Quantitative Characterisation and Analysis of Siliciclastic Fluvial Depositional Systems using 3D Digital Outcrop Models

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Quantitative Characterisation and Analysis of Siliciclastic Fluvial Depositional Systems Using 3D Digital Outcrop Models

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Abstract

Outcrop analogue studies of fluvial sedimentary systems are often undertaken to identify spatial and temporal characteristics (e.g. stacking patterns, lateral continuity, lithofacies proportions). However, the lateral extent typically exceeds that of the exposure, and/or the true width and thickness are not apparent. Accurate characterisation of fluvial sand bodies is integral for accurate identification and subsequent modelling of aquifer and hydrocarbon reservoir architecture.

The studies presented in this thesis utilise techniques that integrate lidar, high-resolution photography and differential geospatial measurements, to create accurate three-dimensional (3D) digital outcrop models (DOMs) of continuous 3D and laterally extensive 2D outcrop exposures. The sedimentary architecture of outcrops in the medial portion of a large Distributive Fluvial System (DFS) (Huesca fluvial fan) in the Ebro Basin, north-east Spain, and in the fluvio-deltaic succession of the Breathitt Group in the eastern Appalachian Basin, USA, are evaluated using traditional sedimentological and digital outcrop analytical techniques. The major sand bodies in the study areas are quantitatively analysed to accurately characterise spatial and temporal changes in sand body architecture, from two different outcrop exposure types and scales. Several stochastic reservoir simulations were created to approximate fluvial sand body lithological component and connectivity within the medial portion of the Huesca DFS.

Results demonstrate a workflow and current methodology adaptation of digital outcrop techniques required for each study to approximate true geobody widths, thickness and characterise architectural patterns (internal and external) of major fluvial sand bodies interpreted as products of DFSs in the Huesca fluvial fan, and both palaeovalleys and progradational DFSs in the Pikeville and Hyden Formations in the Breathitt Group. The results suggest key geostatistical metrics, which are translatable across any fluvial system that can be used to analyse 3D digital outcrop data, and identify spatial attributes of sand bodies to identify their genetic origin and lithological component within fluvial reservoir systems, and the rock record.

3D quantitative analysis of major sand bodies have allowed more accurate width vs. thickness relationships within the La Serreta area, showing a vertical increase in width and channel-fill facies, and demonstrates a 22% increase of in-channel facies from previous interpretations. Additionally, identification of deposits that are products of a nodal avulsion event have been characterised and are interpreted to be the cause for the increase in width and channel-fill facies. Furthermore, analysis of the Pikeville and Hyden Fms contain sand bodies of stacked distributaries and palaeovalleys, as previously interpreted, and demonstrates that a 3D spatial approach to determine basin-wide architectural trends is integral to identifying the genetic origin, and preservation potential of sand bodies of both palaeovalleys and distributive fluvial systems. The resultant geostatistics assimilated in the thesis demonstrates the efficacy of integrated lidar studies of outcrop analogues, and provide empirical relationships which can be applied to subsurface analogues for reservoir model development and the distribution of both DFS and palaeovalley depositional systems in the rock record.
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I would like to dedicate this thesis to my father, Rodney Wade Burnham. Without him, I would not be the scientist or the man that I am today. For you Dad.
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Geologists are never at a loss for paperweights.

Section 1

Thesis Introduction
Chapter 1
Chapter 1
Introduction

1.1 Aim of the thesis

The aims of this thesis is to quantitatively examine the geometries and architecture of fluvial elements observed at outcrop (at local and basin scale) of two different depositional systems and to improve characterisation and analysis techniques of outcrops used as subsurface analogues. The studies presented also provide insight into the efficacy using digital modelling techniques to understand spatial patterns recognised in outcrop and their implication to system-wide trends within fluvial depositional systems.

In order to achieve this, high-resolution 3D digital outcrop models of (i) the La Serreta section of the Huesca distributive fluvial system in the Ebro Basin, Spain, and (ii) the Pikeville and Hyden formations within the fluvio-deltaic Breathitt Group, eastern Kentucky, U.S.A., have been constructed to quantitatively characterise and analyse the sedimentary characteristics observed in each section.

1.2 Rationale

Accurate three-dimensional geometric (3D) and architectural analysis of channel sand bodies is integral to establishing a fundamental depositional understanding of any fluvial system. This requires quantitative analysis of fluvial elements at various scales. Using subsurface data (e.g. core and seismic) presents a level of uncertainty related to the resolution and areal coverage of each data type. Outcrop exposures offer the ability to spatially analyse the fluvial features at a mesoscale (e.g. channel-fill geometry, storey height, stacking patterns), which can be used to char-
acterise elements at the mesoscale of a system. Well-exposed sections along strike or dip-orientations within a basin can be used to quantify the spatial extent of the features, allowing improved basin-wide interpolations. Recent studies investigating the stacking patterns and sand body architecture of major sand bodies in distributive fluvial systems (Owen et al., 2015) and fluvio-deltaic systems (Jerrett et al., 2016) show evidence of the increasing importance to accurately and systematically characterise fluvial element distribution (i.e. sand body thickness, storey height and length). This is important at the mesoscale (i.e. mesoscale of individual outcrops) and across dip-sections of the system (i.e. up-depositional dip and down-dip). Fluvial depositional systems are important area of research by academics and industry professionals because of their significance geomorphologically, hydrodynamically and as hydrocarbon reservoirs (Nichols, 2005; Donselaar and Schmidt, 2010; Kukulski et al., 2013; Weissmann et al., 2010).

Weissmann et al. (2010) recently promoted the distributive fluvial system (DFS) model as a sedimentary system hierarchy which contains a myriad of depositional settings (i.e. mega-fan to small-scale alluvial fan), that they suggest "may represent the norm in the continental fluvial record." Though the model is still not fully accepted by many workers, it has gained attraction to explain reservoir distribution in a number of important hydrocarbon plays (e.g. Kukulski et al., 2013). The degree to which this DFS model reflects the rock record or a significant proportion of modern systems is contested amongst fluvial sedimentologists and geomorphologists (see Fielding et al., 2012). Ongoing research into its significance of DFSs in the rock record remains integral to assess its importance as a subsurface analogue, (e.g. Kukulski et al., 2013; Quartero et al., 2015). The Huesca system in north-east Spain is a classic example of an ancient DFS which has seen a plethora of studies qualitatively describing its geometry, architecture and possibly depositional controls. However, no study has been completed which quantitatively analyses the spatial 3D stacking patterns and lithological heterogeneity.

Accurate characterisation of geometry and internal architecture is critical to understanding possible depositional controls of any fluvial system. Gibling (2006)
collated data from a large number of studies to quantify and categorise the 3D geometry of fluvial channel bodies in the ancient rock record (e.g. small-scale meandering channels to palaeovalleys). That study emphasised the variability in sand body type, width and thicknesses, with often very large ranges of dimensions recorded and uncertainty in geobody definition. They noted in particular the importance of precise identification of fluvial element geometry, and the need for improvement of characterisation and analysis techniques in outcrop studies.

A study of fluvio-deltaic sediments in the Breahitt Group in eastern Kentucky, U.S.A. highlights another problem common to stratigraphic and sedimentological studies; most outcrop studies sand body geometry extends beyond the scale of the outcrop, thus making it difficult to ascertain with certainty their large scale geometry and architecture. This negatively impacts the interpretation of the genetic origin of the sand bodies (i.e. stacked distributary from palaeovalleys from braided sediments).

To reduce these uncertainties, increased quantitative characterisation and analysis is required to ascertain the approximate genetic origin of sand bodies in outcrop, associated fluvial stratigraphic relationships and dimensions, and define and/or refine depositional controls; ultimately enhancing subsurface reservoir development from outcrop analogues.

1.3 Background

Fluvial depositional systems recognised in outcrop have been investigated since the 1970s to acquire quantitative information to generate and continually refine reservoir models. The aim has been to assess the dimensions of the fluvial sandstone bodies across a wide range of depositional environments (e.g. Collinson, 1978; Friend et al., 1979; Bridge and Diemer, 1983; Labourdette and Jones, 2007; Pranter et al., 2013; Colombera et al., 2013; Rittersbacher et al., 2014a). Outcrop studies serve as important tools to obtain necessary geometry, architecture, orientation and connectivity (horizontal and vertical) of sandstone bodies. This information is central to generating accurate representations of subsurface reservoirs to enhance hydrocarbon recovery whilst providing a deeper understanding of the production/performance po-
potential throughout a fluvial system (Alexander, 1993; Bryant and Flint, 1993; Anderson, 2005; Labourdette and Jones, 2007; Pranter et al., 2008). Conventionally, one-dimensional (1D) sedimentary logs or cores are correlated across an outcrop and often accompanied by two-dimensional (2D) photo panels, or photomosaics, and outcrop sketches. These tools for outcrop characterisation and analysis offer invaluable information into mesoscale features for larger megascale interpretations (e.g. sedimentary structures, stacking patterns and stratigraphic relationships), as well as providing essential conceptual information used to characterise subsurface petroleum reservoirs. However, these methods lack quantitative precision and 3D spatial context for measurements which are essential for geostatistical reservoir modelling (Kupfersberger and Deutsch, 1999; Gringarten and Deutsch, 1999; Olariu et al., 2011). Attaining and integrating accurate quantitative and qualitative data on the external and internal architecture and properties of the fluvial sand bodies is necessary to build accurate deterministic, geocellular model realisations and ultimately reservoir model simulations of fluvial depositional systems.

Development of new visualisation and analysis techniques in the past two decades have resulted in a recent surge in outcrop data collection methods with potential to generate quantitative and increasingly accurate information (Rarity et al., 2013; Howell et al., 2014). Improved digital survey techniques facilitated through the use of terrestrial survey equipment allows fast and efficient collection, integration, visualisation and analysis of quantitative geospatial datasets from outcrop (e.g. Xu et al., 2000; Pringle et al., 2004; Bellian et al., 2005; Pringle et al., 2006; Labourdette and Jones, 2007; Pranter et al., 2009; McCaffrey et al., 2010) at a range of scales, from a few hundreds of metres to kilometres (e.g. Minisini et al., 2014; Rittersbacher et al., 2014b). Terrestrial laser scanning (TLS) has over recent years, seen a progressive impetus to increase the range of applications and new data capture techniques with regards to digital outcrop geology. This has lead workers to build progressively more detailed and accurate digital outcrop models (DOMs), allowing advanced visualisation of the outcrop datasets. The development of innovative and effective interpretation and analysis tools alongside improved DOM
construction techniques facilitates quantitative characterisation and spatial analysis of outcrop analogues (e.g. Hodgetts et al., 2004; Thurmond et al., 2006; Pringle et al., 2006; Van Lanen et al., 2009; Fabuel-Perez et al., 2009; McCaffrey et al., 2010; Labourdette, 2011; Pranter and Sommer, 2011; Minisini et al., 2014; Rittersbacher et al., 2014b). These techniques include Point Cloud Classification, that allow discreet classification of lithofacies on a continuous point cloud dataset, as well as the Perpendicular Projection Plane to calculate true sand body width from apparent widths (Van Lanen et al., 2009; Fabuel-Perez et al., 2009). Combining these two techniques into a Geobody Mapping tool allows advanced DOM characterisation and analysis not previously achievable. Continued advancement of these techniques allows enhanced outcrop quantitative characterisation and analysis pertinent to the creation of detailed geostatistical databases of the studied outcrops.

Ultimately, the geostatistical databases allow for the generation of more accurately conditioned deterministic subsurface reservoir simulations of outcrop-scale studies (Chapters 3 & 5). Additionally, when applied to a basin-wide study (Chapter 4), potential depositional controls on the sand body architecture and distribution can be interpolated from the DOMs. Therefore the digital outcrop analyses from the resultant DOMs of the studied sections will demonstrate the effective utilisation of 3D quantitative characterisation methods to solve spatially and geologically complex problems.

1.4 Aims and objectives

1.4.1 Aims

The principle aim of this thesis is to use 3D DOM analytical techniques to better understand fluvial depositional system architecture and provide answers to the following research questions:

(i) Can we quantify and subsequently improve our understanding of depositional patterns from sand body architectural analysis in the medial zone of the Huesca distributive fluvial system?
Can we use new and previously published data in conjunction with DOMs of the limited 2D outcrops of the Pikeville and Hyden Fms to determine fluvial stratigraphic relationships, and define possible depositional controls of the major fluvial sand bodies in the Breathitt Group?

What current techniques can be used to quantitatively analyse DOMs and extract essential geostatistical information to improve reservoir simulations derived from outcrop data?

1.4.2 Specific objectives

(i) Analysis of the fluvial sand body geometry and architecture of the La Serreta section in the medial zone of the Huesca DFS in northeast Spain.

(a) Construct a high-resolution 3D DOM for the La Serreta study area (2 km²).

(b) High-resolution lithofacies analysis (from sedimentary logs and point cloud classification) to elucidate key sedimentological characteristics.

(c) Collate key geometric and architectural measurements from integrated sedimentary logs and DOM characterisation techniques (Geobody Mapping & Point Cloud Classification) to analyse spatial distribution of fluvial sand bodies.

(ii) Statistical and spatial analysis of major sand body architecture across a basin from dip sections (up-dip to down-dip) in the Pikeville and Hyden Fms. of the Breathitt Group in eastern Kentucky, U.S.A.

(a) Construct a series of high-resolution 3D DOMs from outcrops up-dip to down-dip of 2D road-cut exposures.

(b) Analyse sand body architectural (internal and external) elements to determine statistical spatial (basin-wide) trends.

(c) Define fluvial stratigraphic relationships from statistical trends and current understanding of geometric and architectural controls.
(iii) Construction of stochastic and deterministic reservoir simulations from 3D DOMs of La Serreta study area.

(a) Develop several facies models from integrated qualitative and quantitative datasets (sedimentary logs and classified DOMs).

(b) Create reservoir simulations through deterministic and stochastic methods to test accuracy of the models derived from ancient outcrop and modern analogue geostatistics.

1.5 Study areas

The main study area for this thesis, is located in the medial zone of the Oligocene – Miocene Huesca DFS, within the northern rim of Ebro Basin, in northeast Spain (Figure 1.1a & b). The La Serreta section is exposed in outcrops north of the village of Piracés, and presents over 100 m of stratigraphy in a number of natural amphitheatres and continuous horizontal exposures over a 2km² area. The physiognomy of the area provides a superb pseudo-3D exposure of the fluvial geometry, architecture and lithologic heterogeneity, both laterally and vertically, of deposits found in the medial zone of a DFS.

The Huesca, and coeval Luna fluvial system are well-documented and have been studied since the 1970s (e.g. Friend et al., 1979; Hirst and Nichols, 1986; Nichols, 1989; Hirst, 1991; Nichols and Hirst, 1998; Fisher et al., 2007; Donselaar and Schmidt, 2005; Donselaar and Overeem, 2008; Donselaar and Schmidt, 2010; Fisher and Nichols, 2013). This previous work provides a plethora of geologic background information, interpretations and discussions to guide and focus the digital outcrop approaches used, and the results presented in this thesis. The Huesca DFS has been studied previously by both academia and the hydrocarbon industry as a subsurface reservoir analogue. The Clair Field, UKCS Block 206, West of Shetland and the Monteith Formation (Minnes Group) in the Alberta Deep Basin, are prime examples of hydrocarbon fields with a reservoir that has been interpreted to have been deposited predominantly from distributive fluvial processes (Nichols, 2005; Kukulski et al., 2013).
The sub-vertical exposures allow investigation of the 3D geometry and stacking patterns of the channel belts, sand body widths and thicknesses, and their spatial distribution throughout the succession and study area. Previous studies involving the use of lidar that have acquired 3D datasets of the La Serreta exposures have focused on correlating sand bodies and stratigraphic horizons across the area, providing a virtual datum which can be implemented in other 3D fluvial outcrop datasets (Calvo and Ramos, 2015). However, the Calvo and Ramos (2015) study does not examine the detailed lithofacies, sand body geometry and architecture for the La Serreta section. This type of analysis is crucial to understand the variability and possible depositional patterns and control for the medial zone of the Huesca DFS.

The second study area is located in eastern Kentucky, U.S.A., in the middle Pennsylvanian (Upper Carboniferous) fluvio-deltaic Breathitt Group (Figure 1.1c – d). The outcrops are well exposed as extensive 2D road-cuts along either side, or often both sides, of the highways, and are up to 1 km in length and over 200 m in height. The units were deposited in a peripheral foreland basin, and studied outcrops extend from the up-dip orogenic margin to the cratonic margin 80 km down-depositional dip. The sand bodies are encased in marine and terrestrial heterolithic sediments, and have previously been interpreted as palaeovalleys or major distributary sand bodies (Aitken and Flint, 1994; Aitken and Flint, 1995). However, a recent study has demonstrated that some of the sand bodies display architecture reminiscent of stacked distributary channel sands up-depositional dip, which thin or are not present down-dip (Jerrett et al., 2016). These deposits are reminiscent of a progradational DFS, and required a quantitative analyses to determine their genetic origins. The level of exposure and spatial extent of the outcrops across the basin present an ideal opportunity to digitally acquire, construct high-resolution 3D DOMs and quantitatively analyse the major sand body architecture (internal and external) which has not been done before. This will also serve as case study to further test the quantitative geostatistical analyses (e.g. geobody geometry and architectural analysis) which can be done with 3D DOMs, and the resulting impli-
cations to the channel belt interpretations presented by Aitken and Flint (1994) and Jerrett et al. (2016). There has been no study completed using 3D digital outcrop techniques in the Breathitt Group to characterise fluvial sand body architecture, thus providing additional reason to perform the proposed analyses.

Figure 1.1: Location maps for study areas. (A) Huesca, and coeval Luna, Distributive Fluvial System (DFS) within the Ebro Basin surrounded by three coastal ranges (Pyrenees, Iberian and Catalan). (B) The principal source area for the Huesca DFS is within the Pyrenees from the Ainsa and Tremp-Graus Basins, whilst the neighbouring Luna system source area is within the Jaca Basin. (C) Location map of the study area within the U.S.A. (D) Location map of the study area within the Pennsylvanian-Permian Appalachian Basin in Eastern Kentucky. (D) Location map of study localities (black boxes) within the Breathitt Group along US 119 and Ky 7 & 15 highways. From Jerrett et al., (2016)

The two selected study areas provide a range of field based problems from analysing pseudo-3D exposures and the inherent problems associated with analysing heterogeneity across a relatively small area of the depositional system and equating it back to larger system as a whole, to 2D road-cut exposures across a basin which exhibit features that extend beyond the scale of the outcrop. The studies provide
an optimal testing ground for the development of digital outcrop workflows and techniques whilst demonstrating the strength and applicability of the new techniques to other fluvial-based outcrops.

1.6 Methodology

The methodology used throughout the PhD has been adapted from workflows by previous workers (i.e. Fabuel-Perez et al., 2009; Van Lanen et al., 2009; Fabuel-Perez et al., 2010; Rarity et al., 2013). This section provides an overview of the methods used to produce the high resolution DOMs of the La Serreta and Breathitt Group successions. The workflow implemented throughout the studies is presented in Figure 1.2.

1.6.1 Sedimentological field data

High-resolution sedimentological analysis was completed in the La Serreta study area to understand and identify the lithofacies distribution, potential depositional controls and internal architectural components. A total of 19 sedimentary logs were recorded, with a spatial location chosen to provide the best representation of the stratigraphic architecture of the depositional system. Each log focused on the description of grain size, lithology, thicknesses and sedimentary structures. In total 800 m of stratigraphy was logged, with the sediments grouped into two facies associations (FA-1 and FA-2), comprising five sub-associations, 2 within FA-1, and 3 within FA-2. These were defined based on their lithology, grain size and sedimentary structures. Each sedimentary log also has a Differential Geospatial Navigation Satellite System (DGNSS) position attached to the base and top, post-processed to offer sub-metre resolution (i.e. ± 0.60 m), which facilitates a direct integration of the sedimentological information with the digital data. In addition, 254 palaeocurrent azimuth measurements were acquired. Each palaeocurrent measurement is given a spatial position in the digital dataset due to its precise positioning from the DGNSS positions of the logs.

Photomosaics were created using a combination of terrestrial laser scans (explained below in 1.6.2) and its coaxial camera, and a Canon EOS DS 126 with a combination of 50 mm prime lens and a 18 – 50 mm zoom lens. These allowed
Figure 1.2: Workflow illustrating methodology and steps involved with acquiring, processing and analysing a digital outcrop datasets to create the digital outcrop models (DOMs), conceptual geologic models and reservoir models and simulations.

1.6.2 Digital data

Digital data collection of the outcrops was based around the integration of three different terrestrial data acquisition techniques to create the DOMs: (i) intensity-coded point clouds produced from Riegl LMS-Z420i terrestrial laser scanner, and (ii)
a coaxially mounted Nikon D-300 DSLR camera on top of the scanner to co-register the photographs onto the point clouds to create photorealistic representations of the scanned outcrops. (iii) DGNSS measurements acquired at each scan location used to georeference each scan position to real-word coordinates. Satellite-derived and airborne orthoimagery were combined with the digital terrain models (DTMs) produced from airborne lidar surveys to create a coarse 5 m grid to qualitatively reference all of the datasets together.

(i) Intensity-coded point clouds from terrestrial lidar surveys

Intensity-coded point clouds were produced from a Riegl LMS-Z420i terrestrial laser scanner (Figure 1.3). This long-range scanner is capable of distances up to 1000 m, in a full 360° rotational view, but was never used for outcrop exposures beyond 500 m for the studies presented here. Initial 360° scans were acquired at a low resolution, which were used to select the desired areas of the outcrop to fine scan, giving a point spacing of 0.09 – 0.10 m. This allows an effective geometric resolution of ≈ 0.20 m throughout the study area. The fine scans are used to capture the fundamental architectural and geometric elements within the outcrop stratigraphy. A Trimble Yuma I ruggedized tablet computer was used to run RisScan Pro™ v.1.5.0 sp1, a software package that is used for acquisition, visualisation and processing of the laser scan data.

The point cloud produced from a lidar unit is a 3D representation of the backscattering of a near-infrared pulsed beam of light (laser pulse) by the targeted outcrop (Figure 1.5a). This pulse is then recorded by a detector within the scanner as a series of spatial data points (x, y, and z) and the reflection intensity of the outcrop elements. The reflection of the material that the laser pulse interacts with, depending on atmospheric conditions, is controlled by the colour of the material and the distance from the scanner itself (Bellian et al., 2005). Scan locations were chosen to optimise as close to 3D coverage as possible of the desired outcrops. The 2D road-cuts in the Kentucky Breathitt Group study area did not allow the 3D coverage possible in the La Serreta study, therefore scan locations were chosen at various orthogonal and oblique views of the outcrop along the highways which snake...
through the study area. (A point must be made here that the term *lidar* is used throughout the thesis based on Oxford English Dictionary orthography.)

(ii) Coaxial Photography

A DSLR camera (Nikon D-300) mounted on the scanner and calibrated to the centroid of the scanner was used as the primary photograph acquisition technique throughout the studies. Three different lenses (Nikkor AF wide-angle 14 mm, 50 mm and 85 mm) are used to photograph the outcrop elements at different distances.

(iii) Differential Geospatial Navigation Satellite System

Exact positioning of each scan location was provided by a Trimble Pro XT Differential Global Positioning System (DGPS). This provided sub-metre accuracy in real-time due to a geobeacon that was in continuous communication with the receiver. This was used to correct systematic errors on the receiver. All of the positions were then post-processed and spatially corrected within ± 0.60 m by using...
a nearby GNSS Receiver Station in Spain, and a nearby Continuously Operation Reference Station (CORS) in the U.S.A. (Figure 1.4).

Figure 1.4: Digital field data acquisition process with lidar, and real-time corrected DGNSS

1.6.3 Data processing and visualisation

After acquisition of the TLS, photography and DGNSS data, post-processing is required to generate the final DOMs on which the interpretation, measurements and geostatistical data extraction will be carried out. The workflow used in this step involves (i) data merging and georeferencing, (ii) creation of the triangulated surface (mesh) and the colouring of the point clouds and mesh to create photorealistic models and (iii) utilising the tensor analysis functions available in software developed in-house by previous workers, Virtual Reality Geological Studio (VRGS) ((Hodgetts, 2009; Rarity et al., 2013), to visualise key surfaces and elements on the models to aid interpretation and digitisation of sand body geometry on the DOMs.

(i) Merging and georeferencing of scan positions

The primary post-processing software used to align the scan locations is Innovmetric: Polyworks™ v. 11. Since each scan location contains a Scanner Own Coordinate System (SOCS), which contains an x, y and z position, Polyworks allows a large import of all of the associated scan positions for each study. The SOCS position has a DGNSS position attributed to it which, which is imported into the
same project. Initial alignment of the scans are performed in Polyworks by the geometry of the features, providing a rough alignment. The DGNSS positions are then used to spatially location each position into a real-world coordinate reference frame, therefore projecting the entire collection of scan locations used in each study into their respective real-world coordinates. This step is critical to identifying spatial distributions and variability within a single outcrop section, and across a basin.

(ii) Creation of mesh and photorealistic models

Riegl’s own software package (RiScan Pro™) is used to translate the RGB (Red Green Blue) information from the coaxially mounted camera photographs onto the point clouds. This process creates a photorealistic point cloud representation of the scanned outcrops, but inherently lacks spatial information between the data points. VRGS is the primary software package used throughout the studies, and is used to triangulate (mesh), interpret, measure and obtain the necessary geostatistics from the DOMs to complete the aims of each study.

Triangulating a mesh to create a surface, or triangulated irregular network (TIN) (Figure 1.5b), was completed through VRGS, and utilises the same colour-coding method of RiScan Pro™ to translate the RGB information onto the generated surfaces. As with any photographic projection or translation technique, each image must be corrected for lens distortion before it is used. All of these steps lead to the creation photorealistic representation of the scanned outcrops (1.5c). This visualisation technique allows for detailed analysis of any similar intensity coloured features which require interpolation between the point cloud data points to be completed.

(iii) 3D tensor analysis for visualising DOM attributes

The primary attribute utilised from a tensor analysis performed on the 3D DOM (both TIN and point cloud) was a calculation of the co-planarity and dip of the surfaces and/or points, respectively. To visualise each of the parameters of the points/surfaces, a moment of inertia analysis for all of the neighbouring points being analysed, calculating a planar regression for each point (Fernández, 2005), was used.

Equivalent to the orientation-tensor method proposed by Woodcock, (1977)
for defining fabric shape, the planar regression calculation derives an orientation
calculation for the dip and azimuth, the quality of the regression (i.e. degree of
fit and reliability) and the number of points used for the regression, that are then
assigned to the analysed point (García-Sellés et al., 2011). The moment of inertia
of a group of adjacent points/vertices may be used as a proxy for their vector sum
by using the maximum moment of inertia as the pole of the best fit plane (Fernán-
dez, 2005; Seers and Hodgetts, 2014). This allows the calculation of eigenvalues
($\lambda_1$, $\lambda_2$, and $\lambda_3$) and eigenvectors ($v_1$, $v_2$, and $v_3$) from a symmetrical matrix,
which links each neighbouring point to the centre mass of all the points (usually
close to the point being handled/analysed). These values are used to calculate the
coplanarity, collinearity and orientation. As coplanarity is the predominate tensor
analysis attribute used for feature extraction of the fluvial architecture, it is the only
attribute discussed in detail, and is defined as follow: Co-planarity is a reflection of
the degree of fit ($M$) of the adjusted plane which is represented by the ratio between
the first and third eigen values ($M=ln \frac{\lambda_1}{\lambda_3}$) (i.e. the larger the ratio, the more
coplanar the points/vertices). Colour bars used to visualise the coplanarity more
effectively which are normalised to the maximum and minimum values of the calcu-
lation. Visualising the co-planarity and dip of specified surfaces and points allowed
more detailed feature extraction than achievable through RGB visualisation meth-
ods alone. A detailed discussion of the calculation and definition of the eigenvalues
and eigenvectors can be found in other works (e.g. Woodcock, 1977; Fernández,
2005; García-Sellés et al., 2011).

VRGS is designed specifically for integration and analysis of digital outcrop
datasets, thus providing a robust medium in which to perform the myriad of analyses
and visualisation practices of the 3D outcrop datasets. VRGS contains tools, which
allow users to emphasise different aspects of the outcrops through different attribute
analyses (i.e. tensor analysis) to produce realisations and statistical information
about the distribution of surfaces of each DOM (i.e. coplanarity, collinearity, dip,
and azimuth). VRGS is the primary software package used throughout the project
to perform the key interpretations, analyses and obtain geostatistical information
about the sedimentary geometries and fluvial architecture in the La Serreta and Breathitt successions.
Figure 1.5: (a) High-resolution intensity-coded pointcloud. (b) Triangulated mesh surface. (c) Textured mesh surface.
1.7 Structure of the thesis

This thesis is written in alternative format, providing chapters which are suitable for submission as peer-reviewed publications. Some unavoidable repetition is therefore present in order to allow each chapter to stand on its own merit as a potential manuscript. Chapter 1 (Introduction – this chapter) outlines the rationale behind this investigation and details its aims and objectives, includes a methodology and approach to data collection, integration and analysis of 3D geologic models and includes the structure of the thesis. Chapter 2 provides the background context to the studies through a literature review of large distributive fluvial systems in endorheic basins, including sedimentology and stratigraphic architecture, as well as the geologic context for the second study area in the Breathitt Group in eastern Kentucky, U.S.A. The 3 main Research Chapters (Chapters 3, 4 and 5) present the collected field data, interpretation, analysis techniques and modelling performed during the PhD. A final Discussion and Implications chapter discusses the wider implications of the discussed techniques for use as future methods used when investigating outcrop analogues of various sedimentary environments. Figure 1.6 illustrates a summary of the structure of the thesis with the main topics highlighted that will be addressed and discussed in the successive chapters.

The following provides a brief outline of the key aims and content of the Research Chapters in the thesis.

- Chapter 3 discusses the Huesca DFS, the data collection, processing, analysis and modelling techniques used to create 3D DOMs of the La Serreta succession. These models were used to analyse the fluvial geometries, stacking patterns and stratigraphic architecture of an outcrop exposure of the medial portion of the Huesca DFS. The statistical products of the digital quantitative method utilised for the succession were compared to historical studies of the Huesca system and more precisely of the same field area. This chapter has been prepared for submission to the journal Geosphere and is pending submission.
The study presented in Chapter 4 aims to test the analytical tools used for the Huesca DFS, La Serreta succession from Chapter Three, and apply it to a fluvio-deltaic succession in eastern Kentucky, U.S.A. The major sand bodies within the Breathitt Group in eastern Kentucky, are characterised as two end-member sand body types, (i) stacked distributive sand bodies similar to those found in a DFS; (ii) palaeovalley fills which are highly amalgamated. These interpretations are statistically and spatially tested based on observations made within a series of DOMs created for the outcrops. The results, supplemental information and implications for depositional controls of the Breathitt Group have been prepared for submission to the journal *Geosphere* and is pending submission.

