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Combining Terrestrial Photogrammetry, Applied Sedimentology and Hand-Held Gamma Ray Spectrometry to Characterise the Cretaceous Lower Castlegate Formation, Tuscher Canyon, Utah, U.S.A.*

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Abstract

Fluvial sandstones create some of the highest net-to-gross clastic reservoirs in the world, but the quality of these reservoirs, and recovery from them, are strongly controlled by depositional style. However, the internal architectures of fluvial sandbodies are difficult to ascertain from down-hole data alone, and the rapid spatial and temporal variations in lithofacies make inter-well correlations of fluvial strata notoriously difficult. This study addresses the key issues of fluvial reservoir connectivity and sandbody architecture at the reservoir scale by using an integrated approach, with photogrammetry and pseudo-well log data from the Campanian Lower Castlegate Formation at Tuscher Canyon, Utah, USA.

The ~5 km^2 terrestrial photogrammetric dataset collected shows that the 20 m to 60 m thick, high net-to-gross, Castlegate succession has an outcrop to area ratio (OAR) of 0.73, indicating exceptional exposure coverage. Data set analysis extracted over 476 palaeocurrent datasets and five types of depositional architectures. Gamma ray log data were collected, at a spacing of 20 cm for 90 seconds per assay reading. Analysis of such data indicates the complex architecture of the Castlegate was deposited in a highly avulsive, low-sinuosity, bedload-dominated fluvial system, with a high abundance of downstream accreting elements. Key stratigraphical surfaces were used to create a deterministic framework for an object-based, numerical model. Extracted sedimentary architecture statistics from measured palaeocurrent indicators form object vectors that were used to populate the model. Future work will simulate fluid flow through the model and compare results to the more proximal type locality, refining the understanding of mobile oil behaviour in high net-to-gross fluvial systems.

Introduction

Fluvial sandstone reservoirs contain some of the highest percentages of unrecovered mobile oil within known reservoirs (Tyler and Finley 1991) due to their inherently complex internal depositional architectures. Such architectures are difficult to ascertain from down-hole data alone, and the rapid spatial and temporal variations in lithofacies make sub-subsurface correlations of fluvial strata extremely difficult (Miall 1996). This study investigates heterogeneities at a baffle to permeability zonation scale (1-25 m scale; Figure 1) and provides insight into which fluvial architectures drive heterogeneity on a sub-element scale in a low sinuosity fluvial system. The study also addresses the key issue of visualising subsurface fluvial sandbody architecture at the reservoir scale by using terrestrial photogrammetry and pseudo-well log data from the Campanian Lower Castlegate Formation at Tuscher Canyon, Utah, USA (Figure 2).

Scales of Heterogeneity within Fluvial Reservoirs

Reservoir heterogeneity represents a change in reservoir properties between one rock unit and another. These heterogeneities often result from variations in petrophysical properties across facies (Corbett et al. 2012). Such distributions of reservoir heterogeneities in fluvial systems are extremely complex (Miall 1996; Corbett et al. 2012). Jordan and Pryor (1992) stated, “permeability heterogeneities are the principle controls on productivity throughout the life of a reservoir”. Some of the greatest challenges presented in the recovery of mobile oil are produced by reservoir architecture and the relationships of fairway to baffle and barrier heterogeneities (Tyler and Finley 1991). Reservoir geologists commonly recognise four to six broad scales of reservoir heterogeneity across the pore scale, sedimentary structure, fairway and baffle, and genetic unit to fault scale (Figure 1; Tyler and Finley 1991; Jordan and Pryor 1992). Preliminary recovery models of fluvial reservoirs operate at mega- to giga-scopic scale heterogeneities within a reservoir (Figure 1; Tyler and Finley 1991). Given the high percentage of unrecovered oil in fluvial reservoirs, higher resolution realisations must be made. This study looks at the scale of shale baffles within an architectural element. A classic example of this is in the study of point bars in highly sinuous fluvial systems and their associated inclined heterolithic strata (Pranter et al. 2007). Heterolithic baffles of low sinuosity fluvial strata have received little attention by comparison. This may be due to their high net-to-gross nature and homogeneity on the larger, lower, resolution mega- to giga-scopic scale.

