction of point-bar lithofacies architecture. Computers & Geosciences, **105**, 65-80. doi: 10.1016/j.cageo.2017.04.012

Colombera, L., **Mountney, N.P.**, Russell, C.E., Shiers, M.N. and McCaffrey, W.D. (2017) Geometry and compartmentalization of fluvial meander-belt reservoirs at the bar-form scale: quantitative insight from outcrop, modern and subsurface analogues. *Marine and Petroleum Geology*, **82**, 35-55. doi: 10.1016/j.marpetgeo.2017.01.024

Medici, G., West, L.J. and **Mountney, N.P.** (2016) Characterizing flow pathways in a sandstone aquifer: tectonic vs sedimentary heterogeneities. *Journal of Contaminant Hydrology*, **194**, 36-58. doi: 10.1016/j.jconhyd.2016.09.008

Colombera, L., **Mountney, N.P.**, Howell, J.A., Rittersbacher, A. and McCaffrey, W.D. (2016) Geological modelling of outcrop successions to assess analog-based predictions of the sedimentary heterogeneity in fluvial reservoirs. *AAPG Search and Discovery*, **41771**, 1-4.

Colombera, L., **Mountney, N.P.**, Hodgson, D.M. and McCaffrey, W.D. (2016) The Shallow-Marine Architecture Knowledge Store: a database for the characterization of shallow-marine and paralic depositional systems. *Marine and Petroleum Geology*, **75**, 83-99. doi: 10.1016/j.marpetgeo.2016.03.027

Colombera, L, **Mountney, N.P.**, Howell, J.A., Rittersbacher, A., Felletti, F. and McCaffrey, W.D. (2016) A test of analog-based tools for quantitative prediction of large-scale fluvial architecture. *American Association of Petroleum Geologists Bulletin*, **100**, 237-267. doi: 10.1306/11181514227

Medici, G., Boulesteix, K., **Mountney, N.P.**, West, L.J. and Odling, N.E. (2015) Palaeoenvironment of braided fluvial systems in different tectonic realms of the Triassic Sherwood Sandstone Group, UK. *Sedimentary Geology*, **329**, 188-210. doi: 10.1016/j.sedgeo.2015.09.012

Colombera, L, **Mountney, N.P.** and McCaffrey, W.D. (2015) A meta-study of relationships between fluvial channel-body stacking pattern and aggradation rate: implications for sequence stratigraphy. *Geology*, **43**, 283-286. doi:10.1130/G36385.1

Colombera, L., **Mountney, N.P.**, McCaffrey, W.D. and Felletti, F. (2014) Models for guiding and ranking well-to-well correlations of channel bodies in fluvial reservoirs. *American Association of Petroleum Geologists Bulletin*, **98**, 1493-1965. doi: 10.1306/05061413153

Rodríguez-López, J.P., Clemmensen, L., Lancaster, N., **Mountney, N.P.** and Veiga, G. (2014) Archean to Recent aeolian sand systems and their preserved successions: current understanding and future prospects. *Sedimentology*, **61**, 1487-1534. doi: 10.1111/sed.12123

Colombera, L., **Mountney, N.P.** and McCaffrey, W.D. (2013) A quantitative approach to fluvial facies models: methods and example results. *Sedimentology*, **60**, 1526-1558. doi: 10.1111/sed.12050

Colombera, L., Felletti, F., **Mountney, N.P.** and McCaffrey, W.D. (2012) A database approach for constraining stochastic simulations of the sedimentary heterogeneity of fluvial reservoirs. *American Association of Petroleum Geologists Bulletin*, **96**, 2143-2166. doi: 10.1306/04211211179

Colombera, L., **Mountney, N.P.** and McCaffrey, W.D. (2012) A relational database for the digitization of fluvial architecture: towards quantitative synthetic depositional models. *AAPG Search and Discovery*, **40933**, 1-5.

Colombera, L., Felletti, F. **Mountney, N.P.** and McCaffrey, W.D. (2012) A database approach for constraining geostatistical reservoir models: concepts, workflow and examples. *AAPG Search and Discovery*, **40932**, 1-7.

Mountney, N.P. (2012) A stratigraphic model to account for complexity in aeolian dune and interdune successions. *Sedimentology*, **59**, 964-989. doi: 10.1111/j.1365-3091.2011.01287.x

Colombera, L., **Mountney, N.P.** and McCaffrey, W.D. (2012) A Relational Database for the Digitization of Fluvial Architecture: Concepts and Example Applications. *Petroleum Geoscience*, **18**, 129-140. doi: 10.1144/1354-079311-021

Mountney, N.P. and Thompson, D.B. (2002) Stratigraphic evolution and preservation of aeolian dune and damp/wet interdune strata: an example from the Triassic Helsby Sandstone Formation, Cheshire Basin, UK. *Sedimentology*, **49**, 805-833.