Chapter 5 presents methods to construct multiple reservoir simulations from the outcrop models built for the La Serreta study area in the Huesca DFS. The reservoir simulations are constrained by integrated qualitative (i.e. sedimentary logs) and quantitative datasets discussed in Chapter 3 (i.e. minimum, maximum and most likely geobody size), as well as channel object statistics (i.e. amplitude, wavelength and sinuosity) measurements acquired from a modern analogue interpreted to be of similar size, catchment area and climate, to construct an approximate representation of the fluvial facies elements within the DFS. The results and supplemental implications to building reservoir simulations from integrated 3D DOMs are discussed have been prepared for submission to the journal *Petroleum Geoscience* and is pending submission.
Figure 1.6: Schematic overview of thesis structure.
1.8 References


— (1995). “The application of high-resolution sequence stratigraphy to fluvial systems: a case study from the Upper Carboniferous Breathitt Group, eastern Kentucky, USA”. In: *Sedimentology* 42.1, pages 3–30.


Chapter 2
Chapter 2
Geologic Background

2.1 Introduction

This chapter discusses the geological context and fluvial architecture of the two study areas used for this study, the La Serreta succession of the Huesca distributive fluvial system in northern Spain, and fluvio-deltaic succession of the Breathitt Group, in eastern Kentucky.

2.2 Geologic Context

2.2.1 Distributive Fluvial Systems

The distributive fluvial system (DFS) concept is a recent idea in sedimentology that is prevalent throughout modern continental aggradational systems (i.e. alluvial fans, fluvial fans, and megafans) (Weissmann et al., 2010). These systems demonstrate a pattern of channel and floodplain deposits radiating into a distributive pattern from a point source (i.e. apex) into a sedimentary basin, and range in size from <1km to >700km, depending on the basin type and river size. Recently, large DFSs (>30km) have been studied in both modern and ancient settings, and their channel body geometries (i.e. width, thickness, amplitude, wavelength and sinuosity) have been measured and catalogued to gain an understanding into their preservation potential in the rock record (Weissmann et al., 2015). Additionally, a quantitative study by Davidson and Hartley, 2014 has been undertaken which links the drainage area of large modern DFSs to ancient examples to gain a critical understanding of the fluvial geometries found in these ancient systems, and their connection to modern channel elements. Furthermore, DFS apex locations can be estimated systematically through robust palaeocurrent azimuth vectors used
as input parameters into a mathematical model for an accurate estimation (Jupp et al., 1987; Owen et al., 2015). A study measuring planform geometries of modern aggradational DFSs using remotely-sensed data revealed that 58% of the examples occur in exorheic basins (externally draining) whereas the other 42% are found in endorheic basins (internally draining). Large DFSs which contain sinuous channels, and also lower gradients than braided systems, are found predominantly in wetter, more tropical climates contributing to a constant discharge and ultimately more efficient bedload distribution (Hartley et al., 2010). Due to the aggradational nature of these systems, especially in actively subsiding basins, they are theorised to form a significant portion of the preserved continental sedimentary rock record.

2.2.2 Palaeogeographic and stratigraphic setting of the Huesca DFS

The Ebro Basin is a foreland basin that formed during the early Eocene due to flexural subsidence from loading of the Iberian crust by thrust sheets in the Cenozoic Pyrenean orogenic belt (Teixell, 1996). The basin is surrounded by three ranges, the Pyrenees to the north, the Catalan Coastal Range to the east and the Iberian Range to the south west, and is one of the largest Tertiary basins in the Iberian Peninsula (Figure 2.1). Basin drainage was exclusively to the west into the Bay of Biscay and the Atlantic Ocean, as indicated by palaeocurrent and facies distribution data in the marine foreland basin deposits along the foreland trough (Nichols and Hirst, 1998). The western part of the basin exposes turbiditic deposits of the Hecho Group, which are overlain by shallow-marine deltaic sediments and fluviolacustrine deposits of the Campodarbe Group (Figure 2.2). During the Priabonian (c. 36 Ma), tectonic shortening along the Iberian Range and Pyrenees closed the Atlantic Ocean connection to the basin, creating an endorheic basin which would remained closed until the late Miocene (Garcia-Castellanos et al., 2003; Costa et al., 2010). The northern margin of the Ebro Basin is bounded by the External Sierras thrust system which formed during the middle Eocene to the early Miocene. During the middle Oligocene, a distinct ridge formed due to thrust movement (uplift) along the External Sierras, which caused a major shift in the drainage patterns in the southern Pyrenees (Hirst and Nichols, 1986; Nichols and Hirst, 1998)
The principal source areas for the Huesca distributive fluvial system are from the southern Pyrenean zone and the basins within it, the Internal Sierras and the Axial zone of the Pyrenees. Terrigenous clastic sediments which make up the deposits within the Pyrenean basins, the Jaca, Ainsa and Tremp-Graus, are of late Eocene to Oligocene in age. The basins were initially connected during the early Tertiary and formed the southern foredeep of the Pyrenees. However, Oligocene thrusting caused these basins to become disconnected and predominantly degradational in nature (Hirst and Nichols, 1986). During the Oligocene and Miocene, uplift in the Pyrenean axial zone caused erosion of Mesozoic material covering the underlying Hercynian basement (comprised of metamorphic and acid plutonic rocks), which in coordination with carbonates from the southern thrust belt and the clastic fill of the disconnected basins, make up the sediments that were deposited into the Ebro Basin.

The area of active deposition in the Ebro Basin during the Oligocene – Miocene spread as far south as the Cordillera Ibérica, and displays an asymmetric erosional pattern as evidenced by the thickness trend of the deposits tapering to the south. This reflects the tectonic subsidence of the basin caused by flexural loading.
in the northern margin (Nichols and Hirst, 1998). The overall tectonic dip of the Oligo-Miocene deposits range from zero to two degrees, with the only exceptions at the basin margin adjacent to the thrust front (Nichols, 1987). The deposits found adjacent and along the northern margin of the basin, are interpreted as products of alluvial fans, and formed due to the steep topography formed by the External Sierras thrust front. The bulk and remaining clastic detritus was deposited by large distributive fluvial systems, or lacustrine environments, and cover an area more than 5000 km² (Riba 1987). The centre of the basin contained a relatively shallow ephemeral lake, which produced lacustrine deposits in the distal sectors of the system (Nichols, 2007; Nichols and Fisher, 2007). Additionally, hydrologic and topographic models of the Ebro basin by Garcia-Castellanos et al. (2003) summarise that the endorheic basin persisted for approximately 25 Ma A variety of palaeosol characteristics observed by Hamer et al. (2007), correlate to an early successional, an immature and young landscape and an open woodland setting of varying maturity. The mean annual temperature of 10 – 14 °C ± 4 °C and a mean annual precipitation of 450 – 830 mm yr⁻¹ ± 200 mm yr⁻¹ of the coeval systems indicates a humid continental setting (Hamer et al., 2007). This influence governed the majority of the sedimentary and depositional processes into the basin at the time, resulting in the creation of the distinct distributive fluvial systems.

2.2.3 Sedimentology of the Huesca DFS

The internal drainage architecture of the Ebro Basin produced two large and distinct systems, the Huesca and Luna DFSs that formed during the Late Oligocene
– Early Miocene (Hirst and Nichols, 1986). Both systems are part of the Uncastillo (Luna), or equivalent Sariñena (Huesca) Formation (Figure 2.2) (Arenas et al., 2001). These two coeval depositional systems, 60km and 40km wide respectively, are well preserved due to the aggradational, relatively low incisional and endorheic nature of the basin (Figure 2.3). A long history of relative base-level rise, a thick accumulation of fluvial strata due to rates of evaporation exceeding water supply, and a high basin margin spill point are all conditions needed for a basin to remain internally draining and underfilled (Figure 2.4) (Bohacs et al., 2000). The ephemeral lake at the basin centre, during high levels, acted as the downstream
anchor point and buttress for the system, which otherwise was positioned somewhere on the alluvial plain (Holbrook et al., 2006; Fisher and Nichols, 2013). The position of the buttress defined the position in the system where the channelised flow ceased, and unconfined flows which spread across the alluvial plain, or into the lake began. The Huesca and Luna systems developed a long and continuous river profile which behaved differently over a range of temporal scales. Fisher and Nichols (2013) discuss in detail these ranges in scale and their effect on an endorheic basin and the subsequent fluvial systems within them; then are summarised here: (i) the accommodation space available over the short term is determined by the vertical separation between the upper and lower buffers as defined by Holbrook et al. (2006); (ii) the syntectonic subsidence of the Ebro Basin was the main determinant for sediment accumulation and aggradation of the system over the medium term; (iii) by contrast the maximum buttress rise in the long term is determined by the upstream anchor point and basin margin spill point (Nichols, 2004) (Figure 2.4). Sediment accumulation in endorheic basins can force the basin buttress to rise until it reaches the basin margin spill point, and has been estimated to be at least 1000 m in the Ebro Basin throughout the time of deposition (Nichols, 2004).

Figure 2.4: Characteristics of a fluvial distributary system observed in the Huesca and Luna Systems. Tectonic shortening in late Eocene closed the Ebro Basin to the Atlantic, creating an endorheic (internally draining) basin which remained until the late Miocene. (Modified from Nichols and Fisher, 2007; Garcia-Castellanos et al., 2003).
The low gradient of the basin promoted river avulsion over the medium term throughout the systems, by allowing the rivers to follow new paths on the low-lying areas into lobes on the alluvial plane (Figure 2.5). The continual avulsion creates a radial fan shape that is convex upward in profile across the system and concave upward down fan (Weissmann et al., 2010). There is a variation in stratigraphic architecture which results from autogenic differences in balance between sedimentation, stream power and the elevation of the depositional surface relative to the instantaneous equilibrium profile of the river and river profile buttress (Fisher and Nichols, 2013). Contemporaneously to alluvial plain deposition, hinterland valleys back-fill, increasing the profile gradient, but was balanced by the progressive rise in the system buttress (aggradation and sediment accumulation). The accumulation of sediment would continue until the basin margin spill point is reached over the long term, but the resulting thickness of the strata will be greater than the original accommodation, mostly due to subsidence from sedimentary loading (Figure 2.4) (Nichols and Fisher, 2007). As the sediments transition from bed-load to suspended-load at the fringes of the system before feeding into a basin centre lake, the lithological component changes. The percentage of in-channel components decreases down-dip and
becomes progressively finer grained as overbank and floodplain deposits become the dominant lithological element. Previous studies by Hirst (1991) across the Huesca DFS shows an as expected negative correlation with the variation in proportion of sediment deposited in the palaeochannels from up-dip (medial) to down-dip (distal) (Figure 2.6).

Figure 2.6: (a) Variation in proportion of in-channel sediment observed from medial to distal zones of Huesca DFS. (b) Variation of lithofacies across Huesca DFS from medial to distal zones. (Modified from Hirst, 1991).

2.2.3.1 Lithofacies

Several lithofacies associations are defined in the Huesca fluvial area by their lithologies, such as the proportion of said lithology, bed geometry, textural and sedimentary features (Luzón, 2005). The northern part of the Ebro Basin offers a unique opportunity to study the facies variation and architecture throughout a 60 km radial pattern fluvial distributary system. The overall grain size in the Huesca system decreases downstream as the channels undergo a transition from bed-load to mixed-load. This transition is evident of a change in channel depth and width as it flows toward the basin centre, which results in a distal decrease of in-channel deposits and an increase in over bank deposits in vertical section (Nichols and Hirst, 1998). Therefore, the lithology from the system apex to basin-centre contains conglomerate, sandstone and mudstone respectively, which have scoured into the adjacent alluvial plain as channel fill deposits (Hirst, 1991; Nichols, 1987).

The La Serreta study area is located within the medial zone of the Huesca DFS, and contains channel sand body deposits that are primarily very coarse to fine sand-
stone enclosed by an overall mudstone and very fine sandstone strata (Nichols and Fisher, 2007). Through detailed investigation in this thesis, two overall facies associations with five subfacies associations were identified: (1) channel Facies, which make up 46% of the stratigraphy, contain multi-storey stacked deposits and single storey channel deposits, and (2) overbank facies, which make up the remaining 54% of the stratigraphy, is made up of crevasse splay, sheet flood and very fine suspended load flood material (i.e. claystone). The lithofacies types and associations are described here in detail, and summarised in Table 2.1.
<table>
<thead>
<tr>
<th>Facies Association (FA)</th>
<th>Facies Code</th>
<th>Lithofacies</th>
<th>Description &amp; Geometry</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Channel-fill Facies</strong></td>
<td></td>
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</tr>
<tr>
<td>Facies 1a</td>
<td>Se,Ss,Sp,Ss</td>
<td>Scour-fill sand, planar cross-bed with trough cross-beds as dominate type</td>
<td>4 – 16 metres thick multi-storey deposits. Gravel to fine grain sand grains. Fining-up vertical profile. Poor to moderately sorted. Some lag deposits found at the base, containing pebbles, granules and mud chips rip-up clasts. Well sorted sands near the top. Lateral accretion surface sets found in the lower sand bodies. Trough cross-stratification predominant structure throughout. Tabular cross-stratification found near the top. Bioturbation &amp; biogenic mottling is found part-way up, prevalent near top.</td>
<td>The coarse-grained bases of the cross-stratified sandstones represent bedload deposits with the basal lag deposits and mud chips signifying new channel incision into the alluvial floodplain, and pebbles and granules signifying streams with enough stream power to transfer bedload material. The identification of lateral accretion sets in some of the sandstone deposits illustrate a meandering pattern whilst the stacking and amalgamation of multiple sandstone packages demonstrates an aggradational depositional setting.</td>
</tr>
<tr>
<td>Facies 1b</td>
<td>Se,Ss,Sp,Ss</td>
<td>Scour-fill sand, planar cross-bed with trough cross-beds as dominate type</td>
<td>1 – 3 metres thick single storey sand bodies. Medium to very fine sand grains. Slightly fining up sequences. Moderate to well-sorted vertical profiles. Mud chips sometimes found near the base. Trough cross-stratification predominant structure. Bioturbation &amp; biogenic mottling is present.</td>
<td>The medium to very fine sand bodies with primarily trough cross-stratification, and a slightly fining-up sequence suggests these are mobile channels that are distributaries from larger main multi-storey channels. The lack of basal lag deposits and rip-up clasts suggests these were of channels relatively low stream power, transporting small bedload grains. The channels are slightly erosive, but not enough to create a topographic low which can be re-occupied by an avulsion event from another channel.</td>
</tr>
<tr>
<td><strong>Overbank Facies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facies 2a</td>
<td>Sm</td>
<td>Massive sandstones</td>
<td>10 – 20 cm thick sandstone deposits. Very fine grain size. Slightly fining up sequences. Contains slightly erosive bases. Some Channel-like geometry found, which are up to 1 m thick. Typically massive and structure-less. Does contain some biogenic mottling.</td>
<td>Overbank crevasse-splay deposits from the nearby channels. Crevasse-splay progradation is observed in a few cases, but the majority of the deposits are seen as laterally extensive deposits with slightly erosive bases. These are well drained deposits that have been interpreted to be located at various proximities to the main channel. Some spays exhibit evidence of being proximal to the active channel (i.e. more erosive bases, less pedogenic alteration) whilst others that are further away display more sheet-like and sometimes progradational patterns (i.e. lateral stacking) and are generally more pedogenically altered.</td>
</tr>
<tr>
<td>Facies 2b</td>
<td>Fm</td>
<td>Massive (no structures) siltstone</td>
<td>20 cm - &lt;3 m thick deposits. Silt grain size some with fining up sequences. Pedogenically altered horizons. Pink, red and grey successive palaeosoil profiles. Bioturbation and biogenic mottling is present. Lateral extentive for hundreds of metres. Some contain slightly erosive bases.</td>
<td>These deposits are interpreted as sub-aerially exposed overbank material, deposited as suspended-load flood elements, or the distal reaches of spays. The repetition of palaeosoil profiles of red, pink then grey suggest a long-term sub-aerial exposure period, allowing soil drainage with low stature plants and herbaceous vegetation.</td>
</tr>
<tr>
<td>Facies 2c</td>
<td>Fm</td>
<td>Massive (no structures) claystone</td>
<td>10 cm - &lt;7 m thick deposits. Clay grain size. Structure-less and are pedogenically altered. Contains same pink, red and grey successive palaeosoil horizons. Rootlets and bioturbation is present. Lateral extentive for hundreds of metres.</td>
<td>These claystone successions are interpreted as sub-aerially exposed overbank material as well that are deposited the most distal to the source area, or active channel. They are predominantly well drained deposits allowing herbaceous vegetation and low stature plants to grow in an open woodlands environment with a fluctuating water table.</td>
</tr>
</tbody>
</table>
Lithofacies 1a - Very coarse – fine sandstone:

**Description** Four – sixteen metres thick deposits with a gravel to fine grained sand (fining-up) vertical profile. The sand is poor to moderately sorted with lag deposits found at the base in some cases, containing pebbles, granules and mud chip rip-up clasts at the base. These then give way to more well sorted sands near the top. Lateral accretion surface sets are found in the lower sand bodies with trough-cross stratification throughout, and usually tabular cross-stratification is found near the top of the sand bodies. Bioturbation and biogenic mottling is found part-way up the succession, and then prevalent from there to the top. These sands make up 67% of the sandstone packages found in the studied sections.

**Interpretation** The coarse-grained bases of the cross-stratified sandstones represent bedload deposits with the basal lag deposits and mud chips signifying new channel incision into the alluvial floodplain, and pebbles and granules signifying streams with enough stream power to transfer bedload material. The identification of lateral accretion sets in some of the sandstone deposits illustrate a meandering pattern whilst the stacking and amalgamation of multiple sandstone packages demonstrates an aggradational depositional setting (Hirst, 1991; Davies and Gibling, 2010) (Figure 2.6).
Figure 2.7: (a) Thick multi-storey sand bodies incising into overbank deposits. *Geologist (yellow) is 1.87 m* (b) Multi-storey sand body with basal lag at the base of one of the incisional channels halfway up through the sand body succession. *Geologist is 1.7 m* (c) Large barforms containing low angle tabular bedding, indicative of possibly transverse bar construction within braided streams. (d) Complex stacking patterns showing trough cross-bedding, low angle tabular cross-bedding, and laminar bedding at the top of the sand body. (e) Example of trough cross-bedding found in the majority of the sand bodies. (f) Close-up view of a basal lag filled with gravel and mud chips incising into the overbank floodplain below at the base of a channel sand body.
Facies Association 1b – Medium – Very fine sandstone:

*Description* One to three metres thick single sand body deposits with fining up sequences of medium to very fine sand grains. Moderate to well-sorted vertical profiles with small mud chips sometimes found near the base. Tabular cross-stratification is found, but predominant sedimentary structures are trough cross-stratification. Biogenic mottling and bioturbation is present. These sands make up 33% of the sandstone packages found in the studied sections.

*Interpretation* The medium to very fine sand bodies with primarily trough cross-stratification, and a slightly fining-up sequence suggests these are mobile channels that are distributaries from larger main multi-storey channels. The lack of basal lag deposits and rip-up clasts suggests these were of channels relatively low stream power, transporting small bedload grains. The channels are slightly erosive, but not enough to create a topographic low which can be re-occupied by an avulsion event from another channel (Figure 2.7).
Figure 2.8: (a) Preserved single storey sand body approximately 1.3 m thick. No evidence of stream migration, thus it was most likely a chute channel from a nearby stream. *Geologist is 1.65 m*(b) Larger single storey sand body approximately 1.5 m thick. Evidence of migration negligible, thus the stream was relatively immobile across the floodplain. *Geologist is 1.87 m*(c) Erosive sand body with planar tabular cross bedding indicating palaeocurrents orthogonal to the mean direction. (d) Large plant root found in sand bodies, indicating low levels of fluvial activity on the single storey sand deposits, allowing vegetation to accumulate. (e) View of bioturbation marking commonly found in all sand bodies, though are more prevalent in the single storey elements. (f) climbing ripples found at the top of a thing single storey sand body, indicating a rapid flux of sedimentation.
Facies Association 2a – Very fine sandstone:

*Description* Ten to twenty centimetres thick very-fine grained size sandstone deposits with slightly fining up sequences. They are laterally extensive for tens of metres at outcrop, and contain slightly erosive bases. Sometimes the deposits display channel-like geometries which are up to 1 m thick. The deposits are typically massive and structure-less, but does contain some biogenic mottling.

*Interpretation* Overbank crevasse splay deposits from the nearby channels. Crevasse splay progradation is observed in a few cases, but the majority of the deposits are seen as laterally extensive deposits with slightly erosive bases. These are well drained deposits that have been interpreted to be located at various proximities to the main channel. Some splays exhibit evidence of being proximal to the active channel (i.e. thick lateral stacking units, progradational features, more erosive bases, less pedogenic alteration) whilst others that are further away display more sheet-like geometry (i.e. slightly erosive and thinner) and are generally more pedogenically altered (Figure 2.9).

Facies Association 2b – Siltstone:

*Description* Twenty centimetres to <three metres thick siltstone deposits, some with fining up sequences. The majority of the siltstone successions are pedogenically altered and contain pink, red and grey successive palaeosol profiles. Bioturbation and biogenic mottling is prevalent throughout the successions. Several siltstone packages can be found in a succession between the channel sands, surrounded by finer grained material. They are laterally extensive for hundreds of metres, and some contain slightly erosive bases.

*Interpretation* These deposits are interpreted as sub-aerially exposed overbank material, deposited as suspended-load flood elements, or the distal reaches of splays. The repetition of palaeosol profiles of red, pink then grey suggest a long-term sub-aerial exposure period, allowing soil drainage with low stature plants and herbaceous vegetation (Figure 2.9).
Facies Association 2c – Claystone:

Description 10 cm - <7 m thick claystone deposits. The successions are structureless and are pedogenically altered, containing the same pink, red and grey successive palaeosol horizons to those found in the siltstone deposits. Rootlets are found within the palaeosol horizons. Bioturbation is present, but the structureless nature prevents exact measure of level, unlike those found in the siltstone successions. The packages are laterally extensive for hundreds of metres before they are cut into by channel sand deposits.

Interpretation Interpretation: These claystone successions are interpreted as sub-aerially exposed overbank material as well that are deposited the most distal to the source area, or active channel. They are predominantly well drained deposits allowing herbaceous vegetation and low stature plants to grow in an open woodland environment with a fluctuating water table (Figure 2.8).
Figure 2.9: (a) Large crevasse splay channels, proximal to source channel, which show signs of progradation and/or lateral migration. *Geologist is 1.65 m* (b) Thin (i.e. 0.20 m) crevasse splay sheet deposits, distal to the main crevasse channel *Geologist is 1.87 m* (c) Proximal-medial crevasse splays, 0.50 m thick, which are incisional in nature into the floodplain material. (d) Lateral migration of splay deposits which transition into finer floodplain material before become a palaeosol profile. (e) Typical palaeosol profile found amongst floodplain sediments. Red palaeosol constitutes a well drained soil, and is commonly associated with pedogenic alteration, whilst the grey palaeosol isn’t well drained and shows no pedogenic alteration (Kraus, 1997). (f) Example of the burrows reaching into the well drained soil below.
2.2.3.2 Facies associations

Channel facies association

The channel facies association is the second most recognised facies in the studied sections, accounting for 46% of the total stratigraphy. They can be divided into multi-storey stacked channels and single storey channel elements. The multi-storey channel sand bodies make up 67% of the recognised channel facies in the studied sections, and are primarily composed of coarse to medium grained cross-stratified sandstone, with biogenic mottling recognised near the top of the sandstone succession. Multiple individual storeys are found in the successions, demonstrating an amalgamation of channel elements through time.

The single-storey channel elements make up the remaining 33% of the recognised channel facies in the studied sections, and are primarily composed of medium to very fine cross-stratified sandstone, with biogenic mottling recognised throughout the successions. Rarely the sandstones are found to be massive and structure-less, but will still contain elements of mottling.

Overbank facies association

The overbank facies association is the most recognised facies in the studied sections, accounting for 54% of the total stratigraphy. These facies surround the channel sand deposits, and contain multiple palaeosol horizons, typically demonstrating the same pattern. The correlation across the study area is not easily achievable to the erosional nature of the nearby sandstone deposits cutting them out. Claystone deposits are the primary overbank facies observed, which contain the majority of the recognised palaeosol horizons (Figure 2.9e). Small rootlets are often found within the palaeosol horizons, confirming the existence of plant material on the active flood plain, similar to those found in the distal portions of the system (Hamer et al., 2007). Siltstone deposits are the second constituent of the overbank facies, which are laterally extensive and are typically homogeneous, massive features with slightly erosive bases, and are typically found to be vertically stacked in between channel sand deposits (Figure 2.9b). Large crevasse splay deposits are the least recognised facies with in the overbank facies association, and are overlain by finer grained material.
(i.e. claystone) (Figure 2.9c). Crevasse splay deposits range in thicknesses between the different deposits illustrates the variability in the proximity to the main channel and/or size of the splay deposit.

2.2.4 Sedimentary architecture

The sedimentary architecture found in the Huesca and Luna systems has been covered in detail by previous works (i.e. Friend et al., 1979; Nichols, 1989; Nichols and Fisher, 2007; Fisher et al., 2007; Hamer et al., 2007; Fisher and Nichols, 2013), therefore the detailed observations of the La Serreta study area will be discussed here (Figure 2.11). Hirst (1991) observed a down-system change in the Huesca system with regards to sediment body geometry, noting predominant ribbon sandstone body geometry in the medial zone of the system, with sheet-like sand bodies as the subordinate type, compared to sheet-like deposits further in the distal reaches. These relationships are crucial to understanding the heterogeneity found throughout the system, as well as in the different regions, such as the La Serreta study area. As the channels distribute their bedload down-dip, the overall lithological components across the system transition from coarse grained in-channel components which transition to overbank facies (i.e. siltstone and claystone).

In the studied La Serreta succession, the most prominent sandstone bodies are multi-storey stacked channel deposits that amalgamate into a single succession surrounded by the overbank material. These sandstone bodies outcrop for tens to hundreds of metres, and can be up to 14 m thick. The deposits contain lateral accretion surfaces in some of the storeys, with trough cross-bedding as the predominant sedimentary structure type (Figure 2.6a). None of the sand body bases deeply incise into the alluvial floodplain or into one another, providing evidence of lateral mobility of the streams throughout deposition (Sadler and Kelly, 1993). The same incisional characteristic is observed in the other single-storey sand bodies recognised in the study area. These sand bodies represent smaller channels which did not re-occupy their channel belt, therefore creating single storey bodies which can extend for tens to hundreds of metres. There are examples of preserved channel deposits with the margins preserved, reminiscent of chute channels.
Figure 2.10: Typical outcrop type and exposure level of La Serreta section which shows the lateral extent of channel-fill sand bodies surrounded by thick overbank deposits. View of outcrop is facing SE.
2.2.5 La Serreta palaeoflow and provenance

Palaeocurrents were measured in the channel facies association using from planar foreset dip directions, lateral accretion sets and 3D trough cross-strata. These mainly represent in-channel migration of ripples and dunes, the lateral migration of channel bodies across the alluvial plain, and lunate dune and mid-channel bar aggradation, respectively. The overbank facies association do not display any sedimentary structures, and therefore are not used to determine any palaeoflow azimuths. The palaeocurrent data measurements display an entire $360^\circ$ range in values ($n = 254$); however the mean azimuth is $296^\circ$ degrees (WNW). The wide spread of azimuth values illustrates a pattern similar to the meandering pattern that is observed in modern DFS palaeocurrent azimuths. The values were constrained to their channel facies types to filter out any similarities or differences between them. The multi-storey channel facies display a more concentrated radial pattern with a mean azimuth of $292^\circ$, whereas the single storey channel facies display a larger swath of values, some that are $180^\circ$ from one another, with a mean value of $309^\circ$ (Figure 2.10). These values are in accordance with the palaeocurrent pattern of the Huesca DFS interpreted by previous workers (i.e. Hirst and Nichols, 1986; Nichols and Hirst, 1998; Hirst, 1991.)
Provenance studies of the sandstone and mudstone deposits suggest that the sediments were primarily sourced from the Tremp-Graus Basin, with a lower supply from the Axial Zone igneous and metamorphic rocks (Yuste et al., 2004). This aligns with the tectonic framework during the Oligocene – Miocene.

2.2.6 Palaeogeographic, structural and sedimentological setting of the Breathitt Group, eastern Kentucky, U.S.A.

The central Appalachian Basin (Figure 2.11) was one of a series of peripheral foreland depocentres of Alleghenian-Variscan orogenic event which developed cratonward of promontories on the Laurasian continental margin. Initial thrust sheet emplacement along the southeastern margin of Laurasia, during the middle Carboniferous, drove flexural subsidence of the existing cratonic carbonate shelf into an area that is present-day south-eastern West Virginia, and western Virginia (Quinlan and Beaumont, 1984; Tankard, 1986; Greb and MARTINO, 2005). Mud, silt and fine-grained sand sourced from the emerging orogenic belt prograded NW into the early basin, conformably lying over the pre-existing mixed clastic-carbonate shelf. Predominantly arkosic siliciclastic debris was shed from the orogenic hinterland through the late Carboniferous and early Permian to the southeast and travelled north-westward through the basin by a series of deltas (Ferm and Cavaroc, 1968; Ferm, 1970; Horne et al., 1978; Rice et al., 1979; Chesnut, 1994) that are considered to have been largely river-dominated (Englund and Thomas, 1990; Aitken and Flint, 1995). Lithospheric flexure towards the orogenic load in the south-east produced a characteristically asymmetric basin-fill found in the foreland basins. The maximum preserved thickness of Pennsylvanian strata in the Central Appalachian Basin is 1.5 km near the Kentucky-Virginia border (Wanless et al., 1975; Chesnut, 1992). In the central Appalachian Basin, fluvio-deltaic sedimentation was punctuated by regular, cyclic, marine transgressions and periods of subaerial exposure and nondeposition (Wanless, 1939; Chesnut, 1994; Aitken and Flint, 1994; Aitken and Flint, 1995), associated with glacio-eustatically driven rises and falls in sea-level of as much as 100 m (Rygel et al., 2008). Within the study area, to the northwest of the Pine Mountain Thrust (Figure 2.11b), strata are weakly deformed into a major NE SW
striking open fold (the Eastern Kentucky Syncline), with gentle structural dips on the limbs that rarely exceed 10 degrees.