Geological Setting and Previous Work

The Mesaverde Group represents an Upper Cretaceous prograding clastic wedge that transported material from the Sevier Orogenic Belt (to the west) into the Western Interior Seaway (to the east) of central North America. The Group consists of the Mancos Shale, the Blackhawk Formation and the Castlegate Sandstone. The Castlegate Sandstone may be sub-divided into three informal lithostratigraphical units (Chan and Pfaff 1991; Olsen et al. 1995; McLaurin and Steel 2007). The Lower Castlegate Sandstone is an extremely high net-to-gross fluvial sand sheet deposited by a low sinuosity, bed-load dominated, fluvial system. The Middle Castlegate Sandstone has a more isolated channel nature with a higher preservation of overbank material (McLaurin and Steel 2007). The final sub-division is the Bluecastle Tongue, which is genetically similar to the Lower Castlegate Sandstone (Olsen et al. 1995).

The more distal strata, to the east, at Tuscher Canyon, near Green River, show a thinner succession of the high net-to-gross Lower Castlegate Sandstone and an absence of the Middle Castlegate. This is due to a punctuation of the prograding wedge sequence by a transgression at ~78-77 Ma (Fouch et al. 1983; McLaurin and Steel 2000) that deposited the siltstones of the Buck Tongue, overlying the more distal Lower Castlegate. Normal regression resumes with the deposition of the estuarine Sego Sandstone and coastal plain to lagoonal Nelson Formation. The three units are contemporaneous with the proximal deposition of the Middle Castlegate isolated channel belt (Yoshida 2000; McLaurin and Steel 2000, 2007). In both the proximal and distal portions of the Western Interior Seaway Basin, the Middle Castlegate (along with distal equivalents thereof) is unconformably overlain by the erosive prograding Bluecastle Tongue (Chan and Pfaff 1991; Olsen et al. 1995; Yoshida 2000). This study will focus on the high net-to-gross fluvial Lower Castlegate Sandstone.

A detailed facies study of the Lower Castlegate (Chan and Pfaff 1991), shows that, at the type locality, the Lower Castlegate is dominant by trough-cross bedded sandstones and poor overbank preservation. Trough-cross bedded sandstones become less dominant in the more distal, eastern portions of the Castlegate Sandstone. This decrease in trough-cross bedded sandstone is accompanied by the increased preservation of lenticular silt and mud deposits, along with planar-cross bedded sandstones. The Tuscher Canyon area was subsequently interpreted to be within the meander belt region of the Lower Castlegate Sandstone. Further works (Miall 1993, 1994) produced two-dimensional panels of the Tuscher Canyon succession and supplemented them with palaeocurrent data. It was found that there were six major architectural elements constructing the Lower Castlegate at Tuscher Canyon. These were predominantly sandy barforms and downstream accreting elements, showing minimal lateral accretion sedimentation, apart from that found at a within barform scale. This study (Miall 1993) concludes that the system is actually a braided low sinuosity system, dominated by downstream accreting elements showing some macroforms migrating oblique to the regional palaeocurrent direction.

Methodology

The 20 m to 60 m thick, ~5km^2 fluvial strata of the Lower Castlegate Formation, Tuscher Canyon, Utah, was digitally captured using terrestrial structure-for-motion photogrammetry. Analysis showed it had an outcrop to area ratio (OAR) of 0.73, indicating exceptional exposure coverage of the study area. The data set was subsequently interpreted using the Miall's (1985) bounding surface numerical hierarchy scheme. Here bounding surfaces operate from bounding surfaces of the 0th order indicating the smallest scale depositional feature (i.e. foreset laminae) to bounding surfaces of the 6th order indicating a stratigraphically significant boundary, for instance a basal surface of forced regression. For further details, the reader is referred to Miall's (1996) chapter four dedicated to the interpretation of fluvial architectural elements. Figure 3 shows the application of this technique to sections of different scales in Tuscher Canyon.

Four hundred seventy-six palaeocurrent readings were collected from the Lower Castlegate outcrop in the field and on Virtual Reality Geological Studio software (v. 2.39, Hodgetts 2018). One hundred fifty-eight cross bed azimuthal readings were interpreted, along with 155 set surface, and 116 simple and complex channel morphology trends. This high-resolution and dense data set allows for a detailed interpretation about the genetic nature of architecture within the Castlegate to be established.

Finally, high-resolution hand-held spectral gamma ray data were obtained using the RS-230 BGO hand-held gamma ray spectrometer (Figure 1 and Figure 4). Data were collected using 20 cm spacing at an assay time of 180 seconds. Spectral gamma ray data were paired with sedimentary logs, creating pseudo-well log data. Sedimentary log analysis was conducted at an individual bed characteristics scale. The one-dimensional data were paired with two-dimensional geometrical relationships developed from photogrammetric analysis of the outcrop.