Dr Adriana del Pino Sanchez (ADPS)

EDUCATION

University of Leeds Doctor of Philosophy. PhD. **2002 - 2006**
University of Leeds Exploration Geophysics MSc **2000 - 2001**
Imperial College London Geology BSc Honours **1996 – 1999**

WORK EXPERIENCE

Research Associate, University of Leeds; Geologist, Petriva Ltd. June 2019 – Current

- Software development: Writing of software manuals and tutorials to accompany PETMiner software package; Software testing and bug reporting; Advise on additional functionality; Software promotion.
- Database building: Development of bespoke databases to underpin research and consultancy work. Advise on potential database development for commercialisation. Maximising value of current datasets through database QC, data additions and updates.
- GIS Support: Preparation of subsurface maps for research and consultancy, including GDE maps, uplift maps, outputs for play fairway evaluation consultancy work, regional stress field maps; charting of licence round activity. Maps for project scoping.
- Specific projects: Regional top seal analysis of Western Greece – application of regional play fairway evaluation workflows to determine the viability of six regionally extensive seals at various stratigraphic levels across western Greece and its outlying islands. Work included collation of legacy well data, facies analysis and GDE mapping, uplift calculations, derivations of seal properties from wireline data, fieldwork.
- Business activities: Marketing activities; web content and updates; preparation of technical documents.

Research and Teaching Fellow: University of Leeds 2018 –2019

- Project leader: catalogued and appraised subsurface datasets held by the School of Earth and Environment in order to create a digital resource: Application of seismic interpretation skills to link relevant data to specific research interests within the School: Acquisition of datasets for teaching and research through industrial liaison.

Director and Consultant Geologist: Wharfedale Geoscience Ltd 2018 –2019

- Working with High Tide XP, delineating unconventional play concepts in the **US Onshore Gulf Coast Region**.

New Ventures Team Lead, Shell, UK 2015 - 2016

Led a team of six geoscientists in delivering regional and prospect evaluations for five non-operated License Blocks, **Offshore Newfoundland**.

- Delivered innovative regional and prospect scale evaluations in the Flemish Pass Basin using a multidisciplinary team to influence the Operators work programme.
- Built strong relationships with operator Statoil, as Technical Committee Representative through Technical Committee Meetings and subsurface technical workshops.
- Delivery of key regional work products and prospect evaluations to inform potential bid submissions for the 2016 License Round.
- Evaluation of M&A and data licensing opportunities as part of a strategy to increase the company footprint in the region.
- Successfully delivered knowledge share workshops and high-quality documents to the Shell acquiring team in a pressured timeframe driven by drilling decisions.

New Ventures Team Lead, BG Group, Houston 2014 - 2015

Led a team of seven geoscientists to successfully deliver assessments of **North American Shale Gas and Tight Oil Plays** to the BG New Ventures portfolio both through M&A evaluations and the development of **new play concepts**.

- Established Unconventional New Ventures Strategy and brought forward opportunities to the UK based Exploration Leadership, broadening the portfolio of the conventional resource opportunity base.
- Delivered regional screening exercises using extensive geochemical and production datasets available for the onshore US, prioritising evaluations according to internally developed criteria.

- Leveraged extensive unconventional play experience within the team to bring forward and develop new play concepts outside of the main known plays.
- Assessed and documented M&A opportunities across renowned basins and shale plays including Onshore Gulf Coast, Denver-Joules, Powder River, Illinois Basins, and Barnett, Haynesville, Woodford, Niobrara, Mowry plays.
- Analysis of production data and analogues as key inputs to ongoing development of new opportunities in poorly understood basins and shale plays.

Lead Geologist, BG Group, Houston **2013 - 2014**

Responsible for evaluating M&A opportunities and delivering regional evaluations of **Unconventional Plays onshore US, Canada and Mexico** as part of a newly established Exploration Team.

- Worked on delineation of new play concept onshore Gulf Coast: Instrumental in pitching the concept to Exploration Leadership in the UK Head Office. BG leased a 100,000-acre position on the merits of the technical evaluation.
- Evaluation of tight oil M&A opportunities across the US and Canada. High-graded opportunities were recommended to the Exploration Leadership and Assurance teams for inclusion into the BG New Ventures Portfolio. Systematic documentation and data collation of numerous source rocks to develop knowledge base for the newly developed team and underpinning later screening workflows.
- Designed and executed methodology for the systematic screening of source rocks across the entire onshore US using a vast geochemical and internally developed databases. Assessed the presence and quality of source rocks from the Cambrian through to the Tertiary to identify opportunities that were not currently being explored or exploited. This formed the basis of a New Ventures Strategy to evaluate play concepts outside of the main known US plays. The project was commended by Corporate Exploration Leadership and the Chief Operating Officer for impact and innovation.
- Communicated regularly on project progress with key stakeholders building trust with numerous internal stakeholders to progress opportunities in line with the pace of the US market.