![Figure 2.12: (a) Palaeogeographic reconstruction of transpressive collision of Gondwana and Laurentia in the Middle - Late Carboniferous, illustrating formation of the Greater Appalachian Basin. (Modified from Hatcher, 2005). (b) Location map of the Greater Appalachian Basin and the study area within it highlighted in red. (Modified from Hatcher, 2005; Jerrett et al., 2016).](image)

### 2.2.7 Stratigraphy of the fluvio-deltaic succession of the Breathitt Group

In eastern Kentucky, the late Palaeozoic foreland megasequence of the central Appalachian Basin is broadly a coarsening-up succession of marine, marginal marine and terrigenous siliciclastics, coal and rare carbonate, in which evidence for marine conditions generally decreases upwards (Horne et al., 1978; Chesnut, 1992; Chesnut, 1994). This megasequence can be broadly divided into (i) the lower Breathitt Group, (ii) the upper Breathitt Group, and (iii) the Conemaugh Formation, bounded by widespread marine mudstone units. Additionally, between the marine mudstones, the stratigraphy is comprised of typically 2 – 15 m thick cycles characterised by a locally-to-regionally developed marine to marginal marine mudstone which coarsens upward, and forms a robust in-place coal seam correlation framework (Rice and Hiett, 1994). Commonly, much or all of the upper part of the cycle may be truncated by major erosionally-based fining-up fluvio-estuarine channel bodies which underlie the regionally extensive coal (Chesnut, 1992; Chesnut, 1994; Aitken and Flint, 1994; Aitken and Flint, 1995). This robust correlation framework allows confident correlation of the sand bodies through the succession and across the basin.
**Figure 2.13:** (a) Stratigraphic column of eastern Kentucky lithostratigraphy with the intervals investigated in this study highlighted (red box). (b) Correlation panel of stratigraphy and architecture across the study area. (Modified from Jerrett et al., 2016).
2.2.8 Overview of datasets

Both study areas have been studied by several workers over decades (the Huesca for 38 years, and the Kentucky Breathitt Group for 22 years) as examples of endorheic distributive fluvial system development and recognition of sequence stratigraphy within a fluvio-deltaic system. The plethora of pre-existing information for the two study areas has allowed new methods of geostatistical data extraction to be developed and used to both increase the geological understanding and construction reservoir simulations suitable for use as analogues.

The geological information acquired for both study areas were used to guide the geological modelling and analysis process. The development of tools within VRGS has been conducted by previous workers (see Hodgetts, 2009; Fabuel-Perez et al., 2009; Fabuel-Perez et al., 2010; Van Lanen, 2010; Rarity et al., 2013) for the purpose of analysing and extracting geostatistical information (e.g. approximate geobody width and thickness, storey height, length of storey contacts). These tools are used in conjunction with the pre-existent geological information of the Huesca system and study area to approximate the geostatistics in Chapter 3 for the La Serreta section. Additionally, the previous works of the Breahitt Group are used to understand the data analysis results, and their relationship to the fluvial processes within the fluvio-deltaic system. Furthermore, the type of information acquired from past studies was used to constrain the reservoir simulations which are described in Chapter 5.
2.3 References


— (1995). “The application of high-resolution sequence stratigraphy to fluvial systems: a case study from the Upper Carboniferous Breathitt Group, eastern Kentucky, USA”. In: *Sedimentology* 42.1, pages 3–30.


Section 2

Digital Outcrop Models
Chapter 3
3.1 Abstract

Accurate characterisation of the stratigraphic architecture of a fluvially dominated depositional system is fundamental to define geometric relationships, heterogeneity, and lithologic trends. Outcrop analogue studies allow detailed investigation of geometry and architecture of sand bodies within fluvial systems. The Oligocene–Miocene Huesca fluvial fan, in the Ebro Basin in Spain, is a well-documented outcrop that has been studied as an analogue for hydrocarbon reservoirs. The La Serreta outcrop presents well-exposed fluvial channel bodies (i.e. major sand bodies and overbank material) that are key to defining the distribution and geometry of elements found in large Distributive Fluvial Systems (DFSs).

This study utilises techniques that integrate lidar, high-resolution photography and differential geospatial measurements, to create accurate three-dimensional (3D) digital outcrop models (DOMs) of the cliff sections in the La Serreta area of the Huesca DFS. The large quantitative dataset is integrated with traditional field measurements (i.e. sedimentary logs), to further constrain facies models generated from the extensive dataset. The inherent quantitative nature of the dataset allowed accurate 3D interpretations of geobodies within a medial portion of a DFS. This has allowed extraction of relevant geostatistics for analysis and comparison with similar fluvial systems to test the efficacy of DOMs as outcrop analogues. The results presented demonstrate a methodology developed for accurate approximation of geobody widths, thicknesses, architecture and geometric patterns of major fluvial sand
bodies found within the medial portion of a DFS.

3.2 Introduction

Fluvial depositional systems are prevalent throughout the ancient rock record and modern-day settings in both marine margin and continental basins. Alluvial and larger fluvial systems dominate in every modern continental basin, with distributive fluvial systems (DFSs) being the predominate pattern (Weissmann et al., 2010). To understand their lithological impact within the rocked record, detailed investigation into sand body geometry and spatial distribution is required. This is not a trivial task, however, and remains a problem in the study of fluvial successions (Bridge, 1993). Process-based sedimentary and numerical modelling offers insights into the processes which govern the creation of the sand bodies seen in outcrop; however they are merely used to predict and help constrain conceptual depositional models (Paola, 2000). With these principles in mind, accurate outcrop mapping techniques used to determine the spatial and temporal characteristics of sand bodies within a fluvial succession remains paramount to the development and/or refinement of conceptual depositional models, and ultimately accurate outcrop representations used for reservoir simulation purposes.

Quantitative sand body mapping within outcrops of fluvial systems helps to constrain conceptual models by allowing key geostatistical property extraction (i.e. geometry and architecture) and subsequent analysis. One of the techniques, which has seen increased use in the past two decades, is the integration of geospatial mapping methods to create 3D representations of the studied outcrops, or digital outcrop models (DOMs). Three-dimensional DOMs offer a continuous high-resolution dataset that allow accurate interpretation and interpolation of the data across distances unachievable through traditional approaches (i.e. one-dimensional sedimentary logging and/or two-dimensional photo-panels). Accurate geospatial analysis of the sand bodies from 3D DOMs within a fluvial system either requires continuous and connected exposures, or a tightly constrained stratigraphic framework to correlate the sand bodies over great distances. Geologic modelling methods have undergone a significant transition over the past decade. The incorporation of quan-
titative geophysical and geomatic mapping techniques with traditional qualitative methods, have allowed geoscientists to capture, process, analyse and visualise high resolution and precise outcrop information more accurately than ever before. The inherent spatial and temporal variability of sand body distribution in outcrop, has spurred geoscientists to develop methods to digitally acquire, process and visualise an array of geoscientific data.

The Oligocene-Miocene Huesca DFS is a fluvial fan (60 km radius), which offers well-exposed outcrops of the succession through all parts of a DFS, from proximal to distal sections (Hirst, 1991). The section used for the study presented here offers a continuous nearly 3D exposure of the stratigraphy in a small (2 km²) area of the medial portion of the Huesca DFS. This allows for a detailed investigation into the 3D sand body geometry and lithological heterogeneity found within the medial portion of a continental DFS. The integration of traditional qualitative methods (i.e. 1D sedimentary logs) with the DOMs enables detailed 3D quantitative analysis to determine the spatial and subsequent temporal distribution of the sand bodies than ever before. Continued development and application of these methods are necessary to realise the potential of DOMs as outcrop characterisation tools. This leads to a more accurate description of the external architecture (width and thickness) and internal architecture (number of storeys, storey height) and potential depositional controls of the sand bodies, and ultimately to a more constrained conceptual depositional and reservoir model.

3.3 Geologic setting

3.3.1 Palaeogeographic setting

The Ebro Basin is a foreland basin of the southern Pyrenees resulting from flexural subsidence by loading of the Iberian crust from thrust sheets which formed in the Cenozoic Pyrenean orogenic belt (Teixell, 1996). From the early Eocene to early Miocene, the southern Pyrenean zone was an area of southward trend thrust events, which formed the southern foredeep of the Pyrenees (Nichols, 1987). During the final phase of deformation (Late Oligocene), a thrust-sheet frontal ramp developed, and created the present-day topographic expression in the External Sierras (Nichols,
This formed the northern margin of the Ebro Basin.

Figure 3.1: Location map of the Huesca and coeval Luna, Distributive Fluvial System (DFS) within the Ebro Basin surrounded by three coastal ranges (Pyrenees, Iberian and Catalan).

Three mountain ranges surround the Ebro Basin, the Pyrenees to the north, the Catalan Coastal Range to the east and the Iberian Range to the south west, and is one of the largest Tertiary basins in the Iberian Peninsula (Figure 3.1) (Yuste et al., 2004). The earliest Oligocene, compressional stress events in the Iberian and Pyrenean ranges cut off the Ebro Basin from drainage into the Bay of Biscay and Atlantic Ocean. The Ebro Basin became an endorheic, or an internally draining basin, that remained closed until the late Miocene. This allowed thick accumulation of fluvial strata basin until the late Miocene.

The principle source areas for the clastic fill of the Ebro Basin, which make up the Huesca and coeval Luna fluvial fans, are the southern Pyrenean zone, the Internal Sierras and the Pyrenean axial zone. Denudation of three Pyrenean basins (Jaca, Ainsa and Tremp-Graus) during the Oligocene and Miocene, which mixed with older carbonates in the southern thrust belt, constitute the sediment-fill of the Huesca and Luna DFSs (Figure 3.2). The Huesca and Luna were aggradational systems that remained well preserved due to the endorheic nature of the Ebro Basin. The Ebro Basin can be described as having a long history of relative base-level rise and
meets the requirements for the basin to remain underfilled and endorheic throughout deposition (Bohacs et al., 2000). The basin remained closed for approximately 25 Ma, and would not reopen to drain into the Mediterranean Sea until the late Oligocene (Garcia-Castellanos et al., 2003).

Throughout the successions of the Huesca and Luna systems, a variety of palaeosol characteristics reflecting the time of non-deposition have been identified which correlate to an early successional landscape (Entisols), an immature and young landscape (Inceptisols) and an open woodland landscape (Alfisols) of varying maturity (Hamer et al., 2007). The mean annual temperature at the time of deposition, derived from chemical analysis, indicates the climate was a humid continental setting. The climatic setting allows continual channel avulsion across the floodplain, which produced the interpreted fan morphology of the Huesca and Luna DFSs (Slingerland and Smith, 2004; Nichols and Fisher, 2007). Additionally, the basin centre contained a relatively shallow ephemeral lake, with minimal fluctuations in lake level (metre-scale) recorded (Hamer et al., 2007; Nichols and Fisher, 2007). Throughout the time of deposition, both fluvial systems remained aggradational and would continue to be so until the basin spill-point was reached, or the system opened up to external drainage.

3.3.2 Stratigraphy and sedimentological setting

The Huesca fluvial fan sediment is sourced from the Pyrenean hinterland which deposited onto the alluvial plain in a network of trunk channels and subsequent distributary channels that form the main depositional lobe (Hirst and Nichols, 1986; Nichols, 1987). This lobe would have continually avulsed across the alluvial plain, creating the large (60 km) fan morphology (Figure 3.3). The Huesca system is classified as a DFS because it contains a myriad of palaeocurrent indicators that show it was a 'fluvial system which in planform displays a radial, distributive channel pattern", a key criterion which defines DFSs (Hirst, 1991; Hartley et al., 2010). Moreover, the overall grain size of the system decreased downstream, indicating the channels underwent a transition from bed-load streams in the proximal sections to mixed-load in the medial sections before depositing into a basin centre lake (Nichols
The transition in grain size downstream indicates that the channel sizes decreased as well as the sediment was distributed along trunk channels with smaller distributaries formed down-system.

As with any fluvial system, the longitudinal profile is the primary factor that controls the deposition of fluvial sediments into a basin. The ephemeral lake at the centre of the Ebro Basin behaved as the ultimate base-level control for the longitudinal profile of both systems. The minimal fluctuations observed in the lake level would have caused slight profile adjustments, but only control the short-term fluvial profile and adjustments in the upper and lower limits which the system may
aggrade (Fisher and Nichols, 2013; Holbrook et al., 2006). Allogenic upstream controls (i.e. tectonic forces and climate change in the hinterland) caused increase denudation in the hinterland to debouche sediment into the basin. If this sediment supply to the distal sectors exceeds the rate of basin-level subsidence, then the basin-level will rise and aggrade, resulting in a consistent and low angle fluvial profile over the long-term. The resulting low gradient of the fluvial and subsequent basin profile promotes river avulsion and lateral migration, which are important processes to consider when investigating the architecture and geometry of sediment bodies throughout these systems. Regional avulsion of the active river tract over the alluvial plain, combined with the lacustrine sedimentation from the basin centre lake, was the primary cause for the creation of the fan morphology.

There is no evidence for lateral confinement of the channel-belts or incised valley patterns in the proximal to distal parts of the fluvial systems in the Ebro Basin (Nichols, 2004). The lack of deep fluvial incision into the strata corroborates the hypothesis of minimal lake level (i.e. base-level) change (Nichols, 2004; Nichols, 2007; Fisher and Nichols, 2013). This would allow further aggradation of the sedi-
ment within the basin. Accumulation would continue until the basin spill point is reached; however as is the case with the Huesca system, the resulting thickness of the strata will be greater than the original accommodation, due to subsidence from sedimentary loading (Nichols and Fisher, 2007).

### 3.3.3 Study area

The La Serreta area is located within the medial zone of the Huesca system (Figure 3.2), and contains channel-fill deposits that are primarily very coarse to fine sandstone enclosed by a mudstone and very fine sandstone strata (Nichols, 2007). The channel sand bodies are usually ribbon, or sheet-like in shape and are laterally continuous in outcrop for tens to hundreds of metres (Figure 3.4). Some contain decimetre-scale internal structures; others show very little or no structures within a single storey. The predominate fluvial elements are sand bodies that are thick (up to 16 m), multi-storey units which are interpreted as products of laterally mobile channels (Hirst, 1991). These sand bodies also exhibit evidence of sediment accumulation on sandy bars in braided streams of the system (Nichols, 1987; Donselaar and Schmidt, 2005). The bases of the channel geobodies are not deeply incised into the floodplain, providing evidence for the lateral mobility of the streams throughout deposition (Sadler and Kelly, 1993). Deposits classified as in-channel (very coarse sand – fine sand) components within the study area of the system, at 45 km from the calculated apex, constitute 46% of the stratigraphy. The remaining 54% of the deposits are floodplain and overbank sediments, which consist of clay mudstone rocks (floodplain) and very fine sandstone to siltstone deposits, often found in sheet-like geometries (unconfined flow) and interpreted as crevasse splays, both of which are easily discernible from the major channel fill sandstone bodies. In this study, a sand body is defined as a succession of sandy channel-fill elements bounded by fine-grained and muddy (overbank and floodplain) units. Individual storeys are defined according to Friend et al. (1979) and Bridge and Tye (2000). A geobody is termed here as a 3D polygon digitised around an individual storey within a channel-fill element.
Figure 3.4: Photograph of typical La Serreta outcrop exposure. The channel sand geobodies are usually ribbon or sheet-like in shape and are laterally continuous in outcrop for tens to hundreds of metres. Photograph is of SE facing cliffs of the La Serreta study area.
3.4 Methods

3.4.1 Data acquisition

Outcrops in the La Serreta area are continuous amphitheatre-style exposures that extend for over 2 km², and expose over 100 m of stratigraphy in the medial portion of the Huesca succession. The sub vertical outcrop offers exceptional views of the lateral and vertical distribution of the sand bodies in the medial portion of a DFS. The accuracy and resolution of the collected dataset offers an opportunity to investigate several analytical methods to determine the spatial and temporal variability within the medial portion of a DFS.

A 5 m Digital Terrain Model (DTM), derived from airborne stereo imagery, helped visualise the spatial context to collect the lidar data (Figure 3.5). A high-resolution Riegl LMS-Z420i Terrestrial Laser Scanner (TLS) was used to rapidly acquire high-resolution point clouds from targeted locations in the study area (Figure 3.6a). of the targeted locations to approximate the most complete coverage possible and avoid shadows, or gaps, within the final dataset (Figure 3.6b). Over 33 TLS positions were acquired, each with a 360° low-resolution point cloud that was used to align them each position, and select the areas of high interest to scan at high-resolution. These high-resolution scans contain a data point spacing of $\geq 0.01$ m, or equivalent to $\geq 0.02$ m geometric resolution. A range of lenses with different focal lengths (14 mm, 50 mm and 85 mm) for the coaxially mounted DSLR camera allowed the acquisition of photographs, when registered to the point clouds, to produce an accurate pixel-to-point match of the RGB information on the respective point cloud.
Figure 3.5: Location map of the study area. (a) An orthophotograph of the study area translated onto a 5 m Digital Terrain Model (DTM) illustrates the terrain and amphitheatre style exposures of the outcrop. Scanner locations (yellow dots) and sedimentary log positions (red dots) show the high density of data coverage for the project. blue square outlines approximate location of Figure 3.4
Figure 3.6: (a) Typical TLS survey setup for the project. A Riegl Z-420i terrestrial laser scanner is used with a coaxially mounted DSLR camera and a GNSS receiver on top with a GeoBeacon nearby, which receives a real-time differentially corrected signal. The laser scanner and DGNSS system is operated by a small-ruggedised tablet computer. (b) Illustration showing the approximate coverage with the TLS system (green area) within the La Serreta area, north of the village of Piracés.
Fifteen sedimentary logs acquired throughout the study area help to characterise lithological trends across the study area. These allow further constraint when building the 3D geologic models. Characteristically, the medial sections of a DFS contain channel body geometry, which exhibit evidence for a sinuous-braided to meandering pattern in planform. These depositional patterns produced sheet and ribbon-like channel body geometries observed by Hirst (1991) which were interpreted to be laterally continuous across the study area. Sedimentary log locations were chosen to best represent the apparent lateral continuity of the sand bodies. 800 m of sedimentary logs (Figure 3.7) were acquired at a 1:40 scale, which offers a stratigraphic resolution of approximately 0.01 m. 254 palaeocurrents were measured, in addition to important bedforms and structures, which otherwise would not be visible in the lidar or photography data. Each of the logs were digitised (see Appendix A) and each facies element was given a facies code. The facies codes build part of a geostatistical database that used to generate statistics and identify and/or investigate any trends found within the stratigraphy and sedimentary characteristics.

Differential Geospatial Navigational Satellite System (DGNSS) data points acquired at

Figure 3.7: A summary log illustrating the lithological variability in a vertical section in the study area. Note the thick deposits of overbank material between the sand bodies. The common bedding found in most of the channel sand lithology is trough crossbedding with some tabular sections further up in the succession.
each TLS location, as well as the top and bottom of each sedimentary log position, allows direct integration of the entire dataset into a real-world coordinate frame. This gives the final realized geologic model spatial, and subsequently temporal constraint for the sand body analysis performed.

3.4.2 Data processing

Several authors in previous works (e.g. Bellian et al., 2005; Buckley et al., 2008; Enge et al., 2007; Pringle et al., 2006; Buckley et al., 2008) discuss in detail well established TLS methods and techniques for acquiring, processing and building accurate DOMs, which have been adapted for this study. In summary, the processing steps used for this study are:

(i) Align the point clouds to real-world coordinates.

(ii) Colourise the point clouds from the coaxially mounted RGB images.

(iii) Create a Triangulated Irregular Network (TIN) surface mesh from the point data.

(iv) Import the data into a custom geological interpretation software package.

The coarse lidar scans (i.e. 360° scans) along with the associated TLS DGNSS positions were imported into the software package Innovmetric Polyworks™ v. 11. The TLS positions were globally aligned from the DGNSS data, before an Iterative Close Point (ICP) alignment process coarsely aligned the data. Key high-resolution scans from each TLS position imported into the project offered a fine adjustment to the alignment. This allows accurate interpolations on the final DOM. Once properly aligned and projected into real-world coordinates, the point clouds were coloured from the coaxially mounted RGB information through the same software used for lidar data collection Riegl RiSCAN Pro™. Specialized software developed at The University of Manchester, Virtual Reality Geological Studio (VRGS), (Hodgetts2007) allows creation of the final TIN surface mesh. This final process is crucial to accurately interpolating between data points on the DOM.
3.4.3 Visualisation

Visualising the DOMs is a central aspect of the project, and varieties of methods are available which allow accurate and detailed interpretation and interpolation of the geologic models. To accurately identify the key features required to quantitatively map and extract geobody geometry and statistics throughout the study area, photorealistic models and other visualisation methods available in VRGS were used. The major advantage of photorealistic DOMs is providing a user with a realisation of the model, as they would see it in the field, which allows for a detailed inspection of the colour difference of the lithology (Figure 3.8a & b). This colour difference plays a significant role with geobody interpretation as the different lithology displays characteristics upon exposure that aid in the distinction between overbank and channel deposits, which can have similar topography. Another crucial aspect to building realistic geologic models, are the larger sedimentary structures, such as bounding surfaces and scour features which are readily identifiable in a certain parts of the photorealistic models.
Figure 3.8: Attribute generation for a portion of the lidar DOM dataset, illustrating the variation in lithology and characteristics which can be drawn from the various realisations. Scale bars are 5.0 m in all figures. (a) RGB coloured point cloud from the lidar dataset with an RGB channel histogram to illustrate the variation in colour retrieved from the translated photography onto the points. (b) RGB coloured triangulated surface mesh derived from the point cloud dataset, which visibly preserves the morphology of the DOM as seen between figures A and B. (c) Coplanarity attribute realisation derived from a Tensor analysis performed on the DOM mesh to highlight surfaces which have similar planar features. The attribute is used for this study area, to aid the interpreter in distinguishing large continuous sand bodies from overbank splay features. (d) Dip from a triangle orientation derived from a mesh of the DOM. As noted by the distribution plot, the orientation values between 35 – 90 were used, as these are values which would highlight difference between in-situ preserved sediment, and those of scree slopes or vegetation. By delineating between these objects, accurate statistics are obtained from the preserved material for analysis.

The software VRGS offers several methods of further analysis of the DOMs, one of which is performing a tensor analysis, resulting in the ability to visualise structural elements of each DOM such as coplanarity (Figure 3.8c) or dip of the surfaces (Figure 3.8d) (e.g. Fernández, 2005; García-Sellés et al., 2011; Seers and Hodgetts, 2014; Rarity et al., 2013). These realizations improve the ability to approximate geobody geometry and lateral variability within the models by allowing the user to delineate exposed surface boundaries from vegetated or scree slopes accurately, thus increasing the accuracy of the geostatistics derived from the 3D models. Another important product of the tensor analysis is the ability to recognize sedimentary structures within the geobodies that may not be apparent within a grey-scale model or even a photorealistic model. The tensor analysis allows a user to visualise key structural information such as higher-order bounding surfaces or lateral accretion surfaces within the channel bodies by emphasizing subtle topographic expressions of these features, which are not easily visible directly in the model.

3.5 Sand body mapping and characterisation

Aside from the visualisation capabilities of VRGS, a Geobody Mapping tool allows a user to digitise the geometry of sand bodies and storeys throughout the area to investigate their positions in 3D space, which gives each sand body a quantitative spatial context integral for accurate architectural analysis. Once bound by a Geobody polygon, field-based sedimentary information, such as palaeocurrent measurements and other associated sedimentary structures, are attributed to each
polygon and by proxy the sand body it encompasses. These measurements are the main variable used to derive approximated true sand body widths and thicknesses throughout the stratigraphic succession. Once the palaeocurrent data have been attached to the *Geobody* polygon, then the palaeocurrent direction is used to correct the observed width to the true width (see Fabuel-Perez et al., 2009 for a detailed explanation). As each geobody has multiple palaeocurrents observed in the field there is an uncertainty in the direction to be used to calculate the true width, therefore all directions are used to derive a probability distribution function (PDF) for the corrected width data. This PDF provides a minimum, maximum and most likely size for each geobody, with the most likely size being the mean palaeocurrent direction. These measurements are then grouped and categorised into minimum, maximum and average widths for every classified geobody.

In addition to the sedimentary log integration, the mapped geobodies can be classified (Figure 3.9) based on a facies classification scheme developed from the facies codes derived from the sedimentary logs (i.e. 0 = clay, 1 = siltstone, 3 = very fine sandstone etc). The approximate ratio of in-channel deposits (defined as very coarse – fine-grained units and sand bodies within clearly defined margins) was calculated from the sedimentary logs integrated with the DOMs. Key parameters such as width versus thickness (W:T) ratios, facies identified from sedimentary log data and the observed spatial stacking patterns of sand bodies have been used to classify geobodies into multi-storey and single storey sand bodies.

Figure 3.9: (a) Characterised sand bodies within the point cloud derived from the *Geobody Mapping* tool in VRGS. A facies code was attributed to the different facies throughout the study area and assigned to the polygons, which was drawn around each geobody in the DOM. Once digitised, the point cloud can be classified and visualised for easy facies recognised when viewed across an entire DOM. Aside from visualisation purposes, the classified point cloud may also be exported into a format which can be interpreted by reservoir modelling software packages for stochastic modelling purposes. (*Note: The blue paths indicate approximate sedimentary log locations for the associated summary logs in Figure 3.11*) (b-d) Rose diagrams generated from palaeocurrent information gathered from the field and sedimentary logs. (b) Rose diagram attributed to interpreted multi-storey channel elements, with a mean azimuth of 292° from 185 measurements. (c) Rose diagram derived from less common single storey channel elements, with a mean azimuth of 309° from 68 measurements. (d) Rose diagram generated from all of the measured palaeocurrents which demonstrates an overall palaeoflow of the area in the WNW direction (296°). (*Note the scale bar is 5 m*)
3.6 Results

A qualitative data description and analysis is described below which aided the quantitative geospatial analysis of the sand bodies from the DOMs. Histograms and custom-made scatter and box-plots for the characterised sand bodies and their spatial position within the La Serreta stratigraphy are described below: (i) calculated geobody widths (i.e. minimum, maximum, mean) and stratigraphic (i.e. vertical), position relationship, and (ii) geobody width vs. thickness spatial relationship.

3.6.1 Lithofacies characteristics

Results

Based on measuring deposits within the fine sandstone to very coarse grain size ranges and classifying them as in-channel components, they are found to constitute 46% of the stratigraphy, with the majority of those channel-fill sand bodies identified (67%) as exhibiting sedimentary structures found within meandering systems (e.g. laterally stacked and amalgamated channels with a fining up sequence, lateral accretion deposits, and cross-bedded bedforms near the base). The remaining channel-fill elements (33%) exhibit barform structures that are found in braided deposits, as well as many other single storey channel deposits. The remaining 54% of the stratigraphy constitutes floodplain and overbank sediments which consist of mudstone rocks (floodplain) and very fine sandstone deposits. There are frequent occurrences of discreet overbank flooding elements (Bridge, 1984) with slightly erosive bases, but are not more than 0.05 – 0.15 m in thickness. These deposits display pedogenic and biogenic alteration, and offer little-to-no evidence of sedimentary structures. The finest grained (i.e. claystone and fine siltstone) overbank sediment exhibit varieties of palaeosols that range in colour from grey to red. The 250 collected palaeocurrent measurements allowed an approximation of palaeoflow to the WNW (296°) (Figure 7).

Interpretation

The majority of the sand bodies observed in the La Serreta study area are typically multi-storey or highly amalgamated channel elements that are products
of laterally mobile streams within wide channel-belts (Figure 3.10). The continual cut-and-fill processes of these channels truncates the topmost section of the channel-fill, leaving predominantly trough cross-bedded structures near the base. The thick accumulation of overbank siltstone and claystone sediments found between the channel-fills are products of flood events from nearby channels. The range in crevasse splay thicknesses (up to 1 m thick) are a product of the size of splay, or as a proxy for proximity to the channel origin or size of the channel. It is not possible to deduce this from the limited outcrop exposure in the study area.

Figure 3.10: The stratigraphic architecture of the area over a given horizontal distance and approximately 50 m in thickness shows several amalgamated and multi-storey geobodies, with an apparent dominant sheet sand type. Between the geobodies are thick accumulations of overbank deposits which contain splay deposits comprised of very fine grained sandstone or coarse grained siltstone, as well as clay. The overbank areas often contain palaeosols horizons, indicative of climatic and lateral changes of the channels throughout the evolution of the system.
Figure 3.11: Summary logs generated from sedimentary logs collected in the field. These logs are used in lithofacies characterisation and analysis. Thickness measurements are in metres.
3.6.2 Geobody width analysis

Results

Within the maximum widths calculated from the digitised geobodies, the average width is 158 m, with a maximum of 535 m and a standard deviation of 125. The majority of those sand body widths are within 50 – 300 m (Figure 3.12a). The minimum widths calculated from the digitised geobodies demonstrates an average sand width of 98 m, and a maximum of 344 m and standard deviation of 84. The majority of the widths are within 50 – 100 m (Figure 3.12b). The arithmetic mean and most likely geobody widths demonstrate an average width of 127 m, a maximum of 372 m and a standard deviation of 98. However, most of the geobodies in the area are calculated to be within 50 – 150 m in width (Figure 3.12c). Plotting the stratigraphic (i.e. vertical) position of each measured geobody illustrated a vertical trend in geobody widths. The sand bodies continually widened before dropping in width near the top of the succession (Figure 3.13). All width measurements (i.e. mean, min and max) demonstrate the same increase in width vertical trend.

Interpretation

The deposits of the medial zone of the Huesca DFS are interpreted as deposits of laterally mobile channel belts, which decrease in channel width from proximal to distal locations (Nichols and Fisher, 2007; Hirst, 1991). Laterally continuous multi-storey sand bodies constitute a significant proportion of the observed sand body architecture in the study area as seen by the laterally and vertically amalgamated channel-fill beds. The process of channel-fills laterally stacking across the floodplain would yield the potential widths observed in this study. However, from field observations there are a minimum number of the sand bodies that display this characteristic. Most of the sand bodies in the La Serreta area are interpreted to be wide channel belts ($\mu = 127$ m wide, max. = 372 m). These channel-belts remained occupied until the available accommodation was filled, which would cause the channels to avulse to a new position on the flood plain. The increase in channel-belt width are products of increased sediment load to the region by increased upstream changes (i.e. tectonics or climate). These would cause an increase in sediment flux down-
system, and potential progradation of the fluvial system (Weissmann et al., 2013). Alternatively, the increase in geobody width could be due to a regional avulsion further upstream which caused the La Serreta area to be within the new depositional lobe thoroughfare (Nichols and Fisher, 2007; Cain and Mountney, 2009).