Fluvial Architecture at Tuscher Canyon

Five dominant facies were identified within the Lower Castlegate succession at Tuscher Canyon (Figure 3 and Figure 4): trough-cross bedded (*St*), planar-cross bedded (*Sp*), massive (*Sm*), horizontally-bedded (*Sh*) sandstones and planar-laminated very fine sand to siltstones (*Fl*). The predominant facies within the succession are *St* and *Sp* (Figure 3 and Figure 4), these typically comprise medium- to coarse-grained, sub-rounded poor- to moderately-sorted, grey to white quartz arenites. Spectral gamma analysis produced three subtly identifiable electrofacies, the statistical characteristics of which are shown in Table 1. The most notable observation in the dataset is the elevated mean and standard deviation values across API, potassium and thorium for electrofacies *Ga1*.

Four principal sand-dominated architectural elements, and overbank fine facies are identified from the terrestrial photogrammetric data (Figure 5). Channel deposits display a concave-up, down cutting erosional, basal fifth-order bounding surface. These basal surfaces are commonly overlain by an incomplete, waning flow succession of coarse pebble lag deposits and *St*, *Sp*, *Sm*, *Sh* facies (Figure 3 and Figure 4). The finer facies of the successions are often eroded by the down-cutting phase of a subsequent channel form; this is typically found in all architectural components of the Lower Castlegate Sandstone (Figure 3). Some channels show simple internal architectures and represent cut-and-fill geometries. Other channel-fill strata contain heterogeneities at a greater scale than that of facies. Some more complex channel forms contain downstream accreting barforms and lateral accretion deposits.

Downstream accretion elements overly the basal erosional surface of complex channel forms and commonly overly the channel lag deposits. These architectures have a lensoidal to tabular external geometry, and are predominantly comprised of trough-cross bedded sandstone sets, commonly punctuated by third-order reactivation bounding surfaces (Figure 3). Downstream accretion architectures also dominate the succession. Lateral accretion barforms develop lensoidal geometries and are characterised by the presence of lateral accretion deposits. These represent the most heterolithic elements of the Castlegate Sandstone, with inclined siltstone deposits creating baffles within individual architectures. Overbank is poorly preserved and appears in thin lensoidal geometries. This coupled with the population and distribution of architectural elements indicates that this medial to distal succession of the Lower Castlegate represents a highly avulsive fluvial system. When comparing the spectral gamma ray data it was found that the highest emission sands of *Ga1* belonged to the simple channel fill elements. The lower emission sands *Gb1* and *Gb2* correlate to downstream accretion elements and lateral accretion elements respectively (Table 1, Figure 4).

The dominance of downstream accreting barforms, and sandy bedform trains shown in the photogrammetric and palaeocurrent data, suggests a broad eastward palaeoflow, low sinuosity fluvial system. Lateral accretion deposits show a pronounced unimodal, northward palaeocurrent direction, suggesting that only a single occurrence of such an element has been sampled. Downstream accretion elements show a lot of variability through 25°-120°, given the mean accretion direction (76°) this may be attributed to oblique migration of bedforms. Sandy bedform trains show two strong groupings of data ~90° apart. This has been interpreted to represent simple channel switching of preferential flow directions due to autogenic hydrodynamic changes produced by the accretion of local barforms.

Discussion and Further Work

The interpretation of downstream accreting architectural elements and sandy barforms, within the Lower Castlegate, low sinuosity fluvial system, aligns itself with previous studies (Miall 1993, 1994). Although contrasts some of the original sedimentological work conducted on the succession (Chan and Pfaff 1991). This study suggests that lateral accretion elements are more significant than previously thought (Miall 1993). The definition of a single architecture may appear purely academic, but concerning mobile oil recovery, the result may define the elements as non-reservoir, dependent on its genesis and heterolithic nature. Another key observation differing from Miall (1993) is the recognition of overbank preservation. Although limited, it provides a vital insight into the properties of meso- to mega- scale vertical permeability.

The next key phase to the data interpretation is to develop height/width ratios for each of the depositional elements and produce a net-to-gross ratio for these elements. These data may then be used to create a deterministic framework for an object-based numerical model. Objects will be defined based upon architecture geometry, net-to-gross and palaeocurrent vectoring. This will allow for the quality of reservoir rock, size of net sandbodies and the direction of mobile oil recovery to be ascertained.