Lead Geologist, BG Group, UK **2011 - 2012**

Responsible for delivery of first regional evaluation of prolific **deep-water clastic plays offshore Tanzania** providing context for prospect evaluation across three License Blocks and underpinning evaluation of later License Rounds.

- Delivered Play Fairway Evaluation of the Tertiary clastic plays across offshore Tanzania after BG took over operatorship of three blocks. Presented work products to Partners and Tanzanian Government representatives. Generated regional mapping products and accompanying report.
- Project lead on a multidisciplinary team that delivered an integrated regional evaluation which informed prospect evaluations and enhanced the understanding of source rock presence and distribution in the region.
- Execution and delivery of subsurface workflows to deliver prospects for the 2012-2013 exploration drilling campaign. Responsible for geological work that delivered the Mkizi-1 exploration well success: Mkizi-1 added 0.6TCF of gas to a 15 TCF portfolio and continued a 100% drilling success rate in the region.
- Implemented post-well studies through collaboration with contracts and procurement following the 2011 drilling campaign, continually integrating new results into ongoing regional work.

New Ventures Geologist, BG Group, UK **2008 - 2010**

Responsible for producing both regional evaluations and numerous M&A evaluations across a wide geographical remit within **Global New Ventures.**

- Delivered GDE maps, volumetrics and risk analysis for Nigeria deep-water Tertiary plays as part of Company-wide exercise to systematically evaluate portfolio in 2010. Commended for quality of the technical work produced.
- Evaluated the Angola Pre-Salt play systematically ranking numerous blocks offered as farm-in opportunities, authored regional play fairway maps and detailed report.
- Collaborated with a large multi-disciplinary team to deliver block screening prior to 2008 Algeria License Round. Individually responsible for delivering evaluation of two blocks.
- As Project Manager, coordinated regional evaluation of the Tunisian Pre-Salt play, prospect analysis of a farm-in opportunity.

Graduate Development Programme, BG Group **2006 - 2008**

Dr Luca Colombera

EDUCATION

2013 PhD Sedimentology, University of Leeds, Mention for Research Excellence

2010 MSc Geology, State University of Milan, Cum Laude

2007 BSc Geological Sciences, State University of Milan, Cum Laude

WORK EXPERIENCE

2019-2022 Senior Research Fellow, University of Leeds

2013-2019 Research Fellow, University of Leeds

RESEARCH GRANTS

- 2021-present: Fluvial, Eolian & Shallow-Marine Research Group Phase 5 JIP, University of Leeds; 3 sponsors (with Mountney, N.P.). £300.000
- 2018-2020: Fluvial & Eolian Research Group Phase 4 JIP, University of Leeds; 11 sponsors (with Mountney, N.P.). £1,000,000
- 2016-2019: Shallow-Marine Research Group Phase 2 JIP, University of Leeds; 3 sponsors (with Hodgson, D.M., McCaffrey, W.D. and Mountney, N.P.). £300,000
- 2016. Database technology for deep marine clastic characterisation: upscaling for impact. NERC Innovation Scheme: Follow-on Fund Award. NE/P01691X/1 (with Mountney, N.P. and McCaffrey, W.D.). £125,000.
- 2016. Database technology for geological modelling of hydrocarbon reservoirs. NERC Innovation Scheme: Follow-on Fund Award. NE/N017218/1 (with McCaffrey, W.D. and Mountney, N.P.). £122,648.
- 2014. NERC Research Grant. Knowledge to application: meta data approaches to improved geological model conditioning in petroleum industry workflows. NERC Knowledge Exchange Scheme. NE/M007324/1 (with McCaffrey, W.D., Hodgson, D.M. and Mountney, N.P.). £85,000.

SELECTED PUBLICATIONS – first-authored papers from the last ten years

Colombera, L., & Mountney, N. P. (2021) Influence of fluvial crevasse-splay deposits on sandbody connectivity: Lessons from geological analogues and stochastic modelling. Marine and Petroleum Geology, 128, 105060.

Colombera, L., & Mountney, N. P. (2020) Accommodation and sediment-supply controls on clastic parasequences: A meta-analysis. Sedimentology, 67(4), 1667-1709.

Colombera, L., & Mountney, N. P. (2020) On the geological significance of clastic parasequences. Earth-Science Reviews, 201, 103062.

Colombera, L., Mountney, N. P., Medici, G., & West, L. J. (2019) The geometry of fluvial channel bodies: Empirical characterization and implications for object-based models of the subsurface. AAPG bulletin, 103(4), 905-929.

Colombera, L., & Mountney, N. P. (2019) The lithofacies organization of fluvial channel deposits: a meta-analysis of modern rivers. Sedimentary Geology, 383, 16-40.

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