Figure 3.12: Histogram plots of minimum, maximum and arithmetic mean of the geobody widths in the La Serreat succession identified from the corrected width measurements acquired from the DOMs. *Note the lognormal distribution of the data, showing a large number of average widths between the 50 – 100 m range.*
Figure 3.13: A plot to illustrate any vertical trends found within the succession of 42 measured sand bodies. The grey bars illustrate the number of observations used to calculate the distribution of corrected palaeochannel widths for each measured geobody. As observed by the plotted data, there is an increase in the calculated mean width for the middle half of the succession.
Figure 3.14: A width v. thickness ratio plot of the corrected geobody widths derived from the DOMs. The minimum, maximum and arithmetic mean values are plotted for 42 different measured geobody geometries. The width v. thickness (W:T) ratio line, (15:1) calculated by Friend et al. (1979) to determine a difference between measured ribbon and sheet sand geometry, is digitised into the plot to visualise the distribution across the threshold. A line of best-fit was plotted between for the calculated mean geobody width, with a $R^2$ value of 0.51, which might make someone lean toward a greater number of sand bodies occupying a sheet-like geometry. However, when calculating the percentage of geobodies with a greater than 15:1 W:T ratio, exactly 50% were discovered.
3.6.2.1 Geobody width vs. thickness spatial relationship

Results

Geobody thickness measurements display a maximum thickness of 16 m with a mean of 8 m. Geobody W:T ratios display an expected positive correlation between the mean sand body W:T ratio (16.1:1), although this correlation is weak given the variability in width distributions (Figure 3.14). From the 42 measured sand bodies, 50% of them lie below 15:1 W:T ratio line, and the other 50% above it. Based on previous studies of fully preserved channels in the proximal section of the Huesca DFS, it is suggested that the maximum channel thickness during time of deposition was 4 m (Davidson and Hartley, 2014).

Interpretation

Previous interpretations of the sand bodies in the La Serreta area within the Huesca DFS are predominantly sheet-like deposits, with ribbon channels as the subordinate type. The data presented here suggest that they are equally distributed throughout the study area. However, other types of channel geometry including bar forms of possible braided streams are included in these data, which imply an increased width that must be taken into account. This implies that the multi-storey (i.e. up to six storeys) channel-fills are products of continual occupation of the channel belts. The thickest channels could be the products of system progradation, resulting in the vertical increase in geobody thickness. The evidence to suggest progradation of a DFS does not fit within the observations for the La Serreta area. The section is a complete section which preserves typical DFS behaviour of with thick floodplain deposits surrounded multi-storey sand bodies. The emergence of an abnormally thick sand body (up to 6 storeys) that is more highly amalgamated than others suggests this section to be downstream from a regional avulsion point upstream. Previous studies of fluvial systems Therefore, the widest and thickest sand bodies are interpreted to be the products of large channels (i.e. trunk channels), which regionally avulsed to the La Serreta area. Regardless, it is clear that the study area records an increase in sand body channel-belt width and sand body thickness.
3.7 Discussion

As discussed by Hartley et al. (2010), a DFS is defined as a fluvial system, which in planform displays a radial, distributive pattern, and in most cases the channels were not simultaneously active. In the medial portion of the Huesca system, the interpreted fluvial architecture represents laterally mobile meandering channels within wide (i.e. up to 372 m) channel-belts. These channel-belts lie within a depositional lobe that will continually avulse across the floodplain. The medial portion of a DFS is the most sensitive to changes within the longitudinal profile of the system (e.g. regional avulsions) and the position of the depositional lobe (Weissmann et al., 2013). Episodes of significant channel switching (i.e. avulsion) generated by channel backfilling and plugging (Fisher and Nichols, 2013), relate to the distribution of energy and sediment-transport thresholds across the system (Ventra and Nichols, 2014). These processes allowed the thick accumulation of overbank deposits to develop. When analysing the lithofacies distribution within the study area, it has been found that the in-channel component of 46% demonstrates an increase in 22% from previous interpretations (Hirst, 1991). Though the channel-fills contain sedimentary structures which reflect previous workers’ observations and interpretations (e.g. Nichols, 1987; Hirst, 1991; Donselaar and Schmidt, 2005), the question remains why there is an increase in classified in-channel components.

The three-dimensionality of the exposed outcrops in the La Serreta area (amphitheatre style) offer excellent spatial control of the sand bodies. The classified 3D DOMs created for the study area and the subsequent spatial analysis of the sand bodies reveal intriguing trends in widths. As observed in Figure 3.14, some of the sand bodies do extend for hundreds of metres laterally through the succession; however, the majority of them only extend for a little over 100 metres. The width versus thickness ratio of the sand bodies lies on either side of a 15:1 ratio line, which defines the geobodies as either ribbon or sheet-like in geometry if using the ratio values defined by Friend et al. (1979). The descriptive statistics associated with the geobody distributions indicate that 50% of interpreted geobodies occupy the ribbon sand area of the plot, with the other 50% occupying the sheet sand area. This
suggests equal representation of both sheet-like and ribbon sand bodies in the La Serreta area, and possibly throughout the remainder of the medial portion of the Huesca DFS. As discussed by Donselaar and Schmidt (2005) and Fisher and Nichols (2013), the medial channel deposits are expected to display the structure and characteristics indicative of mixed-load channels within a larger DFS. These types of systems maintain the sinuosity of a meandering channel but may contain in-channel bars, giving it a sinuous and sometimes a sinuous-braided appearance in planform (Schumm, 1981). This is suggested for the reason for the presence of barforms interpreted as products of a braided stream observed in the study area. Furthermore, the increase in geobody width and thickness vertically through the succession indicate that there was an increased amount of sediment flux to the La Serreta area. This increase could be cause for system progradation toward the basin centre, in an attempt to fill available accommodation. However, there is not sufficient evidence to demonstrate a vertical grade from distal deposits to proximal deposits of the study area (i.e. coarsening upward succession with increased channel-belt amalgamation near the top), commonly interpreted in progradational systems. Alternatively, the increase in geobody width and thickness could be due to a regional avulsion further upstream which caused the La Serreta area to be within the new depositional lobe thoroughfare (Nichols and Fisher, 2007; Cain and Mountney, 2009). This is suggested to be the case; therefore the widest and thickest sand bodies are interpreted to be the products of large channels (i.e. trunk channels), which regionally avulsed to the La Serreta area. Moreover, given the previous interpretations that the majority of the sand primarily occupied by ribbon-like geometries (e.g. Hirst, 1991), with sheet-like deposits as the subordinate geometry, it is demonstrated here the necessity for a 3D quantitative and spatial approach to accurately define the width versus thickness ratio for fluvial sand bodies.

Previous analysis of the sand body geometries in the study area completed by Hirst, (1991) were used in the exhaustive study by Gibling (2006) to collate the widths and thicknesses of different fluvial sand bodies. This study illustrates the disparity between sand body measurements from 1,5000 separate sand body
width and thickness measurements. Building upon those studies, the work presented here was placed into a similar plot (Figure 3.15), and the measurements enveloped to include all of the sand bodies. The average and maximum sand bodies were used to calculate a separate envelope that shows the uncertainty even with the 3D quantitative measurements obtained for this study. However, it is clear from this plot, a 4 m difference in the thickest sand body, and a 200 m reduction in sand body width is observed. The causes for the disparity between this study and Hirst’s (1991), is the utilisation of a 3D quantitative methodology to calculate sand body thickness and calculate the approximate geobody width. The comparison plot (Figure 3.15) illustrates the need for increased 3D quantitative characterization and analysis of sand body widths and thickness relationships in fluvial sedimentary systems. Moreover, if the notion that DFSs should "make up a significant portion of the rock record," (Weisssmann et al., 2010; Hartley et al., 2010), and discussed in detail by Weissmann et al. (2015), the 3D quantitative approaches presented here will aid researchers to rigorously identify architectural relationships of DFSs in the rock record.

3.7.1 Uncertainty in geobody mapping from DOMs

Geologic uncertainties when considering stratigraphic and sedimentological models remains a concern for geoscientists who create subsurface reservoir models and simulations (i.e. continuity of outcrops used in a study, length and scale of outcrop vs. geologic features, accurate approximation of geometry and architecture of sedimentary bodies). The use of DOMs and the integration of qualitative information provide geoscientists with improved statistics and data constraints for the models to reduce the inherent uncertainties. A summary of uncertainties presented by Fabuel-Perez et al. (2010) and Rarity et al. (2013) provide a good base to start from when analysing the use of DOMs as outcrop analogues. The new techniques and interpretation and interpolation methods presented in this paper have allowed further constraint some of the related uncertainties prevalent in geologic modelling. However, there are some uncertainties that must be considered when DOMs are used to characterise outcrops considered analogues for subsurface reservoirs.
Figure 3.15: Plot of geobody width vs thickness ratios with envelopes encompassing around the arithmetic mean and minimum – maximum measurements from the corrected geobody widths. Red dotted dashed envelopes the minimum and maximum measurements for the geobody widths whilst the grey fill highlights the associated uncertainties between the mean geobody width envelope and the min-max envelope. Note the translated location of the corrected geobody widths and thickness envelopes (purple and red dashed) from the quantified lidar measurements, to the envelopes included of the Gibling, 2006 measurements (transparent blue) for the same formation.
The most important uncertainties are associated with data processing of the DOMs during the various phases of construction, from scan alignment to inaccurate positioning of the photography onto the models. These errors may propagate throughout the modelling process, which can cause errors in the interpretation and interpolation of the data. This type of error has been minimized over the years with improved methodologies, and is believed to be negligible due to the nature of the study area and data coverage.

Other uncertainties are those associated with the lithologic interpolations (e.g. major fluvial sand bodies versus overbank deposits) on the DOMs between the centimetre-scale sedimentary logs collected throughout the study area. Confidence in the textural identification of lithologic distributions decreases with distance from the location of sedimentary log data. The uncertainties associated with the degree of stratigraphic exposure, and the observable spatial extent of the different lithologic elements, are minimized by integrating the 1D log data with the DOMs. Information gathered from diagnostic sedimentary characteristics identified in the high-resolution RGB imagery and other visualisation attributes available in VRGS remain the strongest component of DOMs. These data (i.e. facies proportions and distribution) condition the input information used to build geocellular and reservoir models.

The third and most important uncertainty to consider when building geologic models for quantitative analysis are the errors that can result from gathering geostatistics from the interpreted sand bodies within a field area (e.g. approximated widths and thicknesses). The nature of exposed outcrops affect accurate depiction of the true geometry of the fluvial elements, and careful interpolation is required. However, the improved geobody and sand body width correction technique utilised in this study is able to mitigate some of the errors with interpolation. To mitigate some of these errors, palaeocurrent information was given a bi-directionality value where appropriate, such as apparent azimuth of lateral accretion sets, to produce the corrected widths as accurately as possible. Furthermore, the outcrop used for this study, and indeed any outcrop used for any study, must be considered carefully
as they expose a sample of reality during time of deposition of the system, and display one view of the succession. In the case of this study, it is a sample of a small area within a larger, complex fluvial system. Therefore, careful consideration must be given to the weight of the results produced from studies like this.

3.7.2 Implications for geologic to reservoir modelling

Bridge and Tye (2000) summarise that determining width and thickness of sandstone channel-fill deposits is a primary objective in the exploration for and development of fluvial reservoirs. It is however, a much more complex process when attempting to determine the appropriate geostatistics required in the creation of accurate reservoir models. Connectivity, both horizontal and vertical, is an essential element to understand when predicting the reservoir potential of a system, which can vary over short distances. Traditional, qualitative approaches to mapping the connectivity of sedimentary bodies are unable to consider all of the associated uncertainties, such as structural controls (e.g. dip and azimuth) and the lack of 3D context and spatial control. The associated connectivity and spatial distribution of the sedimentary bodies is commonly difficult to ascertain in outcrop and or from 1D well data (Pranter et al., 2013). However, 3D DOMs of the study area, offer an ideal case study to investigate the lateral extent of the sand bodies in a nearly 3D spatial context. Integrated lidar data with geospatial control and sedimentary log data allow the connectivity of the sheet-like sandstone and ribbon deposits to be investigated with more accuracy than ever before in the La Serreta study area.

In petroleum geology, the term *geostatistics* is referred to as a suite of statistics used to control the distribution of facies and petrophysical data of geobodies (Hodgetts, 2013). However, as with the case of fluvial reservoirs and the benefit of DOMs, this now encompasses characterization in a spatial context. Exposed outcrop analogues are often used to aid geoscientists in determining the statistics required to create accurate subsurface reservoir models, though it is often difficult when using traditional methods (e.g. photo-panels, 1D sedimentary logs and 2D plan maps). With the advent of lidar and the techniques used therein, a quantitative mapping approach can be used that reduces the inherent uncertainties associated with geologic
interpretation of exposed outcrop data. The discussed data integration methods illustrates the importance of accurate data collection, processing and analysis techniques when using outcrops as subsurface analogues, and increases the accuracy of the statistics such as width-thickness ratios (Figure 3.9) extracted from the geologic models, and ultimately reservoir models of fluvial systems.

3.7.3 Geologic model efficacy

The integration of the discussed methods allows geologic models of geobody heterogeneity and facies distributions to be realized with high confidence across the study area. The use of DOMs and the inherent quantitative information that can be extracted from them, such as the geobody interpretation techniques presented in this article, offer geoscientists the opportunity to investigate the outcrop characteristics, of any depositional setting, more accurately. Continuous improvement in characterization, interpretation and analysis techniques of outcrop data allows geoscientists to create high-resolution and detailed geologic models, reinforcing the efficacy of outcrops and DOMs as important analogues for depositional and subsurface reservoir models. It therefore remains true that even without complete sedimentary log coverage, DOMs continue to be a powerful and valuable tool for outcrop characterization.

3.8 Concluding remarks and future work

Fluvial depositional systems are inherently three-dimensional whilst they are contemporaneously eroding and depositing material throughout the catchment area, thus requiring a spatial approach to interpret the resulting sedimentary bodies. The endorheic setting in the Ebro Basin, in which the Huesca DFS accumulated hundreds of metres of sediment, offers a chance to investigate the 3D architecture (internal and external) and connectivity of sand bodies due to a well-preserved stratigraphic architecture. Integration of sedimentary log data with the DOMs of the La Serreta succession, enable a quantitative investigation of the lithological heterogeneity amongst the geobodies and their relationship to the current Huesca DFS depositional model (e.g. Hirst, 1991; Nichols and Fisher, 2007). The interpreted widths, geometry and architecture, as well as the geostatistics acquired for the channel elements,
gives the authors more constraint when building and constructing depositional and reservoir models.

This study summarises a quantitative method of interpreting the geobodies found within the medial portion of a distributive fluvial system. Presented here is a novel technique of using a DOM and its inherent quantitative attributes, to extract key geostatistics such as geometry, architecture and approximated widths and thicknesses of geobodies throughout a 2 km$^2$ study area. Sedimentary logging methods allow the spatial and temporal distribution of geobodies to be better understood in a medial portion of the Huescan DFS. Subsequent geostatistics such as W:T ratios and palaeoflow directions enabled detailed geodatabase generation, which can be utilised for geocellular and reservoir modelling practices.

From the 3D geobody geostatistics presented in this study, we suggest that the La Serreta area demonstrates a succession of DFS deposits that records an upstream regional avulsion event. This caused the active depositional lobe of the Huesca DFS to avulse, switching the longitudinal profile and created a new thoroughfare that encompassed the La Serreta area. There is no evidence to suggest system progradation of the DFS as observed by other workers (e.g. Weissmann et al., 2013; Owen et al., 2015), to cause the observed increase in geobody width and thickness. Therefore, vertical increase is most likely the result of continual occupation of a wide channel belts across the floodplain. The 22% increase of in-channel components for the study area suggests this to be true as well.

Furthermore, an essential aspect of predicting the architecture is obtaining accurate geometrical information (i.e. width-to-thickness ratios, facies classifications, overall sand body), as well as carefully interpreted horizons and surfaces which are bound by the overarching fluvial dynamics of the system. By spatially tracking the channel elements throughout the study area on the 3D geologic models, different channel types and resultant sand body architecture can identified and classified. This study highlights the importance of using a quantitative 3D analytical approach to extracting key geostatistics from outcrop. The geobody widths calculated for this study demonstrate that sheet-like and ribbon shaped sand bodies are equally dis-
tributed. Accurately identifying these components is an integral part of predicting fluvial architecture of the system. Applying these methods to other interpreted DFS outcrops presents significant implications for improving the identification of these systems in the rock record, and improves the current understanding of reservoir characteristics and architecture of distributive fluvial systems.
3.9 References


XRD, petrographic and SEM study”. In: *Sedimentary Geology* 172.3-4, pages 251–268.
Chapter 4
Chapter 4

Quantitative discrimination of palaeovalley-fill from stacked distributary channel sand bodies

4.1 Abstract

Recent advances in the understanding of fluvial systems demonstrate that in plan view, fluvial channels within a distributive system distribute their bedload across an alluvial/fluvial plain, whereas palaeovalleys are tributive. The difference between major fluvial sand bodies interpreted as products of stacked distributary channel-fills and palaeovalley-fills has important implications for aquifer and hydrocarbon reservoir development. Moreover, quantitative analysis of the conceptual depositional models of the deposited sand bodies of each respective fluvial system is integral to approximating potential component of the rock record each system will yield.

This study utilises 3D lidar acquisition techniques to build 3D digital outcrop models (DOMs) to quantitatively analyse the architecture of major fluvial sand bodies of the Breathitt Group in the central Appalachian foreland basin, USA. The analytical techniques utilised in this study demonstrate that sand bodies interpreted as palaeovalley-fills thin down-dip to a lesser degree than those interpreted as stacked distributary channels, contain more storeys and the storeys are thicker relative to sand body thickness down-dip as well. Through 3D quantitative analysis of key metrics of the sand bodies, it has been established that the major fluvial sand bodies are products of both DFSs and palaeovalleys. The data collection and analytical techniques presented here provide a large, and detailed dataset of sand body architecture and distribution 80 km down-depositional dip of a foreland basin. The resultant geostatistics provides empirical relationships which can be used to
determine sand body genetic origin, and can be applied to subsurface analogues for reservoir model development.

4.2 Introduction

Major fluvial sand bodies which may be a succession of stacked distributive channels (SDC) (Hirst, 1991; Nichols, 2005; Donselaar and Overeem, 2008; Kukulski et al., 2013) or palaeovalley-fills (PVFs) (e.g. Jennette et al., 1991; Hampson et al., 1999; Bhattacharya et al., 2015) have been the subject of extensive research because of their hydrocarbon reservoir potential. The difference between these two types of sand body is also critical to the correct reconstruction of palaeogeography, sequence stratigraphy and the accurate prediction of hydrocarbon reservoir geometry. When discriminating between palaeovalley-fills and stacked distributive channels at outcrop, a key challenge is to establish that the lateral extent of both types of sand body typically exceed that of exposure, and thicknesses may be similar. Many incised valleys additionally, do not display a "basinward facies shift" at their base (Blum et al., 2013) – a key criterion historically used to identify palaeovalley-fills (e.g Posamentier and Vail, 1988; Van Wagoner et al., 1988; Van Wagoner et al., 1990). Recent advances in the understanding of fluvial systems demonstrate that in plan view, distributive fluvial channels are distributary, whereas palaeovalleys are tributary (e.g. Weissmann et al., 2010; Blum et al., 2013). In the stratigraphic record, from up-depositional dip to down-dip, preserved storey height should therefore increase along with the scale of the composite sand body in palaeovalleys (PVs), and storey height should decrease along with the scale of the composite sand body in distributive fluvial systems (DFSs). This criterion has been applied to the rock record to interpret distributive fluvial systems (e.g. Nichols, 2007; Weissmann et al., 2013) and more recently to recognise palaeovalley-fills (e.g. Jerrett et al., 2016). In successions that contain both distributive fluvial channels and palaeovalley-fills, basin-wide up-dip to down-dip statistical trends in sand body size and preserved storey height may not be clear. Furthermore, in many cases, original storey heights are not often preserved within the sand bodies due to top-truncation by younger storeys. In such situations, in order to order to correctly interpret sand bodies as
either SDCs or PVFs, a more detailed, quantitative analysis of the internal architecture and geometry of the sand bodies is needed.

The majority of naturally-occurring rock exposures are markedly two-dimensional (e.g. elongate coastal cliffs and road-cut exposures), presenting difficulties for the extraction of plan-view data, and reconstruction of fluvial style. However, recent advances over the past two decades in data collection, processing and analysis techniques have allowed for the quantitative description of the geostatistical properties of exposed successions, using three-dimensional (3D) digital outcrop models (DOMs) (see Bellian et al., 2005; Buckley et al., 2008; Fabuel-Perez et al., 2010; Rarity et al., 2013). In this study, these digital geospatial and remote sensing approaches (ibid.; i.e. lidar integration with coaxially aligned photography and differential geospatial navigation satellite system (DGNSS) measurements) have been applied to a succession of fluvial sand bodies from the Upper Carboniferous (Pennsylvanian) Breathitt Group of the central Appalachian Basin, U.S.A. (Figure 4.1). The upper Breathitt Group contains a succession of fluvial sand bodies that are interpreted as progradational SDCs, and others that are interpreted as PVFs (Jerrett et al., 2016). The Breathitt Group therefore represents an ideal case study to apply these techniques to quantitatively distinguish palaeovalley fills from stacked distributary channel sand bodies and determine potential depositional controls on the resulting architecture.

4.3 Geologic context

The central Appalachian Basin (Figure 4.1) was one of a series of Alleghenian-Variscan peripheral foreland depocentres that developed cratonward of promontories on the Laurasian continental margin (Thomas, 1976; Quinlan and Beaumont, 1984). In the Middle Carboniferous, initial thrust sheet emplacement along the south-east margin of Laurasia drove flexural subsidence of the existing cratonic carbonate shelf in present-day south-eastern West Virginia, and western Virginia (Quinlan and Beaumont, 1984; Tankard, 1986). From current biostratigraphic and stratigraphic isopach data, calculated subsidence rates are suggested of >150 m/Ma on the preserved orogenic margin, and <30 m/Ma on the preserved cratonic margin (Jerrett et al., 2016).
In eastern Kentucky, the late Palaeozoic foreland megasequence of the central Appalachian Basin is broadly a coarsening-up succession of marine, marginal marine and terrestrial clastics, coal and rare carbonate, in which evidence for marine conditions generally decreases upwards (Horne et al., 1978; Chesnut, 1992; Chesnut, 1994). This megasequence can be broadly divided into (i) the lower Breathitt Group, (ii) the upper Breathitt Group, and (iii) the Conemaugh Formation, (Figure 4.2a). The Pikeville and Hyden formations of the upper part of the Breathitt Group are the targets of this study (Figure 4.2b). In outcrop, they contain major sand bodies
up to 640 m wide and up to 32 m thick. Jerrett et al. (2016) have suggested sand bodies with aspect ratios greater than 1000 represent PVFs, and those with aspect ratios greater than 1000 up-dip and less than 1000 down-dip represent SDCs that pass down depositional dip into forced regressive and transgressive PVFs. Sand bodies with aspect ratios of that are typically less than 1000, represent simple normally regressive SDCs (Figure 4.2a). The sand bodies are extensively exposed in a series of road cuts constructed throughout eastern Kentucky since the 1970s (e.g. Horne et al., 1978; Chesnut, 1994; Aitken and Flint, 1994; Aitken and Flint, 1995; Jerrett et al., 2016). Road cuts up to 200 m high and 1 km long have been constructed, but compared to the width of many of the sand bodies, irrespective of genetic type, the road cuts are often too short to provide complete cross sections through the sand bodies, encapsulating their complete external geometries and internal architectures. A robust in-place coal seam correlation framework for the Breathitt Group (Rice and Hiett, 1994) allows sand bodies to be confidently correlated from road-cut to road-cut across the basin, and lateral changes in external and internal architectures within the same sand body to be assessed.

4.4 Methods

4.4.1 Data acquisition

Exposures of the Breathitt Group targeted in this study occur along U.S. Route 119 (US 119), Kentucky Route 7 (Ky 7) and Kentucky Route 15 (Ky 15) in eastern Kentucky, and have previously been described by Jerrett et al. (2016). Road cuts along US 119 and Ky 7 expose the Pikeville and Hyden Formations approximately 40 km down depositional dip from the preserved erosional margin of the basin to the SE, whereas the exposures along Ky15 expose the same stratigraphy another 80 km down depositional dip towards the NW. Six road cuts were chosen for further study: two each along US 119, and Ky 7, and two along Ky 15 (Figure 1.1d – f). These examples were selected because they expose the same succession of sand bodies, which could therefore be compared for differences in dip-parallel architecture. The analysed road cuts along Ky 7 are single-sided (i.e. there is exposure on just one side of the road), whereas the road cuts along US 119 and Ky 15 are double-sided.
Figure 4.2: (a) Chronostratigraphy and lithostratigraphy of the Pennsylvanian foreland basin succession of the central Appalachian Basin in eastern Kentucky. Based on data from Greb et al. (2008), but recalibrated to the timescale of Gradstein et al. (2012). Abbreviations: AC Fm. = Alvy Creek Formation; BC Fm. = Bottom Creek Formation; BR Sst. = Bee Rock Sandstone; WP Sst. = Warren Point Sandstone; S Sst. = Sewanee Sandstone. (b) Correlation panel illustrating up-dip (Kentucky Route 7 and U.S. Route 119 to down-dip Kentucky Route 15) facies relationships over 80 km dip length in the Pikeville and Hyden Formations. From Jerrett et al. (2016).

A high resolution Riegl LMS-Z420i terrestrial laser scanner (TLS) was used to acquire high-resolution point cloud datasets from a total swathe of the road cuts, >4.5 km long. Data were collected from exposures on both sides of the roadway where road cuts were double-sided. Each point cloud contains a detailed 3D representation of the exposures at a data point spacing of 0.05 m (≥ 0.10 – 0.02 m geometric resolution). The position of each TLS location was chosen to capture as much of the exposure as possible, eliminating any shadows, or gaps within the data. Sub-metre DGNSS measurements were acquired for each position to align them to one another at each locality, and into real world coordinates. A DSLR camera was coaxially mounted on top of the scanner and used to photograph (termed ‘on-scanner’ images) the same scanned scenery, registered to its associated point cloud, creating an accurate pixel-point-ratio of the two datasets.
4.4.2 Data processing

Multiple software resources were used to collate, process, align and geoposition the acquired data (outlined in Hodgetts et al., 2004; Pringle et al., 2004; Van Lanen et al., 2009; Fabuel-Perez et al., 2009; Fabuel-Perez et al., 2010; Rarity et al., 2013; Hodgetts, 2013) to produce the DOMs. Each scan location position was exported into Innovmetric: Polyworks™ and integrated with their associated DGNSS measurement. The alignment matrix produced from this process was imported into the scan project for each locality, giving each scan location a real world coordinate position. Additionally, the composite sedimentary logs were digitised and key facies and palaeocurrent azimuth measurements were extracted from the logs to build a detailed geostatistical database. The resultant geodatabase contains information used as conditioning data when analysing the DOMs, and building geologic model realisations (e.g. reservoir models).

4.4.3 Data visualisation

Once these data were collated together, a software package created at The University of Manchester, Virtual Reality Geological Studio (VRGS), was used
for visualisation and analysis of high resolution, spatially accurate 3D representations of the road-cut exposures (techniques outlined by Fabuel-Perez et al., 2009; Fabuel-Perez et al., 2010). The visualisation method used for this study involved a photorealistic approach of translating the RGB information from the on-scanner images onto both point cloud and surface mesh realisations of data, creating a 3D photorealistic model of the scanned outcrops (Figure 4.3 & 4.5). A detailed description of the photorealistic method applied to the models is discussed in Bellian et al. (2005), Pringle et al. (2006), Fabuel-Perez et al. (2010) and has been adapted for this study. These models allow for identification of stratigraphic contacts and stratal architecture from the data visible only in the RGB information.

4.5 Characterisation of sand body architecture from 3D digital outcrop models

In this study, a sand body is referred to as a succession of sandy channel-fill elements bounded by muddy units, irrespective of their genetic origin (i.e. stacked distributary or palaeovalley-fill). Individual storeys are defined according to Friend et al. (1979) and Bridge and Tye (2000) (Figure 4.4). With this in mind, the analysis toolset within VRGS also contains a quantitative analysis toolset which was used to interpret the DOMs. Sand body geometries were quantitatively described using: (i) the Polyline tool, which was used to digitise storey contacts in the three-dimensional space (Figure 4.5), from which the length and approximate spatial position of storey contacts could be extracted (Table 4.1); (ii) The Geobody Mapping tool was used to digitise a 3D polygon around each sand body, into which facies and palaeocurrent data from the sedimentary logs could be integrated, and from which the cross-sectional areas of the sand bodies could be calculated. Thickness measurements were calculated by creating 3D vertical measurements (Figure 4.5) throughout each sand body unit across the outcrops at 100 m spacing.

From these data the external architecture (sand body thickness) of individual sand units was calculated. The height of storeys within each sand body was calculated. Storey height approximately reflects the thalweg depth of channels. However, most storeys within sand bodies are truncated at their top by incision from the overlying storeys, so the storey heights presented represent the minimum channel depth.
The position of storey contacts relative to the base of each sand body was calculated, and is used as a proxy for the degree of storey preservation within each sand body (i.e. more story contacts close to the base of the sand body may be representative of significant erosion, and/or non-preservation of earlier storeys, whereas storey contacts evenly distributed throughout the sand body may be indicative of the more even preservation of storeys during deposition of the sand body). Finally, the average length of individual storey contacts were calculated from the individual storey contacts digitised and measured in in each sand body. As aforementioned, external sand body geometry for this study extended beyond the scale of the outcrops (i.e. sand body margins not observable); therefore to accurately approximate the length of each storey contact, they were normalised against the cross-sectional area of the sand body they were measured from, then normalised again to the highest value. A major limitation is that, as noted by Jerrett et al. (2016), many storey contacts cannot be reliably traced across the entirety of the exposure. This is largely due to vegetation, masking storey contacts, or because sand-on-sand contacts across storey boundaries obscure those storey contacts. Regardless, individual storey contact lengths were used, and with it the number of clear discernible storeys within each sand body, as a proxy for the length of time the sand body is occupied by a channel element.
Figure 4.4: (a) Colour photograph of typical road cut of stratigraphy along a highway. (b) Cartoon illustrating a storey contact separating younger from older storeys. The red arrow lines indicate the calculation of storey height, position of storey contact relative to base of sand body and the storey contact length. *Note scale bar is 4 m*
Figure 4.5: Photorealistic DOM of up-dip outcrop exposure with digitised Polylines (dark green) denoting storey contacts within the digitised sand bodies that are outlined red with the Geobody Mapping tool. The blue solid fill is used to illustrate the vertical and lateral extent of the bounded sand body. Numbers denote amount of palaeocurrents attributed to two sand bodies. Annotated 3D vertical measurements denoting positions of statistical measurements for each outcrop. *Note the scale bar is 10 m*
4.6 Results

Histograms for the four different statistical metrics are described below: (i) the sand body thickness; (ii) mean storey height per sand body; (iii) position of storey contacts in the sand bodies relative to their base; and (iv) mean length of individual storey contact. Basin-wide trends for all sand bodies, up-dip to down-dip trends of sand bodies previously interpreted as stacked distributive channels and palaeovalley-fills and differences between the sand body types up-dip to down-dip for each metric are also described. The data is summarised in Table 4.1.

4.6.1 Sand body thickness

Taking all analysed sand bodies into account, the maximum thickness recorded is 31.2 m, with an mean thickness of 9 m (Figure 4.6). At up-dip locations sand bodies are up to 31.2 m, with a mean of 12.7 m (Figure 4.7). Down-dip, sand bodies are up to 22.5 m thick with a mean thickness of 7.34 m (Figure 4.8). Overall, SDC sand bodies are up to 29.3 m thick, with a mean thickness of 10.8 m. PVF sand bodies are up to 31.2 m thick with a mean of 12.0 m. Up-dip SDC sand bodies are up to 29.3 m thick with a mean thickness of 12.7 m; whilst down-dip they are up to 9.52 m thick with a mean thickness of 5.61 m. Up-dip PVF sand bodies are up to 31.2 m thick with a mean thickness of 12.8 m, whilst down-dip they are up to 22.5 m thick with a mean thickness of 10.8 m.
Figure 4.6: Basin-wide sand body thickness (purple). Sand bodies measured in up-dip locations (blue). Sand bodies measured in down-dip locations (red).

Figure 4.7: All up-dip sand body thickness (light-purple). Sand bodies interpreted as stacked distributaries (blue). Sand bodies interpreted as palaeovalley-fills (red).

Figure 4.8: All down-dip sand body thickness (light-purple). Sand bodies interpreted as stacked distributaries (blue). Sand bodies interpreted as palaeovalley-fills (red).
4.6.2 Mean storey height

Considering all analysed sand bodies, the maximum calculated storey height is 16 m, with an overall mean of 4.84 m, and the most common storey height is 4 m (Figure 4.9). Up-dip locations contain on average the thickest storey heights, and are up to 16 m thick with a mean storey height of 6.06 m (Figure 4.10). Down-dip locations are significantly thinner on average, with a maximum height of 5.75 m and a mean of 3.22 m (Figure 4.11). Sand-bodies interpreted as SDCs on average contain the largest storeys with a maximum of 16 m and a mean of 5.11 m. Sand bodies interpreted as PVFs, on average, contain smaller storeys with a maximum of 7.71 m and a mean of 4.49 m. Up-dip SDC sand body storeys are on average the largest, with a maximum height of 16 m and a mean of 6.31 m, whereas down-dip SDC storey heights are on average contain a maximum height 4.20 m with a mean of 2.70 m. Up-dip PVF sand body storey heights on average contain maximum storey heights of 7.70 m and a mean of 5.55 m, whereas down-dip PVFs storey heights contain a maximum of 5.75 m and a mean of 3.64 m.
Figure 4.9: Basin-wide sand body storey height illustrating average differences between up-dip and down-dip locations.

Figure 4.10: Average storey height found up-dip and separated into sand bodies interpreted as stacked distributaries and palaeovalleys.

Figure 4.11: Average storey height found down-dip and separated into sand bodies interpreted as stacked distributaries and palaeovalleys.
4.6.3 Position of storey contacts relative to the base of the sand body

The highest position where storey contacts are recognised relative to the base of the sand bodies is 16 m with an overall mean position of 6.17 m (Figure 4.12). On average the most common position is 6 m relative to the base of the sand body. At up-dip locations, the highest storey contact position is 14 m, with a mean position of 6.04 m (Figure 4.13). Down-dip sand bodies contain the highest position of storey contacts relative to the base of the sand body at 16 m with a mean position of 6.4 m (Figure 4.14). In SDC sand bodies, the highest storey contact position is 14 m, with a mean position of 6.52 m. In PVF sand bodies the highest position of a storey contact is 16 m, and a mean of 6.11 m. The highest storey contact position in up-dip SDC sand bodies is 14 m from the base, with a mean of 7.8, whilst down-dip the maximum position is 7 m with a mean of 4.25 m. In up-dip PVF sand bodies, the highest position of a storey contact is 9 m from the base of the sand body with a mean of 4.5 m.
Figure 4.12: Average Position of Storey Contacts Relative to the base of the sand body across the basin (up-dip to down-dip)

Figure 4.13: Average position of storey contacts relative to the base of the sand body recognised in up-dip outcrops.

Figure 4.14: Average position of storey contacts relative to the base of the sand body recognised in down-dip outcrops.
4.6.4 Length of storey contacts

Taking into account all sand bodies (Figure 4.15), average storey contact length decreases, but the longest individual storey contacts observed are recognised down-dip (Table 4.1). Up-dip locations contain the largest amount of observed storey contacts \( (n=42) \) (Figure 4.16) than down-dip \( (n=40) \) (Figure 4.17). SDC sand body storey contact lengths are on average longer than those recognised in PVF sand bodies, but PVFs contain the longest observed storey contacts. Up-dip SDC sand bodies contain the most observed storey contacts, and they increase in length down-dip. Up-dip PVF sand bodies contain the shortest storey contacts and increase in length down-dip.
Figure 4.15: Total storey contact length recognised up-dip to down-dip and normalised to sand body cross-sectional area; then normalised to largest value.

Figure 4.16: Storey contact length recognised up-dip and normalised to sand body cross-sectional area; then normalised to largest value.

Figure 4.17: Storey contact length recognised down-dip and normalised to sand body cross-sectional area; then normalised to largest value.
Table 4.1: Table of metric measurements from DOMs

<table>
<thead>
<tr>
<th>Metric</th>
<th>Mean</th>
<th>Max</th>
<th>Median</th>
<th>Mode</th>
<th>Std. Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thickness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basin-wide</td>
<td>9 m</td>
<td>31.2 m</td>
<td>9.36 m</td>
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<td>7.03</td>
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<td>12.7 m</td>
<td>31.2 m</td>
<td>11.1 m</td>
<td>N/A</td>
<td>7.23</td>
</tr>
<tr>
<td>Down-dip</td>
<td>7.34 m</td>
<td>22.5 m</td>
<td>6.46 m</td>
<td>N/A</td>
<td>4.68</td>
</tr>
<tr>
<td>Stacked Distributary Sand Bodies</td>
<td>10.8 m</td>
<td>29.3 m</td>
<td>9.26 m</td>
<td>N/A</td>
<td>6.79</td>
</tr>
<tr>
<td>Palaeovalley-fill Sand Bodies</td>
<td>12 m</td>
<td>31.2 m</td>
<td>9.77 m</td>
<td>N/A</td>
<td>7.82</td>
</tr>
<tr>
<td>Up-dip Stacked Distributary Sand Body</td>
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<td>29.3 m</td>
<td>11.1 m</td>
<td>N/A</td>
<td>6.89</td>
</tr>
<tr>
<td>Down-dip Stacked Distributary Sand Body</td>
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<td>9.52 m</td>
<td>5.45 m</td>
<td>N/A</td>
<td>2.45</td>
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<td>Up-dip Palaeovalley-fill Sand Body</td>
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<td>31.2 m</td>
<td>10.1 m</td>
<td>N/A</td>
<td>8.94</td>
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<td>Down-dip Palaeovalley-fill Sand Body</td>
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<td>22.5 m</td>
<td>8.74 m</td>
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<td><strong>Mean Storey</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basin-wide</td>
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<td>4.00 m</td>
<td>4.00 m</td>
<td>3.29</td>
</tr>
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<td>16.0 m</td>
<td>4.84 m</td>
<td>N/A</td>
<td>3.84</td>
</tr>
<tr>
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<td>5.75 m</td>
<td>3.17 m</td>
<td>N/A</td>
<td>1.31</td>
</tr>
<tr>
<td>Stacked Distributary Sand Bodies</td>
<td>5.11 m</td>
<td>16.0 m</td>
<td>4.1 m</td>
<td>N/A</td>
<td>4.07</td>
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<td>2.64 m</td>
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</tr>
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<td>7.71 m</td>
<td>5.93 m</td>
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<td>5.75 m</td>
<td>3.27 m</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basin-wide</td>
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<td>16 m</td>
<td>6 m</td>
<td>6 m</td>
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<tr>
<td>Up-dip</td>
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<td>Down-dip</td>
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<td>1 m</td>
<td>1.10</td>
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<td>14 m</td>
<td>6 m</td>
<td>6 m</td>
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</tr>
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<td>3.5 m</td>
<td>1 m</td>
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<td></td>
<td></td>
<td></td>
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<td>58.6 m</td>
<td>118 m</td>
<td>41.20</td>
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<td>68.1 m</td>
<td>118 m</td>
<td>38.30</td>
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<td>40.30</td>
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<td>180 m</td>
<td>43.3 m</td>
<td>N/A</td>
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4.7 Discussion

When looking at the overall basin wide trends, sand bodies interpreted by Jerrett et al. (2016) as SDCs and PVFs are relatively indistinguishable at outcrop. They demonstrate similar average thicknesses, and although those interpreted as PVs are slightly thicker (12.0 m) relative to their stacked distributary counterparts (10.8 m), these values have standard deviations of 7.8 and 6.8 respectively. These values are also both within the range of sand body thicknesses described for stacked distributary channels and palaeovalley-fills (e.g. Blum et al., 2013; Owen et al., 2015). The two sand body types display overlapping preserved storey heights, with SDCs containing marginally thicker ($\mu$=5.1 m, SD=4.1) storeys compared to PVs ($\mu$=4.5 m, SD=2.0), and the average position of storey contacts relative to the base of the sand body is also similar ($\mu$=6.5 m, SD=0.75 in SDCs, compared to $\mu$=6.1 m, SD=4.6 in PVFs). The thickness of storeys reflects a combination of the original
channel bankfull depth, and subsequent truncation by overlying storeys, and it is difficult to distinguish between these. However, the fact that the average position of storey contacts in PVFs is lower than in SDC suggests that the reduced thickness of the storeys in PVFs is associated with greater truncation of the lower storeys. This is compatible with the notion that storeys comprising palaeovalleys are formed during a combination of degradation and aggradation (Blum et al., 2013), whereas SDCs are fundamentally aggradational to progradational features (Hartley et al., 2010; Weissmann et al., 2010). Average storey contact lengths are markedly different, however. These are 78.1 m in SDCs versus 61.2 in PVFs. The longest story contacts of up to 180 m are to be found, though, in PVF sand bodies. Hence, on a basin-scale, it seems that using such metrics to distinguish these sand bodies is extremely difficult.

By comparing all up-dip to down-dip sand bodies, a clear difference is revealed which sheds light into possible depositional processes. Overall, average up-dip sand body thicknesses are greater (12.7 m) than those recognised down-dip (7.34 m), and are within a standard deviation for the range of sand body thicknesses of both SDCs and PVFs. However, the down-dip thinning of the sand bodies implies that the channels were smaller, and contained less sediment. The marked decrease in sand body thickness implies that the channels could be interpreted as reflecting the distributive processes of a DFS; channels should distribute their sediment load across the alluvial plain, subsequently creating smaller channels, and coalescing to form smaller sand bodies down-dip. This interpretation is backed by the decrease in overall storey height from up-dip ($\mu=6.06$ m, SD=3.84) to down-dip ($\mu=3.22$ m, SD=1.31). As the channels within a DFS become smaller downstream, the inherent decrease in sediment load reduces the amount of preserved sand. Furthermore, the slight change in the average position of storey contacts up-dip ($\mu=6.40$, SD=0.67) to down-dip ($\mu=6.40$, SD=1.10), suggests that the channels were deposited by a similar process. If these sand bodies were products of an avulsing system, then the continual switching of the channels to distribute the sediment would allow the sand bodies to remain relatively similar in preservation potential of the topmost channel-
fill. Average story contact lengths are longer in up-dip sand bodies (73.2 m) than down-dip sand bodies (64.2 m). However, the longest storey contacts, of up to 180 m, are found within the down-dip sand bodies. Based on the overall trend up-dip to down-dip, these sand bodies are interpreted as products of a distributive fluvial system. Therefore, it remains unclear from the bulk trends observed within the metrics used in this study, that distinguishing between SDC and PVF sand bodies remains difficult. A more detailed analysis of the metrics is required.

Based on detailed mapping by Jerrett et al. (2016), the spatial extent and approximate location of the sand bodies recognised as stacked distributaries and palaeovalleys has been undertaken. By comparing the up-dip to down-dip trends within each end member sand body style, the metrics reveal individual trends for each sand body type discussed below. In detail, those sand bodies previously interpreted as SDCs display a marked decrease in average sand body thickness (i.e. $\mu=11$ m up-dip, to $5.5$ m down-dip), and average preserved story height (i.e. $\mu=6.31$ – $2.70$ m). This remains consistent with the interpretation that they are products of a distributive system, and channel size decreased down-system. Furthermore, the average position of the storey contacts are higher from the base of the sand bodies in down-dip locations, relative to the up-dip locations, in SDC sand bodies ($\mu=7.80$ m, $SD=0.72$ up-dip to $\mu=4.25$ m, $SD=0.98$ down-dip). This implies that the channels were smaller, and contained less sediment down depositional-dip, and remains consistent with the interpretation that they are products of distributive processes. This notion would comply with the evidence for reduced subsidence down-dip (<30 m/Ma) compared to up-dip (>150 m/Ma), which would in turn create less accommodation down-dip Jerrett et al. (2016). With reduced accommodation, the channels would more actively distribute their sediment load down-dip than up-dip. However, the increase in storey contact length down-dip (from up-dip 76.8 m to down-dip 82.7 m), reveals an interesting idea. If the sand bodies are indeed SDCs, then they would have most likely distributed their sediment load through avulsion processes. It has been shown that reoccupation of older channels can elongate the initial scour surface (i.e. storey contact) of a channel (Sheets et al., 2007). This could explain the...
increase in storey contacts observed down-dip in the interpreted SDC sand bodies.

Sand bodies interpreted as PVFs display a decrease in average sand body thickness (i.e. $\mu = 12.8$ m up-dip and $\mu = 10.8$ m down-dip) and average preserved storey heights (i.e. $\mu = 10.1$ m – 8.74 m), though at a lesser rate than those of interpreted SDC. This could be interpreted as a product of sediment distribution by distributive processes. However, the fact that the average position of storey contacts relative to the base of the sand body are closer to the base in relation to the average sand body thickness in PVs (i.e. $\bar{h} = 4.50$ m to $\bar{h} = 7.37$ m) than those in SDC sand bodies, would imply that these sand bodies were more degradational throughout deposition. Even though the average storey contact length decreases down-dip (i.e. 66.7 m to 58.5 m), the number of them observed, along with the longest storey contacts in the study recognised in down-dip sand bodies interpreted as PVFs. The tributive nature of PVs would create a large number of storey contact surfaces that will be relatively short as each successive channel will erode all or part of the initial scour to fill the decreased accommodation available down-dip.

With this in mind, the distributary sand bodies that were deposited into the orogenic margin were most likely the products of large rivers close to the basin input point, and coupled with the high-subsidence rate and slow eustatic sea level rise following maximum flooding, creating thick deposits up-dip that thin and/or disappear down-dip. If the rate of sediment influx kept pace with, or outpaced accommodation creation, this would result in aggradation and/or weak progradation of the deltas cratonward (Jerrett et al., 2016), resulting in thick amalgamated channel fills/storeys reflective of architecture found in proximal deposits of a prograding DFS (Weissmann et al., 2013). Moreover, the sand bodies interpreted as PVFs display an overall decrease in thickness and storey height down-dip, but to a lesser degree. The fact that the average position of the storey contacts relative to the base of the sand body are lower than those of SDC sand bodies implies that the channels at the time of deposition more incisional into older storeys than their SDC counterparts. Even though the accommodation decrease down-dip most likely remained the same for both sand body types, the sand bodies display evidence for deeper
truncation of the older storeys, again implying the notion that storeys comprising PVs were formed during a combination of degradation and aggradation. Furthermore, the longest storey contacts recognised in the sections are found in down-dip sand bodies interpreted as PVFs. Though the storey contact lengths are critical in determining storey bounding surfaces and the number and height of the storeys, the exact implications of this metric remain unclear when investigating outcrop. Further work must be completed to understand the process-to-preservation potential of these features, and their genetic relationship in fluvial sand bodies.

Figure 4.18: Schematic which illustrates the resultant sand body architecture from 3D quantitative analysis of 3D DOMs. Values are in metres and illustrate the basin-wide, up-dip and down-dip trends with respect to both sand body end member types (stacked distributary and palaeovalley). The maximum sand body thickness (far left number), average storey height (topmost number next to vertical arrow), average position of storey contact relative to base of sand body (bottommost number next to vertical arrow), and average storey contact length (number above horizontal arrow) are drawn relative to one another. Sand bodies are not to scale, and are only relative to one another.
4.7.1 Implications

Investigating the broad architectural trends within a system provide useful metrics to determine possible genetic origins of major fluvial sand bodies. The downstream decrease in sand body thickness and storey height in the Pikeville and Hyden formations match the criteria defined for characterising a system as a DFS (i.e. downstream decrease in channel size and storey height). However, through scrutinious analysis of the detailed datasets produced from lidar and other geospatial approaches (i.e. photogrammetry), the spatial extent of the features within a studied system can be quantified, and potential conceptual models tested. It has been shown by this study that internal architectural components are necessary metrics which need to be accurately characterised and analysed, to determine sand body genetic origin (i.e. distributive vs. tributive products). The approaches discussed in this study have implications for quantifying the presence of DFSs in the rock record, a current uncertainty with the model.

Secondly, approximating the genetic origin of sand bodies has large implications for determining connectivity of the sand bodies, both vertically and laterally. Distributive sand bodies display good vertical connectivity in the proximal sections of the system through repeated channel reoccupation and reworking, before decreasing down-system (Owen et al., 2016). The lateral connectivity of the sand bodies within a DFS is higher than in the vertical direction. However, all sand body connectivity decreases down-dip as the channels avulse over larger areas and channels bifurcate, separating sand bodies by floodplain deposits. Tributive channel systems should display an opposite trend however. Down-stream lateral and vertically connectivity should increase as the sand bodies will increasingly amalgamate as more sediment is fed into the system. This will reduce the effect of floodplain material (baffles) within palaeovalleys as they will be eroded out by the increased truncation of the older channel-fills. It is for this reason that proper distinction between these two sand body types is required for reservoir development and enhanced hydrocarbon recovery.
4.8 Concluding remarks

The geostatistics acquired from the outcrops of the Pikeville and Hyden formations enhances an already robust database with quantitative information to determine up-dip to down-dip changes in external and internal architecture of fluvial channel bodies. Through detailed 3D DOM construction and analysis, geostatistics extracted from the data quantitatively describe four general basin-wide trends: (i) Sand body thickness and storey height decreases down-depositional dip in both SDCs and PVF sand body types, with PVFs decreasing at a lesser rate. (ii) Up-dip sand bodies interpreted as SDC contain on average the thickest storeys that markedly thin down-dip, whilst average PVF storey height becomes the thickest down-dip. (iii) Sand bodies interpreted as SDC contain storey contacts which are found further from the base of the sand bodies (relative to sand body thickness) whilst sand bodies interpreted as PVF contain storey contacts that are found predominantly closer to the base (relative to sand body thickness). (iv) Average storey contact length increases down-dip in both sand body types, with the longest identified storey contacts identified in down-dip sand bodies interpreted as PVs. Additionally, up-dip sand bodies interpreted as SDCs contain the most storey contacts, whilst conversely sand bodies interpreted as PVFs contain the most storey contacts down-dip.

From these trends, we suggest that previous interpretations that the Pikeville and Hyden Formations contain major fluvial sand bodies of SDCs and PVFs remains valid. Since a "basinward facies shift" criteria is not recognised in many palaeovalleys, the quantitative architectural analysis techniques described here provide a methodology for characterising basin-wide trends of architectural elements. Their applicability to discern between sand body types (i.e. SDC vs PVF) in fluvio-deltaic systems has been demonstrated in this study. However, further work is required to acquire higher-resolution spatial photographic information (i.e. photogrammetry, gigapan integration with lidar) to examine small-scale (i.e. < 0.10 m) heterogeneities and architecture. Finally, the techniques discussed here are translatable and broadly applicable across different depositional systems containing major fluvial sand bodies.
4.9 References


— (1995). “The application of high-resolution sequence stratigraphy to fluvial systems: a case study from the Upper Carboniferous Breathitt Group, eastern Kentucky, USA”. In: Sedimentology 42.1, pages 3–30.


Section 3

Reservoir Model Characterisation
Chapter 5
Chapter 5

Characterisation and modelling of the medial portion of a Miocene DFS from DOMs: A case study of the Huesca DFS

5.1 Abstract

Outcrop analogue studies are often used to obtain the necessary spatial information used to accurately model hydrocarbon reservoir architecture and geometry (e.g. channel element geometries, heterogeneity and connectivity), not easily obtained through traditional subsurface datasets (e.g. seismic, well-logs). Terrestrial data acquisition, visualisation and analytical techniques (e.g. lidar, photogrammetry) have been used in a large number of studies over the past decade to obtain high-resolution 3D spatial information, to produce accurate representations of outcrop analogues. Construction of 3D Digital Outcrop Models (DOMs) through these techniques allows detailed quantitative analysis of key reservoir units (e.g. sand body width vs. thickness) within the models.

Similar techniques have been adopted for this study which utilises a large continuous 3D lidar dataset to quantitatively analyse sand body architecture (i.e. true sand body width vs. thickness) and subsequent lithofacies proportions within the medial portion of a distributive fluvial system (DFS). These results are integrated with high-resolution sedimentary logs to produce reservoir simulations used to analyse resultant sand body geometry and connectivity within a 2 km² study area. The work flow and results presented in this study demonstrate the efficacy integrated lidar studies of outcrop analogues can produce. The study demonstrates the adaptation, progression and improvements made to the current geocellular modelling-from-outcrop work flow.
5.2 Introduction

Traditionally, datasets used for computer-based geocellular and reservoir modelling include seismic and other geophysical data (e.g. wireline logs, differential gravity maps) in conjunction with core and well data, to provide an increased subsurface understanding of the reservoir. This allows the geologist to build a deterministic architectural framework for final model realisations, and ultimately field development (Fabuel-Perez et al., 2010; Howell et al., 2014). Though the resolution of these techniques has improved over the years, they still do not offer enough detailed information that is required to construct more accurate geologic models. The data are often sparse or unavailable, increasing the uncertainty of the reservoir descriptions and subsurface representations (Bridge and Tye, 2000; Van Lanen, 2010; Olariu et al., 2011). Utilising these types of datasets to model predominantly fluvial systems is difficult due to the complex nature of the cut-and-fill processes of channel systems, as well as resolving the individual channel elements. An effective understanding of the architectural elements (e.g. palaeochannel geometry, stratigraphic heterogeneity and channel body connectivity), in coordination with the geostatistics attributed to fluvial reservoir bodies, provides a deeper understanding of the recovery factor and production and performance potential throughout a fluvial system (Pranter et al., 2008; Anderson, 2005). Fluvial reservoirs vary in size, architecture and heterogeneity, and are unique throughout the ancient rock record. They also share common characteristics that allow correlation (i.e. origin of the depositional system and general reservoir body geometry) (Miall, 1996). Attaining and integrating quantitative and qualitative data on the characteristics of fluvial sand bodies is necessary to build deterministic geocellular model realisations.

To combat some of the inherent spatial uncertainties within fluvial reservoirs, stochastic methods are employed to predict lithological variations across parts of a depositional system. A common practice used in both academia and industry is the detailed investigation of outcrop analogues for various depositional environments. Outcrop analogues are often used to obtain the necessary spatial information to accurately model reservoir behaviour (e.g. channel element geometries, heterogeneity
and connectivity. Outcrops are increasingly being utilised in geologic modelling work flows to resolve spatial disparity issues when estimating the amount of recoverable hydrocarbons in reservoir rocks (Alexander, 1993). Conventionally, one-dimensional sedimentary logs are correlated across an outcrop and often accompanied by two-dimensional photo panels (photomosaics), and outcrop sketches. These tools for outcrop characterisation and analysis offer a detailed look into geometries of mesoscale scale (i.e. 0.01 m to 100 m) sedimentary structures, stacking patterns and stratigraphic relationships, as well as allowing the collection of lithologic samples for petrophysical analyses. However, these methods lack quantitative precision and 3D spatial context for the measurements. This introduces errors that can propagate throughout a geologic model if not constrained properly (Rittersbacher et al., 2014a; Bhattacharya, 2011). The advent of digital data acquisition methods and techniques using lidar (light detection and ranging), in conjunction with geomatic (i.e. Differential Navigation Satellite System (DGNSS)) measurements has allowed geoscientists to create high-resolution 3D representations of outcrops, and acquire key quantitative measurements. These 3D models, generally referred to as digital outcrop models (DOMs), are geospatially controlled virtual realisations of (primarily) sedimentary systems at various scales (e.g. Minisini et al., 2014; Rittersbacher et al., 2014b).

In the past decade, numerous studies have been undertaken to extract quantitative geobody measurements and create work flows and methodologies to build and populate reservoir models and simulations (e.g. Enge et al., 2007; Fabuel-Perez et al., 2009; Rittersbacher et al., 2014a). The inherent quantitative information contained within DOMs has allowed integration of integral data (e.g. geobody measurements, lithologic variability and robust conceptual geologic models) to construct accurate geological models and subsurface analogues for a predominantly fluvial sedimentary system.

This chapter focuses on improving methods of analysis and creation of facies models for the medial portion of a distributive fluvial system (DFS) within the Huesca fluvian fan in the Ebro Basin, NE Spain. Determining crucial geobody measurements within a fluvial reservoir (i.e. width, thickness, spatial distribution) is a
primary focus in hydrocarbon exploration and development (Bridge and Tye, 2000). Since the late 1970’s, the Huesca and coeval Luna DFSs have been studied to develop an understanding of structural controls of fluvial distributary systems, fluvial sand body geometries, lateral and vertical stacking patterns and their relationships to floodplain deposition (Friend et al., 1979; Hirst, 1991) within an endorheic (or internally draining) basin. These studies offer a robust conceptual model of channel element behaviour and a suite of statistical data to refine these models. Therefore, the primary purpose of this study is three-fold: i) Analyse the stratigraphic heterogeneity in the studied succession by investigating the spatial distribution of channel geobody geometries and the lithofacies distribution and proportion relationship to the channel geometries; ii) present and discuss the work flow used to construct the geological models used for the analyses from outcrop analogue to subsurface representations through stochastic modelling techniques; iii) investigate the efficacy of using integrated outcrop analogues and reservoir modelling techniques to analyse the fluvial architecture of the Huesca DFS.

5.3 Geologic Setting

5.3.1 Palaeogeographic and Stratigraphic Setting

The outcrop area selected for this study is the La Serreta succession, located along the northern rim of the Ebro Basin, in northeast Spain. It is a part of the Huesca DFS; a Miocene – Oligocene system which is primarily composed of fluvial deposits with evaporates and lacustrine carbonites found in the basin centre. The Ebro Basin is a foreland basin of the southern Pyrenees which formed as a result of the collision between the Iberian and European plates during the Late Cretaceous through to the early Oligocene (Puigdefàbregas et al., 1992). From the early Eocene to the early Miocene, the southern Pyrenean region underwent a period of compressional stress resulting in thrust fault complexes forming the southern foredeep of the Pyrenees (Nichols, 1987). The subsequent uplift in the Pyrenean axial zone exposed a Mesozoic cover of predominantly metamorphic and Hercynian basement rocks. These rocks, as well as the early Eocene carbonates of the southern Pyrenean thrust belt and the clastic fill of three Pyrenean basins, formed the main sediment
fill found in the northern-extent of the Ebro Basin (Hirst and Nichols, 1986) (Figure 5.1a).

Figure 5.1: (a) Regional palaeogeographical reconstruction and summary map of the Huesca and Luna systems with approximate palaeocurrent distribution and structural relationship. (b) Stratigraphy of the External Sierras allochthonous units and the Ebro Basin north of Huesca (from Puigdefàbregas et al., 1992; Hirst and Nichols, 1986; Nichols, 1987; Jones, 2004; Nichols and Thompson, 2005).

From the late Eocene to the Early Miocene, the Ebro Basin was endorheic, encased by the Catalan Coastal Range to the south east and the Iberian Range to the south west (Figure 5.1a). This isolated basin drainage from the Bay of Biscay and Mediterranean Sea. The basin persisted as an endorheic basin for approximately 25 M.a. (Garcia-Castellanos et al., 2003), allowing a thick accumulation of fluvial sediment to form in the north-central portion of the basin. Due to the internal drainage structure of the Ebro Basin, two large, distinct systems formed: the Huesca (60 km) and the Luna (40 km), both of which have been characterised as distributive fluvial systems. Both systems are part of the upper Uncastillo, or equivalent Sarriñena formation (Figure 5.1b) which fed into a basin-centre lake. This relatively shallow ephemeral lake, which sometimes inter-fingered with deposits of the distal sectors of the system (Nichols and Fisher, 2007), acted as a basin-level buttress, causing changes to the fluvial profile and preservation space potential throughout the two systems. The resulting system would aggrade, avulse and laterally migrate repeatedly, creating a vertical profile of multi-storey channel complexes amongst thick deposits of overbank (mudstone) material. The channels were not laterally
confined (Hirst, 1991), nor is there evidence of incised valley complexes that are often observed along the fluvial profile in other continental fluvial systems (Shanley and McCabe, 1994). As a result, accumulation of the sediment would continue until the basin spill point was reached. It is worth bearing in mind that the resulting stratal thickness of the deposits will be greater than the original accommodation due to sedimentary loading and subsidence (Nichols and Fisher, 2007).

The Huesca DFS is characterised by several lithofacies defined by their proportion, bed geometry, textural and sedimentary features (Luzón, 2005). The overall grain size of the Huesca system decreases downstream as the channels undergo a transition from bed-load to mixed-load, a result of a change in channel depth and width as it flows toward the basin centre. The resulting lithology of these processes for the two systems, from basin margin to basin centre, contains conglomerates and sandstone and mudstone respectively, which have scoured into the adjacent alluvial plain as channel fill deposits (Nichols, 1987; Hirst, 1991).

5.3.2 Sedimentology and Fluvial Architecture

The La Serreta study area itself is located within the medial zone of the Huesca DFS, and contains channel sand bodies that are primarily very coarse to fine sandstones, enclosed by mudstone and very fine sandstone strata (Nichols and Fisher, 2007). The channel sand bodies are usually ribbon or sheet-like in shape and are laterally continuous in outcrop for tens to hundreds of metres (Figure 5.2). Some contain decimetre-scale internal structures and others show very little to none within a single story. The dominant geometries observed are multi-storey sand bodies with single-storey as the subordinate channel type. The bases of all of the channel geometries are not deeply incised into the floodplain, providing evidence for the lateral mobility of the streams throughout deposition (Sadler and Kelly, 1993). The channels sometimes contain preserved bar forms commonly found in braided streams, indicative of a transition to a higher sediment flux period (Friend et al., 1979; Hirst and Nichols, 1986; Nichols, 1987; Donselaar and Schmidt, 2005). The cause of this is unknown, but we suggest it could be due to a regional avulsion episode upstream. This caused the active depositional lobe of the DFS to occupy the La Serreta area.
5.3.3 Conceptual Geological Model

The conceptual geological model provides a clear image of the architecture and associated processes, which is necessary to construct a robust and sensible reservoir model (Ringrose and Bentley, 2014b). Analogue photographs or satellite images as well as sketches of 3D block models are often used as conceptual models in the modelling process. However, the study presented here used information from previous works, in coordination with the DOM analyses from Chapter 3 to construct a conceptual model for the La Serreta succession.

In a study performed by Gibling (2006), fluvial sand body geometries were collated from across the literature to identify any trends which might be apparent in different bedrock and Quaternary depositional environments. The channel geometries for the Huesca DFS are compiled from several studies in the area (i.e. Friend et al., 1979; Nichols, 1987; Hirst, 1991), and grouped together when plotted onto a log – log scale of width versus thickness (see Chapter 3). Gibling (2006) illustrates the approximate geometry and stacking pattern and architecture of the fluvial sand bodies in the Huesca DFS, based primarily on a previous study by Hirst (1991)
(Figure 5.3a). From these studies, the evolution of the DFS conceptual depositional model started, with the Huesca and Luna systems being the primary example of the distributive nature of the channel elements across the system. It is therefore critically important to constrain the model as much as possible and modify, if necessary, any of the model characteristics. Multiple studies have been completed which analyse many of the modern day geomorphic examples of DFSs (i.e. Weissmann et al., 2010; Hartley et al., 2010; Davidson and Hartley, 2014; Weissmann et al., 2015), along with an increasing number of ancient examples (i.e. Kukulski et al., 2013; Quartero et al., 2015) with their link to geometric and architectural relationships of modern examples investigated (e.g. Weissmann et al., 2015). Following these studies, the use of digital acquisition and analysis techniques have been used to classify and interpret the La Serreta outcrop exposure in the Huesca DFS to obtain geostatistical information to enhance both the depositional and potential reservoir

Figure 5.3: (a) Huesca fluvial architecture schematic from Gibling (2006). (b) La Serreta fluvial architecture schematic used to create approximate conceptual depositional model to guide the fluvial reservoir modelling process. cf(Nichols, 2007).
model of a medial portion of a large DFS (see Chapter 3). These results are used to refine the conceptual model for the La Serreta succession, and medial zone of the Huesca DFS, which is presented here and used as a guide for the reservoir modelling process (Figure 5.4).

Figure 5.4: Conceptual depositional model for channel elements within the La Serreta succession. (a) Block model illustrating approximate stacking pattern derived from 3D DOM analysis (Chapter 3). (b) Channel-scale block model illustrating approximate mesoscale stacking patterns, crevasse splay and palaeosol development. These models are integral to evaluating the final reservoir simulation.
5.4 Methodology

5.4.1 Study Area

The following section provides a detailed review of the methodology used to demonstrate the utilisation of digital geospatial acquisition and analytical techniques to analyse the vertical and lateral variability of fluvial deposits within a medial portion of a DFS. The geostatistics acquired are used to condition a geocellular model to provide the most accurate representation of an outcrop to be used as a subsurface analogue. The La Serreta study area was chosen for this study not only for its relevance as a well-studied site by academia and industry, but also because of the quality and style of exposure of the fluvial system. The study area is approximately 2 km², large enough to be a suitable reservoir volume, and offers some of the best vertical, lateral and nearly 3D exposures of the medial section of an endorheic fluvial succession. The amphitheatre style of exposure (Figure 5.5) through the succession provides a unique opportunity to utilise digital spatial acquisition methods to build a 3D reconstruction of the area, and ultimately a detailed representation of a similar subsurface reservoir. Therefore, the La Serreta outcrop allows detailed high-resolution sedimentological analyses (e.g. spatial distribution and proportions of lithofacies, lateral and vertical stacking patterns of sedimentary bodies) of the fluvial architecture of medial deposits found in the Huesca DFS. Studies in the past decade which use lidar data and DOMs for architectural and geometric analysis of sedimentary systems (e.g. Phelps and Kerans, 2007; Phelps et al., 2008; Van Lanen, 2010; Fabuel-Perez et al., 2010; Rarity, 2012; Rittersbacher et al., 2014b) primarily concentrate on long continuous cliff faces as the main outcrop exposure type to create the DOM and subsequent model realisations, however these studies lack a nearly continuous 3D outcrop. The study presented here provides a more complete, nearly 3D outcrop (Figure 5.5) with which to build a geocellular outcrop model and subsequent reservoir model realisations.
Figure 5.5: (a) Orthophotograph of the La Serreta study area with approximate lidar scan locations (yellow) and sedimentary log positions (red). (b) Schematic of La Serreta area highlighting approximate lidar data coverage area. (c) View of amphitheatre style of outcrop with subvertical scree-covered slopes.
5.4.2 Digital Outcrop Model

The fluvial architecture of the Huesca DFS has been thoroughly discussed through traditional analysis methods, and therefore provides a plethora of information to build preliminary models (reservoir and depositional) (see Friend et al., 1979; Hirst and Nichols, 1986; Nichols, 1987; Nichols and Fisher, 2007; Fisher and Nichols, 2013), however these datasets lack the quantifiable spatial context necessary to analyse the 3D spatial distribution of lithofacies and architectural components. Building upon previously established data collection, processing, integration and visualisation methods (i.e. Fabuel-Perez et al., 2009; Van Lanen, 2010; Rarity et al., 2013), the DOMs created for the study area allow for an extraction of the key measurements required to build accurate models (e.g. facies, depositional and geocellular and reservoir models) of the medial portion of a DFS.

5.4.2.1 Data Collection

Terrestrial laser scanning (TLS) has been a strong component used in digital mapping and outcrop modelling studies for a decade as subsurface analogues. Similar techniques have been used previously (see Pringle et al., 2004; Enge et al., 2007; Labourdette and Jones, 2007; Buckley et al., 2008; Jones et al., 2008; Fabuel-Perez et al., 2010; Van Lanen et al., 2009; Rarity et al., 2013). A RiegI LMS-Z420i TLS with a coaxially mounted Nikon DSLR camera was placed in 33 strategic positions around the La Serreta study area to maximise spatial coverage (Figure 5.5). A Trimble Pro XT DGNSS was used to approximate the scan location position to within 60 cm accuracy. Fifteen traditional sedimentary logs (positioned with GPS) were collected throughout the study area to provide high-resolution (i.e. 1:40 scale ≈ 0.02 m resolution) qualitative information. Eight hundred metres of stratigraphy was collected including grain size analysis, palaeosol characteristics, sedimentary structures indicative of palaeoflow recorded and any palaeoenvironmental indicators (e.g. bioturbation or fauna markers). From the sedimentary logs, over 254 palaeocurrents were measured (Figure 5.6).

The point clouds generated from each scan location were georeferenced and a similar differential geospatial technique to the scan location positioning was applied
to the top and bottom of each sedimentary log position. This allowed for direct translation and integration with the DOMs. The TLS scans contain dense point clouds with a 10 cm point spacing, giving a 20 cm resolution of geometries in the data. The resulting point cloud dataset is 121 million points \((x, y, z)\) positions, each containing RGB information related to their respective scans provided by the coaxially DSLR. The scans offers complete coverage of over 2 km\(^2\) of the La Serreta succession. This information is integrated into the DOM for subsequent use in the geocellular modelling process.

![Rose diagrams indicating palaeoflow azimuth of multi-storey sand bodies](image)

Figure 5.6: (a) Rose diagram indicating palaeoflow azimuth of multi-storey sand bodies with a mean of 292°. (b) Rose diagram indicating palaeoflow azimuth of multi-storey sand bodies with a mean of 309° (c) Rose diagram indicating palaeoflow azimuth of multi-storey sand bodies with a mean of 296°

### 5.4.2.2 Data integration and visualisation

Integration, visualisation and interpretation of the DOM data was performed in a variety of software packages, both commercial and proprietary. RiScanPro™ is primarily used for data collection with the TLS and translating the images acquired from the coaxially mounted DSLR onto the point clouds. Polyworks™ is used as a spatial positioning program to collate and align the datasets together. The lidar point cloud scan locations and sedimentary log positions were checked for spatial accuracy by integrating them with a 5 m Digital Terrain Model (DTM) derived from airborne lidar data from the study area.

These software packages lack essential tools for geological interpretation and analysis, leading to the use of in-house developed software, Virtual Reality Geo-

logical Studio (VRGS) for the data analysis. Once the spatial accuracy of the data
was verified, it was integrated in VRGS. This platform is crucial to interpreting the fluvial sand body geometries throughout the field area, associated bounding surfaces and any palaeosol horizons that are used as stratigraphic markers. VRGS offers the ability to produce several types of visualisation realisations of the DOMs to aid the interpretation process. The most useful for this type of depositional environment is the ability to create a photorealistic representation of the outcrop to distinguish between channel sand bodies and overbank floodplain material. The voxels of each scanned dataset are assigned the acquired RGB colour information, giving the model an accurate pixel-to-point ratio (Figure 5.7a & b). Additionally, a more advanced visualisation technique utilises the results of a tensor analysis applied to the DOM data (see Fernández, 2005; García-Sellés et al., 2011; Hodgetts, 2013; Rarity et al., 2013). This method extracts several attributes pertinent to interpretation of key features, such as larger bedding structures (e.g. lateral accretion or storey contacts) as well as discerning in-situ deposits from scree or vegetation on the slopes of an outcrop exposure. These different DOM visualisations were used throughout the La Serreta succession to identify not only sand body geometries, but also the existence of laterally continuous splay deposits amongst scree slopes within the overbank material (Figure 5.7).

Figure 5.7: Attribute generation for a portion of the lidar DOM dataset, illustrating the variation in lithology and characteristics which can be drawn from the various realizations. Scale bars are 5.0 m in all figures. (A) RGB coloured point cloud from the lidar dataset with an RGB channel histogram to illustrate the variation in colour retrieved from the translated photography onto the points. (B) RGB coloured triangulated mesh derived from the point cloud dataset, which visibly preserves the morphology of the DOM as seen between figures A and B. (C) Co-planarity attribute realization derived from a Tensor analysis performed on the DOM mesh to highlight surfaces which have similar planar features. The attribute is used for this study area, to aid the interpreter in distinguishing large continuous sand bodies from overbank splay features. (D) Dip from a triangle orientation derived from a mesh of the DOM. As noted by the distribution plot, the orientation values between 35 - 90 were used, as these are values which would highlight difference between in-situ preserved sediment, and those of scree slopes or vegetation. By delineating between these objects, accurate statistics are obtained from the preserved material for analysis.
The fifteen sedimentary logs acquired were digitised (see Appendix A) and imported into the reservoir modelling software package Petrel™ as pseudo-well logs. This allowed a direct integration of the vertical facies components with the geocellular model via a facies log digitised from each respective field sedimentary log. Additionally, a facies codes is assigned to each lithofacies, resulting in a quantitative geostatistical database in Petrel™ that can be used for a number of analyse including, but not limited to, the composition of the facies in each log and across the study area. Additionally, a geobody classification technique, which uses the codes as criteria for classifying different lithofacies types in the DOMs, aided in the creation of spatially accurate facies models and trends within the reservoir model.

5.4.2.3 Geobody Mapping and Classification

Discriminating between different types of channel sand bodies, their lateral connectivity and their heterogeneity, is central to the interpretation of a fluvial system in order to create an accurate geocellular realisation of the outcrop. The 3D exposures of the La Serreta succession offer excellent spatial control of the sand body architecture, allowing an accurate interpretation of sand body geometries throughout the outcrop. This 3D geospatial analysis, integrated with DGNSS controlled sedimentary log data, is used to build a detailed geodatabase (e.g. lithofacies model, depositional element (channel, splay or overbank), bounding surfaces, and palaeocurrent information) for the study area. The geodatabase includes information which is used by a variety of tools within VRGS to provide essential information in the geocellular modelling process (i.e. palaeocurrent distribution across the model(s), facies classification, structural and sedimentary surface mapping). One of these tools, the Geobody Mapping tool, is used to create a continuous polyline that is interpreted around sand bodies within the point cloud (see Chapter 3). Once a geobody object is interpreted, a set of attributes for that object becomes available from the integrated geodatabase.

For this study, a lithofacies classification scheme was developed for the succession and applied to each geobody (Figure 5.8). Additionally, the apparent width and thickness of the geobody is calculated from the interpreted polyline. To reduce
the inherent uncertainty (apparent width and thickness) from measuring channel dimensions from outcrop, and determine a more accurate measurement of true channel width and thickness, a technique developed by Fabuel-Perez et al. (2009) has been improved to include a corrected suite of width and thickness values (mean, minimum, and maximum), for each mapped geobody (see Chapter 3). Once palaeocurrent data from the log database has been attributed to the geobody polygon, the associated palaeocurrent direction is used to correct the observed width to the true width (Fabuel-Perez et al., 2009). As each geobody has multiple palaeocurrents measured in the field, there is an uncertainty in the direction used to calculate the true width, therefore all directions are used to derive a probability distribution function (PDF) for the corrected width data. This PDF provides a minimum, maximum and most likely size for each geobody, with the most likely size being the mean palaeocurrent direction. The values and PDFs produced from this method provide a collection of conditioning data used in the final object modelling process.
Figure 5.8: (a) Classified DOM point cloud in VRGS. (b) Classified DOM point cloud imported into Petrel™ for advanced spatial facies analysis (c) Upscaled classified DOM point cloud in Petrel™ used for final facies modelling. Yellow points and geocells are multi-storey channel elements, and orange points and geocells are single-storey channel elements.
5.5 Geocellular Outcrop Modelling

A geocellular model of the study area was built using data from the La Serreta DOMs (e.g. classified point clouds, mapped stratal horizons, sedimentary logs) in Petrel™ (Figure 5.9). A standard work flow was used for the generation of the La Serreta geocellular outcrop model and entailed the following steps:

(i) Interpretation of stratal horizons in the DOMs.

(ii) Generation of a key 3D surfaces from the interpreted stratal horizons for stratigraphic and model zonation.

(iii) Construction of a 3D stratigraphic and structural grid for the geocellular outcrop model.

(iv) Import sedimentary log sections as pseudo wells.

(v) Import classified point cloud geobodies as discrete elements.

(vi) Upscale all of the conditioning data (pseudo-wells and classified points).

The stratal horizon identification in the La Serreta area is limited as the sedimentary system is predominantly fluvial, resulting in few discernible stratigraphic markers across the study area. However, a well-defined palaeosol horizon (Figure 5.9b) was identified in the succession and was digitised as a polyline across the DOM, allowing a stratigraphic boundary to be used in the modelling process. However, the facies population procedure of the geocellular outcrop model primarily utilises the classified point cloud dataset instead of the sedimentary log sections. This provides more conditioning data throughout all of the studied sections, and ultimately a more robust statistical geodatabase to use when steering the facies modelling algorithms, improving the various simulation results.

Since the classified point clouds are imported into PETREL™ as discreet elements, they are filtered based on their classification scheme (e.g. multi-storey channels, single storey channels and overbank). To keep the model as geologically realistic as possible, the model boundary established for the La Serreta geocellular outcrop model was based on the input data (i.e. DOM coverage) to ensure the most
accurate simulation results. The La Serreta geocellular outcrop model covers an area of 2.5 km x 1.4 km (Figure 5.9a), to make sure all of the classified point cloud and sedimentary log information is included in the subsequent analyses and model realisations.

Figure 5.9: (a) Bounding box illustrating extends of model just outside of the lidar datasets to ensure complete coverage of both the classified DOM and the sedimentary logs derived realisations. (b) Palaeosol digitised as the only mappable stratigraphic horizon to create the modelling zones around. (c) Geocellular grid size (10 m x 10 m x 1.5 m) (d) Final geocellular model created from upscaled classified DOM and full lidar dataset, with sedimentary log (pseudo-well logs), georeferenced in modelling grid.

The modelling grid was defined based on parameters described in Fabuel-Perez et al. (2010). To increase the accuracy of the model realisations to the channel
body geometries, the plan view grid (X and Y orientation) was orientated along
the broad palaeoflow azimuth of the La Serreta section, 296° (WNW). Additionally,
to ensure that all of the geological features are represented in the realisations, the
cell dimensions are calculated based upon the smallest observed geometric objects
in the data to allow accurate characterisation. Fabuel-Perez et al. (2010) proposed
a rule to efficiently model sedimentary system objects (i.e. sand bodies) which saves
computation time, but still ensures that the simulated geology is fully connected
and accurately represented. The rule presented is as follows:

Horizontal resolution = 0.5 * Minimum object width
Vertical resolution = 0.5 * Minimum object height

The smallest recognised objects are crevasse splay deposits (i.e. 0.2 m), whilst
the smallest recognised and classified sand body is 3 m thick and 20 m wide. The
computation time which would be required to efficiently simulate crevasse splay sized
objects would be too long. Additionally, the computational load of the model would
be too high, making analysis and visualisation nearly impossible. Therefore, the
smallest sand body measurements were used to construct the cell dimensions of the
modelling grid, which was defined at 10 x 10 x 1.5 m (Figure 5.9c). The resultant
grid resolution is sufficient to accurately capture the smallest channel elements from
the classified objects and coarse enough to run in an adequate time for analysis
(Figure 5.9d). The final geocellular model of the La Serreta outcrop contains a total
of 3.9 million grid cells.

5.5.1 Distribution Analysis

5.5.1.1 Geobody Distribution

Using the Geobody Mapping tool in VRGS, the spatial distribution of the channel geobodies was analysed for two different reasons: (i) Identify a spatial (vertical or lateral) trend in the distribution of the interpreted geobodies and their associated internal and external geometries, and (ii) Compare the width versus thickness distributions and trends to historical studies of the same succession.

Sand body geometry is defined as having 3 dimensions, but these are rarely
seen in outcrop. Width and thickness are used to define the sand bodies. Channel body thickness is defined by the preserved and compacted sediment accumulation. Channel body width measured in 2D at outcrop is an apparent representation of the true channel width (Cuevas G. and Martinius, 1993). By minimising this effect, a more accurate distribution of the channel body geometries was produced through the succession. (Figure 5.10a). The results of this distribution illustrate the variability in the geobody size up through the stratigraphy, with wider geobodies occupying the middle portion of the succession. Further analysis is required to determine the effect this will have on the facies proportions throughout the study area, and is addressed in the next section (Facies Distribution).

A qualitative 2-D photo-panel technique was the initial method used to map and analyse the channel body geometry for the Huesca DFS (Hirst, 1991). The resulting statistics were used in a study by Gibling (2006) to generate width versus thickness plots for ancient examples of the Huesca and Luna fluvial sedimentary systems. A similar plot was constructed for the measurements attained from the values derived from the La Serreta area to directly compare the two analytical results (Figure 5.10b). An envelope was drawn around the collection of mean geobody width values with a separate envelope around the minimum and maximum values for the plot generated for this study (purple = mean; red dashed = min – max) and other envelopes around the plot generated from Gibling (2006) (transparent blue), versus the associated geobody thicknesses. This is used to illustrate the range of channel body geometries between the two studies. These studies provide a wealth of information, and an excellent comparative example between the traditional 2D approach, and the more quantitative 3D approach used in this study. (Discussion of the width versus thickness plot generated from the studies is addressed in more detail in Chapter 6). The integration of traditional 2D data collection techniques with 3D mapping and analysis methods has allowed detailed facies distribution analyses of the study area to be completed. These results are discussed below, and are used in the final reservoir modelling process.
Figure 5.10: (a) A plot to illustrate any vertical trends found within the succession of 42 measured sand bodies. As observed by the plotted data, there is an increase in the calculated mean width up through the stratigraphy. (b) Plot of geobody width vs thickness ratios with envelopes encompassing around the arithmetic mean and minimum – maximum measurements from the corrected geobody widths. Red dotted dashed envelopes the minimum and maximum measurements for the geobody widths whilst the grey fill highlights the associated uncertainties between the mean geobody width envelope and the min-max envelope. Note the translated location of the corrected geobody widths and thickness envelopes (purple and red dashed) from the quantified lidar measurements, to the envelopes included of the Gibling, 2006 measurements (transparent blue) for the same formation.
5.6 Facies Distribution

5.6.1 Sedimentary Log Analysis

The inherent quantitative nature of a DOM and the associated geodatabase provides an extensive spatial dataset which can be analysed to identify statistical distributions and trends that can be used when constructing a geocellular, and indeed a potential depositional model for the La Serreta succession. The approximate percentage of each facies component was calculated from the pseudo-well logs (Figure 5.11), which was used to plot their respective distributions in an overall histogram (Figure 5.12). This process provides an essential component that is used to populate the conditioning parameters to construct accurate reservoir simulations.

Deposits classified as in-channel (very coarse sand to fine sand) components within the study area of the system at 45 km from the calculated system apex constitute 46% of the stratigraphy. The remaining 54% of the deposits are floodplain and overbank sediments, which consist of mudstone rocks (flood plain) and very fine sandstone units, deposited in sheet-like geometries (unconfined flow) and interpreted as crevasse splays. These are easily discernible from the major channel fill sandstone bodies. The differences in grain size and geometry make interpreting the channel geobodies from the overbank floodplain deposits straightforward, and help geoscientists develop depositional models for these types of fluvial systems. The results of these distributions yields a 22% increase in the channel body facies (very coarse sand – fine sand) in volume than previously stated by Hirst (1991) and more closely matches the sand-to-silt ratio presented by Donselaar and Schmidt (2005). These percentages are used as a set of conditioning parameters to populate the reservoir model during the simulation process, along with a vertical proportion curve from the classified DOM. The implications this increase in channel facies has for the depositional model of the Huesca DFS will be discussed in Chapter 6, but it is important to recognise the significance this has when building a reservoir simulation.
Figure 5.11: Example of the digitised sedimentary logs integrated with reservoir model. Facies logs created for each well log, inherently creating a facies code which can be used to analyse lithofacies percentages in study area.
5.6.2 Probabilistic curves

An important aspect of creating accurate geologic and reservoir models for a fluvial sedimentary setting, is the approximation of the proportion of facies and geobody distribution trends. Stochastic modelling algorithms in Petrel™ use the proportions observed in the log data to stochastically populate the different modelling zones. As is often the case, the vertical distribution of the facies is not equal in all parts of the zones, as evidenced by the distribution of sand bodies interpreted from the classified DOMs (Figure 5.10a). It is therefore critical to appropriate the vertical facies proportion throughout each zone to honour the approximate facies distribution observed in outcrop. The vertical facies associated to each pseudo-well log in the modelling grid allows an accurate approximation of this distribution through the use of a probabilistic curves. These curves are used to conduct vertical analyses of the individual architectural elements in the final model that are computed with the input data (Labourdette and Jones, 2007). Petrel’s™ Data Analysis tool was used to calculate the vertical distribution of the facies along each upscaled pseudo-well track (Figure 5.13), as well as the classified DOM (Figure 5.14). The resultant probabilistic curves are used in the final model simulation process to produce the stochastic realisations used in this study.
Figure 5.13: Input sedimentary log data from digitised logs that were upscaled, and used to calculate a probability curve for the geocellular model of the La Serreta study area.

Figure 5.14: Input sedimentary log data and calculated probability curve derived from upscaled classified DOM. Note the similarity in curve behaviour and lithofacies percentage to sand body width and approximate stratigraphic positions (Figure 5.12a)
5.6.3 Variogram analysis

The most common geostatistical tool used in reservoir characterisation studies is the directional variogram, which is used to investigate and model the facies, and other petrophysical properties, spatial variability in relation to distance (Gringarten and Deutsch, 1999). The directional variograms for the study area were computed in three directions, a major horizontal, minor horizontal and vertical direction. Since the maximum lateral continuity of fluvial sedimentary structures is dependent upon the palaeoflow, the major horizontal direction is calculated along the mean vector of the palaeoflow direction. The standard method of variogram calculation was used (Gringarten and Deutsch, 1999; Hohn, 1999), which involved the calculation of an experimental variogram for each lithofacies in the selected directions for each zone of the model. The variograms were calculated in Petrel™ from the 10 m up-scaled pseudo-well logs and the geocellular model. This allowed direct comparison with the classified DOMs.

The major horizontal variograms of both lithofacies generally have an undulating appearance, reflective of the repetitive channel geobodies, and agree with observations made at outcrop. The minor horizontal variograms of both lithofacies show a slightly undulating appearance, but not as strongly as the major horizontal direction. This reflects the channel stacking pattern observed in the mean palaeoflow direction. However, due to the physiognomy of the outcrop exposure (sub-vertical slopes covered in scree), the vertical direction variogram does not illustrate any variance within the data, as expected. Cleaner and nearly vertical faces are needed to accurately calculate a vertical direction variogram for the study area. These variograms are used to condition the model algorithm used for the pixel-based realisations to approximate the architecture of the study area.

5.6.4 Digital outcrop analysis

The classified DOMs generated in VRGS provides the spatial context required for a further detailed analysis of the facies. The classified point clouds from VRGS were imported into Petrel™ to (i) visualise the spatial distribution of the facies; (ii) examine the facies proportions for the study area and (iii) be used as hard condi-
tioning data for stochastic model realisation generation. A vertical facies analysis of the classified geobodies in Petrel™ reveals a distribution that shows an increase in channel facies vertically the base of the model area (Figure 5.14). This shows a pattern similar to the geobody width distribution generated from the DOM analysis. The final realised model from the conditioned DOMs should produce the most representative reservoir simulation of the fluvial architecture recognised in the La Serreta study area. Discussed below are the various stochastic reservoir simulation techniques used for this study.

5.7 Reservoir modelling techniques

There are two main uses identified for reservoir models:

(i) Provide a 3D digital representation of the hydrocarbon reservoir. New data can be inputted to help maintain and support ongoing lifecycle needs (i.e. volumetric updates, well planning and production forecasting via reservoir simulations.

(ii) Build and maintain a field database with which several fit-for-purpose models can be constructed. These can be used to investigate different scenarios and, in the case of this study, provide a model for visualisation of the channel elements present in the three different axial directions. The database can also provide the resulting geostatistics for each simulation (Ringrose and Bentley, 2014a).

The following sections presents several three-dimensional reconstructions of the study area created in the reservoir modelling package Petrel™. They utilise the results attained from the statistical and geometric analyses of the DOMs, and examine the validity of various stochastic methods to accurately simulate the observed sedimentary architecture for the La Serreta area. The study area presents a near fully three-dimensional representation of the fluvial architecture, providing excellent spatial control of the facies throughout the modelling area. The model realisations and results presented provide an ideal case study for a potential reservoir analogue found in the medial zone of a large DFS in an endorheic basin.
5.7.1 Stochastic facies modelling

In the facies modelling process, several methods can be used to generate facies distribution model realisations (Falivene et al., 2006), including pixel-based Truncated Gaussian Simulation (TGS) and/or Sequential Indicator Simulation (SIS) and object-based stochastic methods. Two different realisations for both pixel-based methods were produced: (i) All of the facies derived from the upscaled sedimentary log; (ii) the calculated in-channel lithofacies (fine sand – very coarse sand) from the upscaled sedimentary logs (Figure 5.15). As expected, they did not accurately reflect the sand body geometry within the study area. Therefore, an object-based approach was chosen as the primary modelling technique because of its ability to reflect and honour sand body geometry and dimensions within a fluvial system.

Figure 5.15: Pixel-based reservoir simulations. (a) SIS realisation illustrating a full model realisation of all recognised lithofacies from upscaled sedimentary logs. (b) Fence diagram of SIS realisation of all lithofacies. (c) SIS realisation of in-channel lithofacies from upscaled sedimentary logs. (d) TGS fence diagram illustrating all recognise lithofacies from upscaled sedimentary logs. (e) TGS fence diagram illustrating in-channel facies recognised from upscaled sedimentary logs.
5.7.1.1 Object-based modelling

In the object-based modelling approach, different shaped objects of varying dimensions are placed into the geocellular model to replace the background facies until a set of conditions are met (e.g. facies proportions, object shape and dimensions) (Falivene et al., 2006) The approach used for this study utilised geostatistics gathered from the upscaled classified DOMs and upscaled sedimentary logs to condition the facies distribution for each respective resultant realisation. The different constraints used in the creation of the object-based models are discussed below.

(i) Body geometry

Petrel™ offers a suite of predefined geobody geometries which can be used to model an array of lithofacies of various genetic origins (i.e. from large-scale fan lobes, to small-scale channels). The adaptive channel body was used to model the sand bodies.

(ii) Facies proportions The facies proportions are directly taken from the in-channel lithofacies derived from the upscaled pseudo-well logs and the classified DOMs. Since the model does not have a clearly defined zone boundary; the object-based modelling was completed as 'one zone.'

(iii) Orientation

The palaeocurrent azimuth distributions were used as primary orientation information. Due to the wide distribution and the number of palaeocurrent data, a truncated Gaussian distribution curve was used as the input definition. One standard deviation from the arithmetic mean (296°) was used as input for the minimum and maximum values.
Fluvial facies dimension and channel geometry

The three groups of corrected sand body widths were used to produce three different model realisations, minimum, maximum and arithmetic (most likely). These values were used as channel width geometry constraints for fluvial channel modelling. Similarly, the minimum, maximum and average sand body thicknesses were used as channel geometry constraints in accordance with the respective sand body widths (i.e. minimum sand body width and minimum sand body thickness). Channel object statistics (i.e. amplitude, wavelength and sinuosity) were acquired from the Atuel DFS, in South-west Argentina South America. This is a modern analogue, proposed by Davidson and Hartley (2014) which best represents the catchment size, climate and equivalent channel geometry of the Huesca DFS.

Six different realisations were generated which reflect the conditioning data from the in-channel lithofacies recognised in upscaled sedimentary logs (Figure 5.16) and classified DOMs (Figure 5.17). Utilising the continuous lateral classified DOM data and combining it with the upscaled pseudo-well logs (Figure 5.18), a third set of models were constructed. The combined conditioning data provides the most realistic geometric and lithofacies constraints to the object models.

5.8 Results and analysis

5.8.1 3D model analysis

Evaluating the quality and accuracy of the sedimentary architecture produced from stochastic realisation can be completed one of two ways: qualitative visual inspection or quantitative approaches (e.g. pseudo-logs through the model, geobody connectivity). Visual qualitative inspection of the different realisations offers a wealth of information but lacks quantitative criteria, which makes the observations subjective. To combat this subjectivity, the visual assessment was quantified by ensuring that observed thicknesses and proportions were comparable to the original outcrop data. Additionally, the lithological component ratio and facies connectivity was compared for all nine simulations to quantify any lithological and/or connectivity change of the different conditioning data constraints. The quantitative method
used for the different realisations provides a more robust set of criteria to analyse the model’s accuracy.

5.8.1.1 Qualitative visual analysis

It is demonstrated that the object-based stochastic simulations generate more clearly defined channel element margins and sharply defined objects compared to the more noisy SIS and TGS realisations. The model realisations derived from the pixel-based methods produced inaccurate representations of the fluvial architecture (Figure 5.15). Even with robust conditioning data from upscaled sedimentary and classified lidar data, the pixel-based modelling techniques do not produce realisations which are conducive to assess sedimentary architecture in fluvial systems.

The object-based simulations for the La Serreta are believed to be the most comparable to observations made in the outcrop exposures in shape and geometry (width and thickness) of the channel elements, and provoke a more detailed visual analysis. The model produced from the upscaled sedimentary log conditioned model yielded results which are geometrically more accurate than pixel-based methods, however the architecture does not represent the observed outcrop architecture. They are an idealised representation of channel objects which might be found in subsurface datasets. The classified DOM conditioned realisations produced a more accurate representation of observed outcrop architecture. However, this approach is biased toward the most prominent sand bodies, as they are not covered by scree or vegetation. These realisations do not include the fine-scale geobodies which are only observed in the sedimentary log data. Conversely, the object-based realisations constrained by the combined conditioning data from the upscaled sedimentary logs and classified DOMS produced the most accurate representation of outcrop sand body architecture. To further test their applicability as potential reservoir models, a quantitative assessment of the facies component percentage and the element connectivity is required of all realisations.
Figure 5.16: In-channel lithofacies identified within upscaled sedimentary log conditioning data. (a) Block model of reservoir model. (b) Minimum geobody widths realisation. (c) Maximum geobody widths realisation. (d) Average of all geobody widths realisation.
Figure 5.17: In-channel lithofacies recognised from upscaled classified DOMs. (a) Block model of reservoir model. (b) Minimum geobody width realisation. (c) Maximum geobody width realisation. (d) Average of all geobody widths realisation.
Figure 5.18: Combined conditioning data from upscaled sedimentary logs and classified DOMs. (a) Block model of reservoir model. Single channel element displays one instance of one realisation of channel object model generation in model simulation. (b) Minimum geobody widths realisation. (c) Maximum geobody widths realisation. (d) Average of all geobody widths realisation.
5.8.1.2 Quantitative analysis

To quantify any lithological change between the different simulations, the connectivity and lithological component ratios were calculated for the object-based simulations as the pixel-based realisations are not representative of the fluvial architecture. The results of the quantitative analyses performed on the model realisations are summarised in Table 5.1.

5.8.1.2.1 Upscaled sedimentary log models

The object model generated from the upscaled sedimentary logs produced lithofacies component and connectivity percentages which closely match the approximated lithofacies ratio calculated from the original logs. The model constrained by the calculated minimum geobody widths demonstrate 59% overbank and 41% in-channel facies component, and 57% overbank and 43% in-channel connectivity. The calculated maximum geobody width model realisation illustrates 56% overbank and 44% in-channel facies component, and 60% overbank and 40% in-channel facies connectivity. Finally, the arithmetic mean reservoir simulation produced 58% overbank and 42% in-channel facies component and 57% overbank and 43% in-channel facies connectivity (Figure 5.19a).

Upscaled sedimentary logs most accurate and representative lithological component in the model realisations. This technique provides the most vertical lithological detail, but it is limited in horizontal connectivity. Thus a more laterally continuous method is required.

5.8.1.2.2 DOM conditioned models

Though the object model realisations generated from the classified DOM produced sand body architecture closer to what is observed at outcrop, the resultant simulations overestimated the overbank component, in turn underestimating the in-channel lithofacies. The model constrained by the calculated minimum geobody widths demonstrate 84% overbank and 16% in-channel facies component and connectivity, respectively. The calculated maximum geobody width model realisation illustrates an 83% overbank and 17% in-channel facies component and connectivity,
respectively. Finally, the arithmetic mean reservoir simulation produced 85% overbank and 15% in-channel facies component and connectivity, respectively (Figure 5.19b).

This technique does produce a more accurate representation of outcrop architecture, it lacks the lithological component and potential connectivity that is calculated from the upscaled sedimentary logs. Thus, a combination of the two conditioning data sources should produce the most accurate reservoir simulation of the La Serreta outcrop analogue.

5.8.1.2.3 Combined DOM and upscaled sedimentary log model

Though the object model realisations generated from the classified DOM produced sand body architecture closer to what is observed at outcrop, the resultant simulations overestimated the overbank component, in turn underestimating the in-channel lithofacies. The model constrained by the calculated minimum geobody widths demonstrate 80% overbank material and 20% in-channel facies component and connectivity, respectively. The calculated maximum geobody width model realisation illustrates a decrease in sand body facies and connectivity to 17%, with 83% overbank. Finally, the arithmetic mean reservoir simulation an overall increase of in-channel lithofacies component and connectivity to 22%, with a remaining 78% of the facies as overbank material (Figure 5.19c).

Combining the conditioning data produces the most accurate representation of the sand body architecture, as well as the in-channel facies connectivity. The approximate lithofacies component percentage is still a biased approximation because it is dependent on outcrop exposure, therefore the overbank and in-channel lithofacies are over and underrepresented, respectively. However, this simulation is suggested to be the most accurate reservoir simulation from outcrop data.
Table 5.1: Lithofacies component and connectivity percentage

<table>
<thead>
<tr>
<th>Sedimentary Log</th>
<th>DOM</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Connectivity %</td>
<td>Facies %</td>
</tr>
<tr>
<td>Overbank</td>
<td>57.11</td>
<td>58.58</td>
</tr>
<tr>
<td>In-channel facies</td>
<td>42.89</td>
<td>41.42</td>
</tr>
</tbody>
</table>

| Max Geobody Widths |
|---------------------|------------------|------------------|------------------|
| Sedimentary Log     | DOM              | Combined         |
|                     | Connectivity %   | Facies %         | Connectivity %   | Facies %         | Connectivity % | Facies % |
| Overbank            | 60.15            | 56.23            | Overbank         | 83.17            | 83.21          | Overbank         | 82.77          | 82.79 |
| In-channel facies   | 39.85            | 43.77            | In-channel facies | 16.83            | 16.79          | In-channel facies | 17.23          | 17.21 |

| Average Geobody Widths |
|-------------------------|------------------|------------------|------------------|
| Sedimentary Log         | DOM              | Combined         |
|                         | Connectivity %   | Facies %         | Connectivity %   | Facies %         | Connectivity % | Facies % |
| Overbank                | 57.22            | 58.36            | Overbank         | 84.53            | 84.55          | Overbank         | 78              | 78.02 |
| In-channel facies       | 42.78            | 41.64            | In-channel facies | 15.47            | 15.45          | In-channel facies | 22              | 21.98 |
Figure 5.19: Static volume connectivity of three different reservoir simulations. (a) Up-scaled sedimentary log conditioned model. (b) Classified DOM conditioned model. (c) Combined conditioning data model. Volume 0 represents overbank material. Volume 1 & 2 represent in-channel facies.
5.9 Summary and discussion

The increased use of DOMs as outcrop analogues over the past decade, and the inherent quantitative nature of the datasets, has allowed more accurate analyses of mesoscale sedimentary system architecture. This in turn creates a more detailed geostatistical database that can be used in reservoir simulation studies (Howell et al., 2014). The reproduction of more accurate sedimentary system architecture and geometries from the DOMs requires an increased use of hard conditioning data. VRGS allows discreet elements to be classified, based on a chosen classification scheme, within the DOMs, which can be utilised as a set of hard conditioning parameters in the geostatistical database when construction geological model simulations.

5.9.1 Modelling fluvial architecture

An accurate representation of the architecture in any sedimentary system is essential for accurately predicting distribution of porosity and permeability properties, any baffle or barrier locations, and approximate flow performance and directional trends in subsurface reservoirs. In order to model these properties appropriately, the proper scale at which to resolve the approximate architecture, geometry and ultimately connectivity of the sand bodies for the depositional system must be chosen carefully (Graham et al., 2015). The data available from 1D boreholes and well log instruments produces essential formation information through advanced imaging and data analysis techniques (e.g. Formation Micro-Imaging). However the spatial distance is too great between wells, and the spatial resolution is too coarse even with high resolution and accurately processed 3D seismic surveys, to properly reconstruct the mesoscopic sedimentary architecture of fluvial sand bodies (Bridge and Tye, 2000; Olariu et al., 2011). Since fluvial sedimentary bodies are orientation dependent (e.g. palaeoflow azimuths), accurate approximation of their individual widths and thicknesses are dependent on knowledge and integration of the azimuth measurements (Bryant and Flint, 1993; Cuevas G. and Martinius, 1993). The reservoir simulations produced from this study demonstrate the advantages from data integration of 1D well log and continuous 3D classified data.
5.9.1.1 Reservoir model simulation accuracy and efficacy from lidar data

Of all of the stochastic reservoir simulations tested, the object-based methodology proved to be the most accurate for producing realistic fluvial geometries and architecture. Within those models, the models conditioned to the upscaled sedimentary log data illustrate the most accurate lithological component for the study area. The logs offer the highest resolution data, and is not biased to outcrop exposure. Conversely, the classified DOM data is biased to the outcrop exposure by underrepresenting the total in-channel facies, leaving the overbank material as the predominant lithofacies type simulated. However, the DOM conditioning data did allow for increased geometric representation of the fluvial architecture. With this in mind, a combination of the two conditioning data types produces the most accurate in-channel lithofacies connectivity and sand body architecture of the realisations.

There is a decrease in channel facies connectivity from the minimum geobody widths to the maximum geobody widths of 3%. This is suggested to be a product of a larger number of small channels to accommodate the lithofacies percentage condition. Due to the high number of channels present within the modelling grid, they will undoubtedly connect vertically and laterally. Conversely, the larger the channels, like those within the maximum geobody width models, will be not need to be generated as often to accommodate the input lithofacies component. This will reduce the chance that they will connect within the modelling grid. However, the average (most likely) calculated in-channel lithofacies connectivity illustrates the highest ratio of all of the combined realisations. The fact that this conditioning data is an average of the minimum and maximum, it stands to reason that there will be a high number of small channels created while at the same time coevally wide channels are created. These channels will connect more often throughout the modelling volume than the other two previously combined. The resultant model is a representation of a bimodal distribution of channel facies, with a high population of small channels and large channels, with minimal medium-sized channels created.

A detailed understanding of lithofacies connectivity within a reservoir volume is integral to accurate calculation of static connecting, maximising potential hydro-
carbon recovery. Accurate identification of the reservoir type and quality is critical to understand the dynamic connectivity when attempting to recover the in-place hydrocarbons (Snedden et al., 2007). The largest connected volumes will inherently increase the potential recovery factor when a reservoir volume is swept. The models presented here demonstrate the potential sand body architecture and static connectivity of a well-studied fluvial hydrocarbon reservoir analogue. Moreover, the different modelling techniques produce lithological component and facies connectivity results which differ greatly from one to another (i.e. sedimentary log connectivity – 3D lidar connectivity). Since outcrops are consistently used as subsurface analogues, the differences described here have implications for how data should be collected, and analysed from outcrop studies. These implications must be considered in order to gain a more complete understanding of dynamic connectivity during the recovery process. It is important that reservoir geologists carefully consider the type of data which is collected from outcrop, and the limitations and/or over-simplification of the geology in the reservoir model.

However, even with the combined conditioning datasets, it is clear that model accuracy is dependent on the level and degree of exposure. Regardless, combining high-resolution sedimentary logs and continuous 3D DOM datasets, the resultant reservoir simulations show a promising method to reproduce accurate sedimentary architecture and lithofacies connectivity from outcrop analogues. This will in turn allow increased accuracy in volumetric analysis of the lithological components and static connectivity across a study area. With this in mind, we suggest that a combination of 3D digital outcrop and traditional sedimentological data collection and analysis techniques provide the most accurate and robust dataset to model reservoir architecture and behaviour. The uncertainties encountered in this approach are discussed in the next section.

5.9.2 Modelling uncertainties

Reservoir heterogeneity and anisotropy are strongly influenced by sandstone facies and facies distribution (Alexander, 1993), it is therefore important to consider: (i) the type of outcrop which will be used as an analogue for the subsurface (i.e.
comparable depositional environment including sediment transport capacity and availability, comparable tectonic and palaeoclimate conditions), (ii) the scale of the features which will be represented in the model and the correct tools to collect the necessary data and (iii) the type of modelling and simulation procedure which will be used.

The study presented here addresses the type of outcrop used for the analogue because it is a well-studied fluvial reservoir analogue, and is exposed at an appropriate scale for digital data acquisition and 3D outcrop modelling techniques to investigate heterogeneity in the rocks. Additionally, a modern analogue has been proposed by other workers (i.e. Davidson and Hartley, 2014), which was used in this study to gather necessary channel statistics for the object-based modelling procedure. Furthermore, the methodology used for this study has been adapted from previous workers (e.g. Fabuel-Perez et al., 2009; Van Lanen et al., 2009; Fabuel-Perez et al., 2010; Rarity et al., 2013) to increase the accuracy of the input data to better honour the observed outcrop geology. However, there still remains uncertainties related to the steps taken in the modelling work flow which need to be addressed when analysing the results of the reservoir simulations. These work flow uncertainties can be grouped into three different types:

(i) **Uncertainties related to processing errors when creating the DOMs.**

These errors include misalignment of scan positions within the study area, DGNSS processing errors when positioning the scan positions, decimation of the triangulated mesh and inaccurate registration of the coloured photographs onto the DOMs. Interpretation errors can arise based on these misalignment practices throughout the model. These errors are believed to be minimal for this study as all of the data integrated together was quality checked for optimum accuracy. This was done using ground-truthed data (field observations in sedimentary logs) and continual post-processing techniques (i.e. least squares adjustment for photograph registration, DGNSS correction) to ensure the DOM results were as accurate as possible.
(ii) **Uncertainties associated with the geostatistics acquired from the modern analogue used in this study.** The Atuel DFS, proposed to be the closest modern equivalent to the Oligo-Miocene Huesca DFS in climatic regime, palaeo-drainage and basin catchment size, was chosen based on a regression analysis of its characteristics. These produced generally a good agreement between the estimated values and planform type recognised for the Huesca system. It is however only a predictive relationship, and will not reflect exact palaeo-drainage patterns and/or planform geometry. With this in mind, care must be taken when using modern analogues to collect channel geometry statistics, as the geometries will undoubtedly be different from the ancient analogue.

(iii) **Uncertainties related to estimation of lateral facies distribution.** Even though the classified lidar provides a large geostatistical database of lithofacies components from the DOMs across a large spatial extent in the study area, it does not allow complete 3D coverage. Additionally, the over-bank facies in the study area are covered by highly vegetated scree slopes, skewing the lithofacies analysis in the material surrounding the channel sands. The approach taken during this study to minimise this effect was to use a combination of modern analogue geostatistics coupled with the classified point clouds and sedimentary logs to reduce the lateral distance between lithofacies data points. Furthermore, the creation of multiple realisations with different seed numbers is an additional method to reduce this effect. However even with the combination of data sources, uncertainty will always remain as there is insufficient data to constrain the model to a full three-dimensions across the modelling grid to condition the lithofacies presented in the model with exact certainty.

(iv) **Uncertainties related to data collection from fluvial outcrops.** Martinius and Naess (2005) outline the inherent problems when collecting essential data from fluvial outcrops which may affect object-based stochastic simulation studies. A significant uncertainty which needs to be considered from their
study is the number of accurate observations made of sandstone body dimensions and their true probability distribution, in accordance with the reliability of palaeoflow directions measured from the outcrop sedimentary structures (Martinius and Naess, 2005).

5.10 Concluding remarks

The main objective of this study was to characterise and model the fluvial architecture of the medial zone of a large DFS. To accurately characterise the channel geometries of a DFS, traditional qualitative observations and interpretations made from outcrop studies were integrated with a digital field study (e.g. DGNSS, lidar) of over 2 km$^2$ of outcrop exposure of the Oligocene – Miocene Huesca DFS. The integration of spatial and traditional outcrop data (e.g. sedimentary logs) into DOMs allowed the construction of high-resolution geocellular outcrop models, and quantification of the geometric and architectural elements of three different radial locations (derived from modern analogues) in the DFS model. These different realisations allowed a quantitative investigation of the channel geometries and connectivity in a small reservoir-sized model, to test the efficacy of using these techniques to build more accurate reservoir models of distributive fluvial systems.

The work flow presented here allowed a detailed quantitative analysis of the channel sand bodies of the DOMs and a direct integration with a pre-existing geostatistical database. Even though the major channel sand bodies (i.e. multi-storey and single-storey sand bodies) are well exposed in outcrop, the detail in overbank material recognised in the sedimentary logs is underrepresented in the classified DOM data. This caused a misrepresentation of the lithological components in the DOM conditioned realisations. However, a combination of upscaled sedimentary log and DOM conditioning data, produces the most accurate geometric and lithological connectivity reservoir simulations. It is suggested that the laterally continuous and 3D classified data, and subsequent geobody analysis (i.e. width v. thickness relationships), integrated with sedimentary logs produce accurate subsurface reservoir simulations from outcrop. The methods presented here further exemplify the necessity for increased collection and analysis of hard conditioning data when analysing
outcrops as subsurface analogues.

Finally, the model results presented here demonstrate a novel use of digital outcrop datasets to constrain an outcrop recognised as a potential reservoir analogue. As this study was undertaken in a small area of the Oligocene – Miocene Huesca DFS, it is suggested that further work is needed to collect additional 3D spatial data for other outcrops of the system in order to produce the most accurate fluvial and reservoir model.
5.11 References


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Section 4

Synthesis and Concluding Remarks
Chapter 6
Chapter 6
Discussion and implications

This chapter synthesises key results and conclusions and discusses implications of the use of quantitative methods to improve characterisation and analysis of fluvial geometries and architecture in siliciclastic depositional systems. The uncertainties recognised throughout the studies are discussed and their implication to depositional model refinement.

6.1 Introduction

This study focuses on the application of digital surveying techniques, in particular lidar combined with DGNSS, to quantitatively characterise and analyse the fluvial geometries and architecture of two different localities: (i) the medial portion of a large fluvial fan, and (ii) the major sand bodies present in a fluvio-deltaic system. The central aims of the studies were to develop 3D characterisation techniques and a robust workflow that can be used to obtain quantitative geostatistical information about the fluvial architecture (internal and external) of the fluvial elements present in each study locality. The methods discussed in the two research chapters (Chapters 3 and 4) can be used as effective characterisation techniques for reservoir modelling practices, and have been used in the third research chapter to address the La Serreta section (Chapter 5). The following chapter sections discuss the wider implications of the methodology presented to fluvial sedimentology, in particular to a refinement of the Huesca DFS conceptual depositional model, and architectural trends observed in the fluvio-deltaic Breathitt Group with a link to a larger depositional control on the system.
6.2 Spatial analysis

One of the primary aims of the PhD was to quantitatively analyse the efficacy of using the DOMs as analytical datasets for accurate description of key components within the La Serreta section and the Pikeville and Hyden Fms. Outcrop studies allow geoscientists to assess depositional elements, which range in scale from a few centimetres (e.g. small-scale features such as ripple cross-lamination, mud drapes) to kilometres long exposures to obtain large-scale geometric information. Regardless of the scale, it is important to relate all of the acquired information into a spatial context to analyse any observable trends in the data. This inherently lead to the use of the Geobody Mapping tool and subsequent analysis discussed in Chapter 3 to spatially map and classify the sand bodies (by facies association) found in the medial portion of the Huesca DFS. The integration of qualitative and semi-quantitative information (i.e. sedimentary log information including grain size analysis, palaeocurrent directions, bedding structures) with the DOMs, has allowed an insight into the distribution of sand body width versus thickness ratios for the La Serreta section. Likewise, the results presented in Chapter 4 demonstrate that even with limited 2D outcrops, depositional controls on a fluvial profile can be determined through statistical spatial analysis (i.e. up-dip to down-dip) of the architecture of major sand bodies. By characterising sand body thickness, storey height, storey contact distance from the base of the sand body and its respective contact length for each sand unit, it is possible to evaluate the potential depositional controls for the Pikeville and Hyden Formations.

6.2.1 La Serreta results

Previous analysis of the sand body geometries in the study area completed by Hirst, (1991) were used in the exhaustive study by Gibling (2006) to collate the widths and thicknesses of different fluvial sand bodies. In Chapter 3 the quantitative measurements made from DOMs using the adapted Geobody Measuring tool available in Virtual Reality Geology Studio (VRGS) provide more precise geometric sand body measurements which further expand the envelopes presented for this system (Figure 6.1).
The study demonstrates a 4 m difference (from 12 m Hirst (1991) to 16 m (this study) = 33% increase) in the thickest observed sand body. There is also a reduction in the widest observed sand body of 100 m (from 650 m Hirst (1991) to 550 m (this study) = 15% decrease). The quantitative nature of this study compared with the Hirst (1991) study is the significant advantage gained by having a 3D spatially controlled dataset offering 20 cm resolution of the fluvial elements in question. Because of this spatial distinction, each sand body was placed into stratigraphic context, enabling temporal differences in sand body width to be analysed. The data demonstrate an increase in sand body width up through the stratigraphy before a relatively sharp decrease near the top of the section (Figure 6.2b). As described in Chapter 5, the classified point clouds, which were imported into the reservoir modelling software package Petrel as discrete elements, were used to generate a vertical lithofacies proportion analysis of the recognised sand bodies against a background facies (i.e. overbank material). The analysis illustrates an increase in net to gross vertically through the section, comparable to the same trend observed in the sand body thickness plot (Figure 6.2a). Fifteen sedimentary logs for the La Serreta study area section were used to compute a proportional analysis of the in-channel component versus overbank material. This builds upon a study by Hirst (1991), to determine any trends which might correlate to the increase in sand body widths and lithofacies. The in-channel components in this study refer to lithofacies that are fine sand to gravel in grain size. The percentage of each lithofacies component (Figure 6.3) were calculated for each log across the study area. The calculated percentages match closely with a similar sand to silt ratio proposed by Donselaar and Schmidt (2005), but shows a 22% increase compared to the study by Hirst (1991).

These results, plotted on a graph comparable to the one created by Hirst (1991), identify a modification to the distribution of the in-channel sands within the medial to distal portion of the system (Figure 6.4). The 46% in-channel component calculated from the DOM analysis shows an increased amount of channel sands within the 45 km radial position from the apex (Figure 6.4b). The overall trend of the data is comparable to the previous interpretation of the Huesca, and demonstrates the
downstream reduction in grain size as predicted by the DFS model, due to loss of stream power, channel bifurcation and/or increased unconfined flow events (Nichols and Fisher, 2007; Weissmann et al., 2013; Owen et al., 2015). These revised sand body widths and thickness distribution provides improved understanding of the depositional architecture found in this section of the Huesca DFS.
Figure 6.1: Corrected geobody to true width vs thickness distribution on log – log scale.
Figure 6.2: (a) Calculated lithofacies percentage from the classified DOMs. (b) Sand body widths vertically through section demonstrates the increase in width until before broad gradual decrease near the top of the section.
Figure 6.3: (a) Corrected geobody to true width vs thickness distribution on log – log scale. (b) Input sedimentary log data and calculated probability curve derived from the classified DOMs. (c) Sand body widths vertically through section demonstrate the increase in width until the top of the section.

Figure 6.4: Variation in proportion of in-channel sediments from medial to distal position within the Huesca DFS. Shaded gradient illustrates transition from medial to distal location. (a) Original plots of variation in in-channel lithofacies proportion from the medial to distal portion of the Huesca DFS (Modified from Hirst, 1991) (b) Modified in-channel lithofacies proportion from this study, from the medial to distal portion. In-channel percentage calculated from DOM analysis (red square). This illustrates the increase (22%) of in-channel component.
The Huesca DFS was interpreted as a radial distributive system based on palaeocurrents taken from various localities around the system (Hirst and Nichols, 1986; Jupp et al., 1987; Nichols, 1987; Hirst, 1991; Nichols, 2007; Fisher and Nichols, 2013). In addition to the radial dispersive pattern from an apex, a downstream change in channel size was observed and, also demonstrates a downstream decrease in the grain size (increase in overbank material to in-channel deposits).

The in-channel component calculated by Hirst (1991) from various sections in the Huesca system were spatially plotted and contoured at 10% intervals. The results from the DOM analysis were also plotted to determine trends (Figure 6.4), and illustrate a change in the trend of channel deposition through time from what has been previously published. There is an increased proportion of in-channel component to the west, which follows the general trend of a westerly to south-westerly palaeoflow of the Huesca system (Hirst and Nichols, 1986; Nichols and Hirst, 1998).

The distributary pattern for the Huesca was previously interpreted to be controlled through continual avulsion across the alluvial plain (Nichols, 2007). This process created the approximate fan shape of the system, and is fundamental to the DFS model, which predicts the avulsion creates depositional 'lobes' at various times in the life of the system. The controls of avulsion for the Huesca DFS are not known, but are thought to be a combination of two factors: (i) a variable discharge and a decrease in downstream discharge and (ii) a reduction of in-channel load capacity, most likely from a high sediment to water discharge ratio, causing an increase in the rate of deposition (Kulikova, 2013). Additionally, the types of avulsion for the Huesca are unknown, but are suggested to be regional, which create individual active depositional lobes across the entire DFS, with local or nodal avulsions occurring throughout the depositional lobe (Slingerland and Smith, 2004; Weissmann et al., 2013).

The location of the measured section in this study, within the medial zone on the westerly trending system, suggests it should be prone to preserve evidence of a depositional lobe. The switch of the lobes to the westerly – south-westerly direction
(including the La Serreta section in it) is most likely from a regional avulsion event. The site of the avulsion event would be in the proximal zone, and would have been eroded out and reworked by in situ channels.

6.2.2.1 Channel sand body distribution control

The increase of in-channel components and the width of preserved sand bodies recognised in the La Serreta section suggest that this region saw an influx of sediment most likely due to avulsion processes. The presence of an abnormally thick sand body (i.e. 14 m), comprised of multiple storeys (6), which is above the average (2-3), and implies increased sediment supply and channel activity at this locality. Additionally, the majority of the thickest sand bodies seem to be restricted to one region of the section, equating to an area of 249 m². The controls for the presence of this abnormally thick sand body and deposition of the thickest sand bodies to this area are uncertain (i.e. allogenic vs autogenic). However, a few interpretations can be considered, including:

(i) Geomorphic control: increased sand deposition caused by a regional avulsion event randomly switching the depositional lobe preferentially to this area. This produced a major channel-belt to flow in the westerly direction, with contemporaneous smaller distributaries bifurcating from the main channel across the flood plain. Additionally, the thickest and most internally complex sand body, could be the product of a nodal avulsion event further upstream (Cain and Mountney, 2009).

(ii) Tectonic control: uplift of the hinterland related to the compressional tectonics producing a large influx of sediment deposited through the system and change in the longitudinal river profile. This increased sedimentation in the active channels and channel belts (braided or highly sinuous meandering) could have created the large number of storeys recognised (Holbrook and Schumm, 1999).

(iii) Climatic shift: from drier to wetter conditions, causing increased degradation in the hinterland and contemporaneous increased deposition rates in the fluvial system.
In order to check the causality for each respective depositional events, a similar time signature (i.e. palaeosol marker-bed, increased grain size in the deposits) would have to be correlated across the system. However, the continual cut-and-fill process causes any correlatable surfaces to be eroded away whenever the floodplain is occupied by another channel or other fluvial element (i.e. crevasse splay, chute channel). In the La Serreta study area palaeosols are rarely observed laterally more than tens of metres. Any time-equivalent evidence of increased denudation in the hinterland (by climate or tectonic) cannot be correlatable to the medial zone, due to the aforementioned cut-and-fill processes.

Previous case studies demonstrate evidence for the various avulsion styles (regional, nodal and local) found in fluvial fan systems (Cain and Mountney, 2009; Kulikova, 2013). Therefore, it is suggested that the overall increase in sediment to the La Serreta area is due to a regional avulsion of the active depositional lobe to the westerly – south-westerly direction. The contour map (Figure 6.4) showing the spatial location of study areas and their respective observed in-channel component proportions, provides further evidence for possible regional avulsion events producing depositional lobes on the fluvial fan. The contour map shows the west – south-westerly trend of the possible depositional lobe. Furthermore, the thickest sand body is suggested to be a product of a nodal avulsion further upstream from the La Serreta area. (Figure 6.5).

These interpretations do not contest the previous Huesca DFS interpretations; it serves as a proxy to constrain the DFS depositional model by affirming through quantitative observations, that the effects of regional, compounded with nodal avulsions, are possible and likely in the Huesca DFS. If these models are to be used to predict fluvial architecture distribution, and ultimately to help build improved reservoir models, the results of this study suggest a simple "fan-shaped" model with equal lithofacies representation is not accurate for all DFSs, even ones which deposit within an endorheic basin. Increased understanding of the roles of avulsion events within a DFS are key to accurately predicting subsurface sand body architecture. Moreover, detailed quantitative analyses must be completed on current outcrops pre-
Figure 6.5: Approximate facies component percentage spatial trend contour map showing similar westerly trend of interpreted in-channel component facies, denoting a possible depositional lobe creating a thoroughfare for channel belts to occupy during deposition.

6.2.3 Pikeville and Hyden sand body characterisation

The Breathitt Group (Pikeville and Hyden Fms) represents an ideal case study to apply 3D quantitative characterisation and analysis techniques from DOMs of the outcrops to quantitatively distinguish palaeovalley fills from stacked distributary channel sand bodies, and determine potential depositional controls based on their respective architecture. Moreover, the study presented in this thesis (Chapter 4) offered the opportunity to address a significant challenge encountered when analysing sand bodies at outcrop, that often the geometry of the sand bodies is greater than the scale of exposure. Because of the scale of the sand bodies and the physiognomy of the exposure, it is difficult to reliably discriminate between palaeovalley-fills and stacked distributary channel-fills at outcrop. Their thicknesses may be similar up-dip to down-dip, and often palaeovalleys do not display a 'basinalward facies shift,' making it difficult to discriminate between them. This distinction

sented as DFS analogues to understand thickness changes and controls (autogenic and allogenic) on these systems.
is integral to accurate prediction of palaeogeography, sequence stratigraphy and subsurface hydrocarbon reservoir geometry. A quantitative understanding of the basin-wide architecture of the sand bodies, and their relationship to genetic origin, was the primary focus of this study.

6.2.4 Pikeville and Hyden results

Results

From the analysis, the sand bodies displayed size and thickness distribution that conforms to the model for stacked distributaries. They were either not present or significantly decreased in thickness down-dip, and also displayed a decrease in storey height. The position of storey contacts relative to the base of the sand bodies remained high across the basin. The sand bodies interpreted as palaeovalleys also demonstrate a similar decrease in sand body thickness and storey height, though to a lesser degree. However, the position of storey contacts relative to the base of the sand
bodies in palaeovalleys are closer to the base. Relative to sand body thickness this was consistent up-dip to down-dip. Average storey contact lengths increase down-dip in sand bodies interpreted as stacked distributaries, and decreased in length in sand bodies interpreted as palaeovalleys. The highest number and longest storey contacts observed in the study were recognised in down-dip sand bodies interpreted as palaeovalleys. The results are summarised in a schematic below (Figure 6.6).

**Interpretation**

From the sand body thickness and storey height metrics, it could be interpreted that both sand body types are products of a distributive process. The thickness of storeys reflects a combination of the original channel bankfull depth, and subsequent truncation by overlying storeys, and it is difficult to distinguish between these. However, by analysing the position of storey contacts relative to the base of the sand body, different depositional processes of the sand bodies are suggested. The fact that the average position of storey contacts in palaeovalley fills is lower than in stacked distributive channels suggests that the reduced thickness of the storeys in palaeovalley-fills is associated with greater truncation of the lower storeys. This is compatible with the notion that storeys comprising palaeovalleys are formed during a combination of degradation and aggradation (Blum et al., 2013), whereas stacked distributary channels are fundamentally aggradation to progradational features (Hartley et al., 2010; Weissmann et al., 2013). Aside from a few studies which discuss scour lengths and depths of channels in flume tank studies and those in seismic, (e.g. Sheets et al., 2007; Snedden, 2013), the preservation of the scours in outcrop scale remains unclear. Thus, the exact interpretation or relevance of the length of storey contacts in this study require further analysis to quantifiably determine its exact relevance in outcrop and statistical significance in digital outcrop studies.

### 6.2.4.1 Pikeville and Hyden Formation sand body control

The trends documented in this study support the previous interpretations that the Pikeville and Hyden Formations contain major fluvial sand bodies of stacked distributaries and palaeovalleys. The depositional controls on sand body architecture
are complex, but are suggested to be a combination of abnormally high subsidence rates across the basin, coupled with fluvial system aggradation and progradation (i.e. DFS) followed by degradation and incision (i.e. palaeovalleys).

Continued thrust sheet emplacement along the Laurasian continental margin during the Middle Carboniferous, caused crustal loading and flexural subsidence across the cratonic shelf, which resulted in differing subsidence rates across the basin (Quinlan and Beaumont, 1984; Tankard, 1986). Throughout the depositional history of the Pikeville and Hyden formations within the Breathitt Group, the different subsidence rates (up-dip: >150 m/Ma, down-dip: <30 m/Ma) allowed the thickest deposits to accumulate up-dip before thinning or disappearing completely down-dip (Jerrett et al., 2016), irrespective of genetic origin. The different subsidence rates are suggested to be the primary control on sand external sand body architecture (i.e. thickness and storey height) for the Pikeville and Hyden Fms.

The quantitative architectural analysis techniques described here provide a methodology for characterising bulk trends of internal and external architectural elements recognised across a basin. Since a 'basinward facies shift' criteria is not recognised in many palaeovalleys, especially when sand body geometry extends beyond outcrop scale, the methods described here demonstrate their applicability to quantitatively discriminate between stacked distributary and palaeovalley-fill sand bodies. However, further work is required to acquire higher-resolution spatial photographic information (i.e. photogrammetry, gigapan integration with lidar) to examine small-scale (i.e. < 10 cm) heterogeneities and architecture.

6.3 Implications to improved reservoir characterisation and modelling

Accurate representation of the 3D sedimentary architecture at sub-metre scales is integral for approximating flow performance prediction (baffle and barrier locations, petrophysical property distribution) in subsurface reservoirs (Olariu et al., 2011). In order to model these properties appropriately, the proper scale at which to resolve the approximate architecture, geometry and ultimately connectivity of the sand bodies for the depositional system must be chosen carefully (Graham et al., 2015). The results presented in this thesis demonstrate the efficacy of DOMs
to acquire quantitative information and geostatistics required to build an accurate geodatabase which could house all of the aforementioned data.

6.3.1 La Serreta fluvial architecture modelling

The La Serreta geocellular model and reservoir simulation (Chapter 5) was produced from an adaptation of a workflow by previous workers (e.g. Fabuel-Perez et al., 2009; Van Lanen, 2010). The advancement of the Geobody Mapping available in VRGS allowed accurate and discreet classification of the sand body geometry and its lithofacies component of the La Serreta section. The classified point cloud integrated with the detailed sedimentary logs used as 'pseudo-well logs' provides a
robust dataset of the spatial variability of lithofacies. These are crucial parameters considered necessary to accurately model the facies distribution (vertically and laterally) throughout the resultant reservoir model (Falivene et al., 2006). This allows proper conditioning of the deterministic and stochastic models by constraining the model through increased hard conditioning data.

Since fluvial sedimentary bodies are orientation dependent (e.g. palaeoflow azimuths), accurate approximation of their individual widths and thicknesses are dependent on knowledge and integration of the azimuth measurements (Bryant and Flint, 1993; Cuevas G. and Martinius, 1993). Therefore, modern analogue channel geometry statistics (i.e. amplitude, wavelength and sinuosity) were used to condition all of the object-based models created in the study. The limitations of using a modern analogue is that it represents an instantaneous view of a single channel, or channels, but does not represent the true planview geometry of what is seen at outcrop, channel-fill elements. This was taken into account when the reservoir simulations were created using stochastic and object-based approaches.

Stochastic object-based reservoir simulations constrained by the DOM and up-scaled sedimentary log data proved to be the most accurate for reproducing realistic fluvial geometries and architecture for the La Serreta model (see Chapter 5). However, the static connectivity and lithological component percentages calculated from the object-based models conditioned by the upscaled sedimentary log data is suggested to be the most accurate representation. This makes it clear that even with the use of continuous 3D outcrop information (i.e. classified lidar data), model accuracy is dependent on the level and degree of exposure. Therefore, it is suggested continued use of qualitative sedimentary log information integrated with continuous 3D lidar data remains the best approach to accurately characterising and modelling fluvial architecture.

The final reservoir model of the section offers a more accurate representation of sand body geometry, architecture and potential reservoir connectivity for the medial zone of a DFS, than is normally achievable through standard subsurface modelling methods. The integration methods presented in the study demonstrate a promising
method to reproduce accurate sedimentary architecture, and an improvement over traditional approaches to reservoir modelling.

### 6.3.2 Breathitt Group reservoir potential

The depositional controls presented in Chapter 4 have wider implications to basin-scale reservoir heterogeneity of palaeovalleys and distributary sand bodies in similar foreland basin settings. The extent of palaeovalley-fill sand bodies, their complex internal heterogeneity and their relationship with hydrocarbon recovery has been studied extensively (e.g. Miall, 1988; Wood and Hopkins, 1992; Batson and Gibling, 2002; Kvale and Archer, 2007). However, the advent of the DFS model as an explanation for previously interpreted sandstone units as palaeovalleys which are substantially thick up-dip, and disappear down-dip in the Breathitt Group, provides new insight into foreland basin deposition and evolution (Jerrett et al., 2016). The study presented in this thesis only touches on the type of architectural information attainable from 3D DOMs across a basin. Even so, the study invokes a necessity to acquire more high-resolution data to analyse the internal architecture of the sand bodies, and the relationship to the processes and sand body architecture presented here, thus providing potential system-wide constraint on reservoir heterogeneity.

### 6.4 Key challenges and limitations

There are limitations inherent to the type of information which can be collected from the outcrop exposures both by digital and traditional means, as well as the techniques and survey systems used to collect, construct and analyse the resultant DOMs and reservoir models. This section outlines the most common challenge associated with outcrop studies, and the required analysis techniques which were adapted for each study to approximate accurate geostatistics.

#### 6.4.1 Outcrop scale and exposure

It has been shown through Chapters 3 and 4 that the scale and exposure level of the outcrop are important factors which need to be considered before any survey and analysis is to be done. Two different outcrop exposures types were studied to determine not only the efficacy of using digital outcrop techniques to accurately
characterise fluvial geometries, but also served as different platforms (i.e. nearly full 3D exposure in La Serreta versus 2D road-cuts in the Breathitt Group) to test and modify the methodology used to extract the most accurate geostatistics from the DOMs.

6.4.2 La Serreta section

Even with the amphitheatre style of exposure in the La Serreta study area, the ever-present problem of calculating the true sand body width and thickness versus the apparent width and thickness observed at outcrop depending on orientation, remains a major challenge. Without a full 3D view of the outcrop, true channel width measurement is impossible. To overcome this, a technique introduced by Fabuel-Perez et al. (2009) was adapted here to include the creation of a probability distribution function (PDF) used to calculate the true width of the sand body from the palaeocurrents observed in the field (Chapter 3). This technique demonstrated that over-estimation of sand body width for the La Serreta study was common (i.e. 15% difference) through traditional 2D methods (i.e. photo-panel interpolation). This has implications for sand body recognition in the rock record of other DFSs, as well as net-to-gross estimation in reservoir analogues.

Even though this technique overcomes many of the limitations to approximate the true channel body width, and provides a quantitative database which can be used to constrain the distribution of channel body sizes, it still does not replace the necessity for qualitative data collection in the field. Detailed facies analysis is required in some cases to approximate any trends (i.e. fining-up, coarsening-up) or the exact number of recognised vertical storeys present, which is only obtainable for field logs and analysis.

6.4.3 Breathitt Group succession

The sand bodies recognised within the Breathitt Group were initially analysed to potentially determine their true sand body width and thickness ratio distribution across the basin, however due to the physiognomy of the exposures, it became apparent that this was not possible. Which highlights another critical component when studying outcrops to as analogues for modern and subsurface reservoirs, es-
pecially large 2D road-cuts, such as those found in eastern Kentucky. Because of
the limited 3D control at each location, a larger scale study must be completed us-
ing regional data to determine potential basin-wide trends. Additionally, the types
of analyses necessary to discriminate between sand body types (i.e. stacked dis-
tributary channel-fill vs. palaeovalley-fill) could only be achievable with the spatial
extent of the DOMs used. The scale of this study (80 km from up-dip to down-dip
sections), compared with the La Serreta study, illustrates the method adaptation
required when using 3D quantitative information to analyse outcrops at large scales
(i.e. kilometres).

6.4.4 Limitations of digital survey and analysis techniques

Equipment Logistics

High-resolution survey equipment used for the studies is costly, and continues
to rise as the technology advances, producing lighter, faster acquisition and more
versatile laser scanners. This causes users to typically retain the TLS equipment
they have, which can be quite heavy (22 kg) to carry long distances, or traverse
challenging terrain, as is usually the case with outcrop exposure work. Additionally,
shipping this type of equipment is costly and often difficult to clear customs in some
countries or territories.

Data collection and processing time

Digital outcrop datasets can be labour intensive both on the acquisition and
post-processing end. On top of the digital data collection time in the field, additional
qualitative information is collected (e.g. sedimentary logs), adding to the total time
required in the field. For example, the La Serreta dataset consisted of 33 lidar scan
stations, taking over 20 field days to collect and several weeks of additional work
to spatially align and post-process the greater than 120 million point cloud dataset
back in the office. Furthermore, the DGNSS equipment and processing methods and
algorithms used will produce inaccurate spatial positioning of the final dataset, so
care must be taken to ensure accurate and precise measurements are recorded. This
can be achieved by occupying each position for long periods of time, and choosing
nearby base stations to post-process the data.
Visualisation and resolution

The visualisation and subsequent interpretation of large digital outcrop datasets in real-time is problematic in terms of computing power required, especially with point clouds in the 100s of millions points. The RGB information translated onto the point clouds adds an additional workload to the GPU and processor of a desktop machine. The ability to filter the point clouds, as well as creating photorealistic surface models from the RGB photographs allows further decimation of the required visualisation power without losing the spatial information inherent to the DOM (Xu et al., 2000; Bellian et al., 2005; Thurmond et al., 2006). However, as with any data filtering, reduction, surface meshing and photo-texturing, care must be taken in the methods used to interpret and interpolate the features present in the DOMs, as errors will propagate throughout the model the further away the visualisation is from the raw data.

Digital Outcrop Model analytical techniques and workflows

Interpretation and interpolation of sedimentological features on lidar data, even with the help of photo-mosaics and photorealistic surface models, is labour intensive and time consuming. The advent of digital annotation and interpretation methods like the one used in this thesis, (i.e. VRGS) along with others (e.g. Wang et al., 2013), increases the accuracy and speed of interpretation. However, these methods rely on complete and precisely aligned models, which is ultimately limited by the spatial positioning equipment, software and processing techniques.

Additionally, the workflow used to produce the final DOMs (Chapters 3 and 4) and ultimately reservoir models discussed in this thesis (Chapter 5) utilised a combination of software packages, which are not necessarily designed for geologic applications. The result of this is requires a series of work-arounds which are implemented to produce the desirable models, and are often time-consuming and technically difficult to use. For example, the techniques presented in Chapters 3 and 5 to classify the point clouds based on the lithofacies type, and calculate the true channel width and thickness involved the use of eight separate software applications (RiScan Pro™, Innovemetric: Polyworks™, Trimble Pathfinder™, Trimble Terrasync™,
QGIS\textsuperscript{TM}, Adobe: Photoshop\textsuperscript{TM}, VRGS, and Petrel\textsuperscript{TM}). Furthermore, the majority of software packages are industry standard, such as Petrel\textsuperscript{TM} for reservoir modelling, and are not designed to deal with the dense datasets produced from lidar. Thus, they have problems accurately gridding surfaces and representing true facies heterogeneities observed at outcrop. This is shown in Chapter 5 by the creation of the modelling grid size built to the size of the smallest sand body, not necessarily the smallest/thinnest element observed at outcrop (i.e. crevasse splays = 20 cm).
6.5 References


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Chapter 7
Chapter 7

Concluding Remarks

7.1 Concluding remarks

A fundamental understanding of the precise 3D geometry within any depositional system is paramount to establishing an accurate architectural and depositional framework. The Geobody Mapping tool and analysis technique applied to the La Serreta section within the medial zone of the Huesca 'Megafan' proved to be an effective tool to establish a more accurate and robust 3D sand body distribution (Chapter 3). This study, integrated with previous work (e.g. Hirst, 1991, further constrains and supports the DFS depositional model for the Huesca fluvial system. New insights into the width versus thickness and the interpreted in-channel lithofacies components are demonstrated for the Huesca DFS, suggesting a more westerly trending system. An increase in channel sand thickness is observed through the stratigraphy, and thickness distribution suggests that this system was deposited as depositional lobes, due to regional avulsion events. Furthermore, the concentration of abnormally thick (16 m) multi-storey and highly amalgamated sand bodies in a relatively small area, suggests the La Serreta area was downstream from a nodal avulsion point. Other studies of DFSs suggest avulsion events (of all levels: regional, nodal and local) to be the primary control on fan development. The study presented in Chapter 3 provides evidence for two types of avulsion which took place within the Huesca DFS, and implies this concept to remain valid for the lifespan of the system.

An important aspect illustrated by this thesis is the level of geological knowledge of a sedimentary system that is required before successfully generating accurate 3D geological facies and subsurface reservoir models. This is integral to creating the
most accurate 3D model and realistic representation of sand body architecture and distribution. Subsurface datasets are the typical data sources used to generate reservoir models. However, the level of geological detail required for accurate geological representation is not typically achievable through limited subsurface datasets (i.e. course resolution, large well spacing etc.) The 3D sand body analysis (i.e. geometry and lithofacies classified point cloud) for the La Serreta section (presented in Chapter 5) provides a continuous and high-resolution dataset which was used to condition deterministic and stochastic reservoir simulations. Though laterally continuous, the lidar data is limited by resolution and vegetation coverage. However, the lidar data was integrated with detailed sedimentary logs, which provided necessary qualitative facies and high-resolution vertical data input. Additionally, channel statistics (i.e. amplitude, wavelength and sinuosity) were acquired from a modern analogue chosen that best represents the Oligocene – Miocene Huesca DFS (Davidson and Hartley, 2014). These are used to further constrain the final reservoir model realisation produced from all of these data. The final reservoir simulation produced sedimentary geometries and architecture which reflect outcrop observations (Chapter 5). It has been shown in this thesis that integrating high-resolution vertical sedimentary log (i.e. well log) geostatistical data with continuous and quantitatively classified data from outcrop, increases the accuracy of subsurface representations from outcrop analogues.

Discriminating stacked distributary from palaeovalley-fill sand bodies are difficult at outcrop due to individual fluvial geometries being larger than the outcrop, and the lack of a clear 'basinward facies shift' is commonplace. The necessity to quantitatively analyse sand body architecture to identify genetic origin is integral to discriminating between stacked distributary and palaeovalley-fill deposits in the rock record. Through detailed 3D DOM construction and analysis, four general metrics can be used to identify key criteria to discriminate between these two sand body types: (i) sand body thickness, (ii) storey height, (iii) position of storey contacts relative to the base of the sand body, and (iv) storey contact length. With these metrics, the trends observed for the sand bodies recognised in the Pikeville and
Hyden Formations suggest that previous interpretations remain valid; they contain major fluvial sand bodies of stacked distributaries and palaeovalleys. Furthermore, the study shows that a 3D spatial approach to determine basin-wide architectural trends is integral to identifying the genetic origin, and preservation potential of sand bodies of both palaeovalleys and distributive fluvial systems.

Finally, the quantitative analytical techniques discussed in this thesis are translatable to any sedimentary system which is predominantly fluvial in nature. These systems are notoriously difficult to generate accurate measurements (e.g. sand body width, thickness, storey height and length), but the methods presented in this thesis provide quantifiable data which can be analysed and subsequently used to produce accurate 3D geological models.

### 7.2 Recommendations for future work

Digital outcrop geology is no longer a novel technique used to visualise 3D photorealistic representations of outcrops. It is a recognised tool to aid quantitative analysis of the geologic features. Future developments in digital outcrop geology will further enhance the types of analyses and results presented in this thesis. Therefore it would be prudent to discuss future work possible for each associated study presented in this thesis.

#### 7.2.1 Huesca DFS: Depositional model refinement

(i) The currently contested DFS model is one which needs continual refinement to establish its significance in the rock record. With this in mind, the work presented in this thesis demonstrates the type of quantifiable data which can be gathered from DFS outcrops, and the quantifiable results it can produce. It would behove current and future workers to utilise the digital data terrestrial collection methods (i.e. lidar, DGNSS, photogrammetry) available and the analytical techniques discussed in this thesis. The well exposed outcrops of the Huesca and Luna DFSs supply a plethora of potential exposures across the system (proximal to distal) that would be perfectly suited for digital outcrop geology and subsequent geostatistical analysis. By creating 3D DOMs of these outcrops, a more robust and quantitative depositional control for the system
can be developed. By integrating current palaeoflow techniques being applied to modern DFSs and a limited number of ancient DFSs (e.g. Owen et al., 2015), a larger database can be created to properly determine the significance of a DFS system in the rock record.

(ii) Behind-the-outcrop studies have been done in the La Serreta section of the Huesca DFS, but have not been added to this dataset. The potential to combine DOMs with borehole data holds an inherent interpretive power which would be critical to determining the true 3D geometry of the sand bodies. Other near-surface geophysical tools would be another avenue where invaluable 3D data can be acquired to investigate even further the connectivity of the sand bodies in different parts of the system. What is the true connectivity of the proximal sand bodies and what is the downstream change in connectivity ratio? Variability in the medial portion has been shown in this thesis; however, further work to quantify the controls for this would be crucial to determining potential reservoir connectivity in analogue subsurface systems.

(iii) Finally, calculating the downstream architectural change in a DFS is critical to understanding not only the architectural change, but is crucial to determining preservation potential as it relates to the long term and instantaneous fluvial profile. Essentially, what are the sequence stratigraphic controls which can be extracted from future studies of the Huesca or Luna DFS? Previous studies have looked at a 2D approach to determining the downstream change in channel geometry and the relationship and role of overbank architecture (e.g. Kulikova, 2013. The next step would be to implement a 3D stratigraphic forward modelling (SFM) approach to encompass the changing channel geometries that can be calculated from DOMs of relevant outcrops, their relationships to overbank architecture (i.e. avulsion deposits, crevasse splays).

7.2.2 Breathitt Group: Outcrop geostatistics

(i) The Breathitt Group is a fluvio-deltaic system which demonstrates complex depositional patterns, and due to new findings by Jerrett et al. (2016), it
presents a rare example of documenting a down-dip transition from a Type 1 or Type 2 sequence boundary. The techniques presented in this study would allow an even more quantitative approach to mapping the distribution of sand packages which hold these sequence boundaries. It would again behove future workers to collect more, and higher resolution digital outcrop data to constrain the architectural change in more detail. Additionally, the road ways in eastern Kentucky are continually being constructed through the Appalachians which expose hundreds of metres of the Breathitt Group stratigraphic succession that would be ideal for digital outcrop work. The more data that is collected on the fluvial sand bodies, the more refined the depositional model and possible controls will become.

(ii) Additional investigation is needed to properly assess the role of storey contact lengths in outcrop, and its application to other formations within the Breathitt Group, and predominantly fluvial outcrops in general. Additionally, the DFS processes presented as the primary form deposition for the thickest sand bodies found up-dip inherently needs more investigation and its relationship to other DFS studies in fluvio-deltaic systems.

(iii) SFM is a method which provides a powerful predictive capability of the deposition and evolution of sedimentary facies within a known stratigraphic framework (Huang et al., 2015). SFM is reliant on precisely controlled input parameters, but if conditioned properly by a multitude of data sources (i.e. boreholes, GPR, seismic outcrop data), the resultant model could simulate the processes which created the final depositional framework of the Breathitt Group. Continued work to constrain the conceptual depositional model is critical for this process, however with the quantitative analytical techniques presented here, which are continually being developed, could provide the parameters necessary to fully constrain a stratigraphic forward model.
7.3 References


Appendices
Appendix A

Digitised Sedimentary Logs.

*See CD-ROM for digitised sedimentary logs*
Appendix B

Published works.
Introduction

Fluvial depositional systems are prevalent throughout the geologic record. Distributive fluvial and alluvial systems forms in every modern continental basin, with distributive fluvial systems being a predominate pattern (e.g. Weissman et al., 2010). The focus of this work has been on a medial portion of the Late Oligocene – Early Miocene age continental Huasca distributive fluvial system (DFS), in the north-central part of the foreland Ebro basin in North Central Aragon, Spain (Figure 1). The well exposed sections of the stratigraphy throughout the study area north of the village of Piracés (Figure 2), allows for a detailed investigation into the three-dimensional variability and heterogeneity found within the system. By accurately mapping and interpreting the 3D nature of the geobodies, the extent and origin of the geo-bodies within a succession can be determined, often problematic with fluvial exposures (Bridge, 1993). The three-dimensional exposures in the study area allow integration of multiple mapping, logging and modelling approaches. In this way, stratigraphy can be represented in a more accurate 3D context than previously achieved through 1D (logs) or 2D (photo-panel) methods. The integrated techniques used throughout the project include lidar, Differential Geospatial Navigation Satellite Systems (DGNSS), and sedimentary field logs have allowed the authors to generate high resolution 3D Digital Outcrop Models (DOMs) of the exposures. This will serve as a foundation for further modelling of the system.

Figure 1&2 (1) Location map of the Ebro Basin, and subsequent Huasca DFS, which is the southern foredeep of the Pyrenean orogenic belt. (2) The field area, Piracés, is highlighted in red with data collection locations plotted in yellow.

Digital Outcrop Modelling

Geologic models have undergone a significant transition over the past decade. The incorporation of quantitative geophysical and geomatic mapping techniques with traditional qualitative methods, have allowed geoscientists to capture, process, analyse, and visualize high resolution and accurate outcrop information more accurately than ever before.

Digital Outcrop Modelling is a method of producing 3D geologic models from digitally acquired data of exposed outcrops, either from airborne or terrestrial techniques (e.g. lidar, photogrammetry, or laser range finding). The intrinsic information associated with each scan is integrated with other geomatic measurements (such as DGNSS) to accurately geoposition each DOM into real world coordinates before being aligned with one another. Multiple software resources are used to process, align and geoposition the lidar data for the final triangulation step in the modelling procedure.

One such example is Virtual Reality Software (VRGS) developed at the University of Manchester. This offers several methods of further analysis of the DOMs, e.g. producing photorealistic models (Figure 3). Colour differences between lithology types, as observed in the field, are recreated on the DOMs, allowing a user to identify subtle differences between overbank and channel deposits, which can have similar geometries. Another analysis method in VRGS is performing a tensor analysis on DOMs, resulting in the ability to visualize values and degrees of elements of each DOM such as coplanarity (Figure 4) or dip of the surfaces (e.g. Seers et al., 2013; Hodgetts, 2013). These
realizations improve the ability to approximate geobody geometry and lateral variability within the models by allowing the user to accurately delineate exposed surface boundaries from vegetated or scree slopes. This increases the accuracy of the geostatistics derived from the 3D models. Another important product of the tensor analysis is the ability to recognize sedimentary structures within the geobodies that may not be apparent within a grey-scale or photorealistic model. The tensor analysis allows for a user to visualize key structural information such as bounding or lateral accretion surfaces within the channel bodies allowing a facies classification scheme to be used on future geologic models.

![Figure 3](image.png)

*Figure 3* Photorealistic model a meshed (TIN) DOM for the study area. A model like this is key in identifying natural colour variations in the geobodies, which allow similar observations and connections to be made from the field.

![Figure 4](image.png)

*Figure 4* Coplanarity tensor analysis of a meshed (TIN) DOM for the study area. The colour scale chosen represents well exposed fluvial geobodies in blue with unusable scree or eroded material, which isn’t in-situ, in red.

**Description of the Data**

Terrestrial Laser Scanners (TLS) have been a strong component in the creation of the 3D geologic models because of the inherent spatial attributes, long range acquisition capabilities, and high accuracy and precision of the data return. In addition to acquiring the lidar point clouds, high resolution digital photographs taken from a coaxially mounted DSLR camera and DGNSS attributed to each scan location allows the authors to build high resolution DOMs that are spatially accurate.
(60cm) to real world coordinates. Supplementary to the acquired digital data, traditional sedimentological information (grain size, palaeoflow directions and bed form structures) was gathered throughout the study area. Locations for sedimentary logs were carefully chosen to best represent the lithological heterogeneity across the study area to offer lithologic constraint to the resulting geologic model. Several authors in previous works (e.g. Bellian et al., 2005; Buckley et al., 2008; Enge et al., 2007) discuss in detail well-established TLS methods and techniques for acquiring, processing and building accurate DOMs which have been adapted for this project. The software used throughout each process of the project include Riegl RiSCAN Pro for data acquisition and preliminary point cloud processing, Innovmetric: Polyworks v. 11 for global alignment of the point clouds with the DGNSS data, specialised software developed at The University of Manchester, VRGS, which allows the workers to accurately interpret key stratigraphic horizons, architecture and geometry of the geobodies found within the study area, and Schlumberger: Petrel 2013 for reservoir characterisation, modelling and analysis of the interpreted geobodies.

Geobody Mapping

One aspect of the project is to investigate the lateral connectivity and homogenous nature of the channel deposits found within the study area. This is an integral part of predicting fluvial architecture of the system, which in turn improves the use of outcrop exposures as reservoir analogues. An essential aspect of predicting the architecture is obtaining accurate geometrical information (width/thickness ratios, facies classifications, overall architecture and associated uncertainties), as well as carefully interpreted horizons and surfaces which are bound by the overarching fluvial dynamics of the system. The three-dimensionality of the exposed outcrops in the Piracés area combined with the 3D benefits of the geologic models offers a unique look into the paleo-history of the medial portion of the Huesca fluvial fan. By spatially tracking the channel elements throughout the study area, some of the geobodies are found to extend for hundreds of meters as predicted, whilst others exhibit shorter lateral movement but accrue thicker, more amalgamated channel complexes. This type of fluvial interaction requires a 3D investigation into the actual geobody geometry, which is achievable through VRGS and the ‘Geobody Mapping’ tool which has been developed. The tool allows a user to digitize the geometry of channel bodies throughout the area to investigate their interaction in 3D space, allowing for a more quantitative approaching to understanding the architectural relationship. Once digitised and bound by the geobody polygon, statistics derived from the digital dataset and the combined sedimentary logs, are integrated into a database to aid in building

![Figure 5 Classified DOM data imported into Petrel for reservoir property analysis and characterization. Spatial distribution and quantitative sedimentary log analysis can be completed as well.](image-url)

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a depositional and reservoir model of the Piracés study area. The associated connectivity and spatial distribution of the sedimentary bodies is normally difficult to ascertain in outcrop and with 1D well data (Pranter et al., 2013). However, with the addition of DOMs to the physiognomy of the study area provides an ideal case study to quantitatively investigate the lateral extent of the channel-fill geobodies. Classification schemes were attributed to the interpreted geobodies based on their geometry and partnered lithofacies. Visualizing this on the 3D point cloud allows the extent of each element can be interpreted and projected (Figure 5).

Once the data is imported into reservoir modelling software, quantitative analyses and geostatistical data can be extracted and modelled. Vario gram analysis and object modelling derived from the classified data produces models which help reduce the uncertainty inherent in geologic modelling. By integrating methods and techniques together with the datasets, workers are able to create more accurate realisations of subsurface reservoir models.

Conclusions

Fluvial sedimentary systems are complex due to their inherent cut/fill nature during deposition and are difficult to model and produce accurate realisations of their geometric and architectural relationships. Geobody mapping and modelling is a key component in producing and predicting model behaviour in the subsurface, and with the advent of geomatic and modern mapping techniques, geoscientist are able to more accurately realise the depositional architecture required to produce realistic determinations. Due to its exposure and depositional setting, the Huesca DFS offers an excellent opportunity for geoscientists to utilise the aforementioned techniques to accurately model and extract geostatistics to improve both the depositional and reservoir model for the medial portion of the system.

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References