Further work will simulate fluid flow through the numerical object-based vector model to understand the internal interactions of facies and sedimentary architecture, and the affects that such architectures have upon fluid migration within a fluvial reservoir. This has important implications for fluid migration at both exploration and production stages in high net-to-gross fluvial reservoir settings. Finally, the project will look at how these results contrast with other data collected at other field sites, for example the type locality north of Price, Utah.

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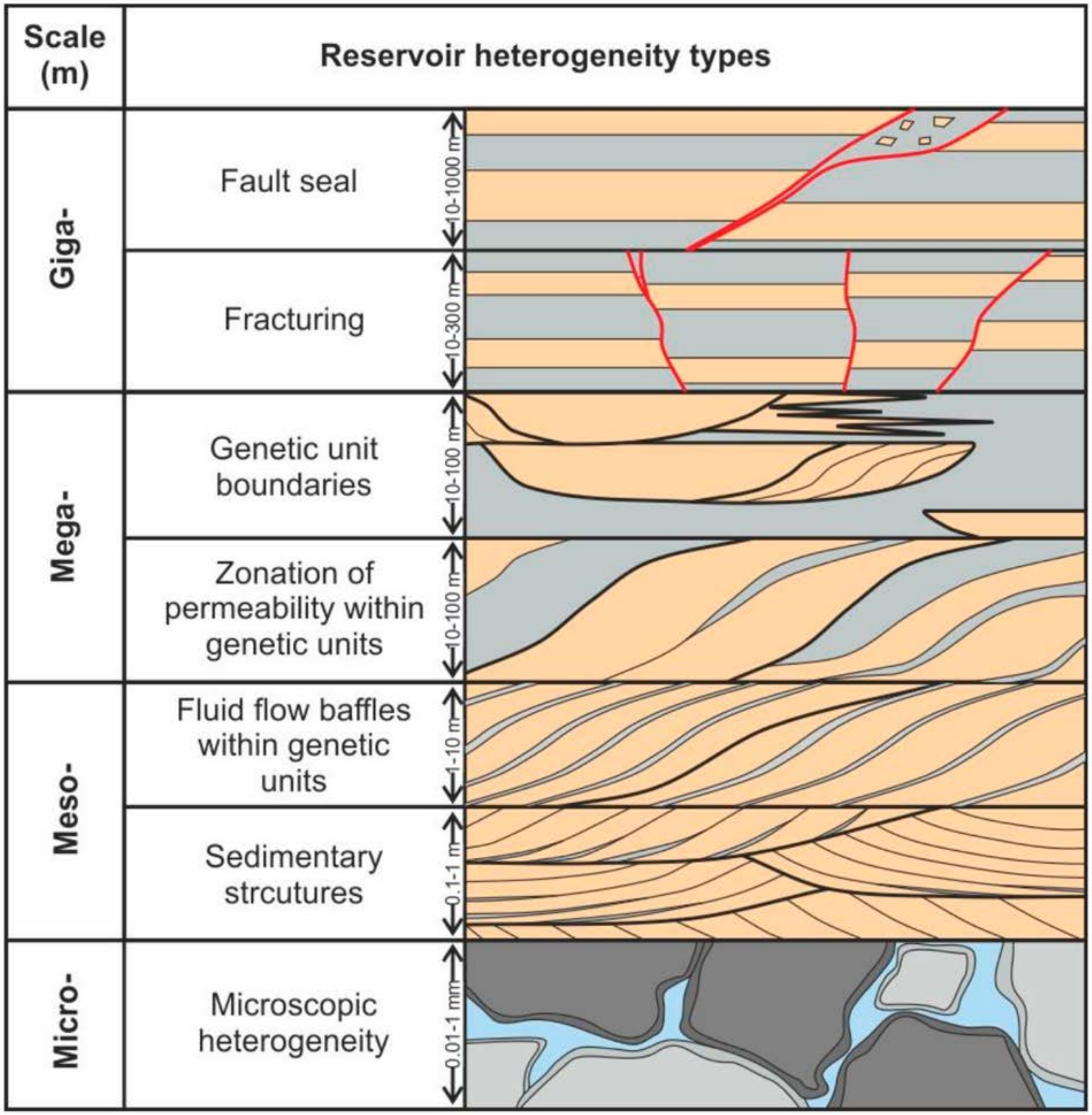


Figure 1. The scales of fluvial reservoir heterogeneity, adapted from Tyler and Finley (1991) and Morad et al. (2010). Note the scales of this study: Fluid flow baffles within genetic units and zonation of permeability within genetic units.

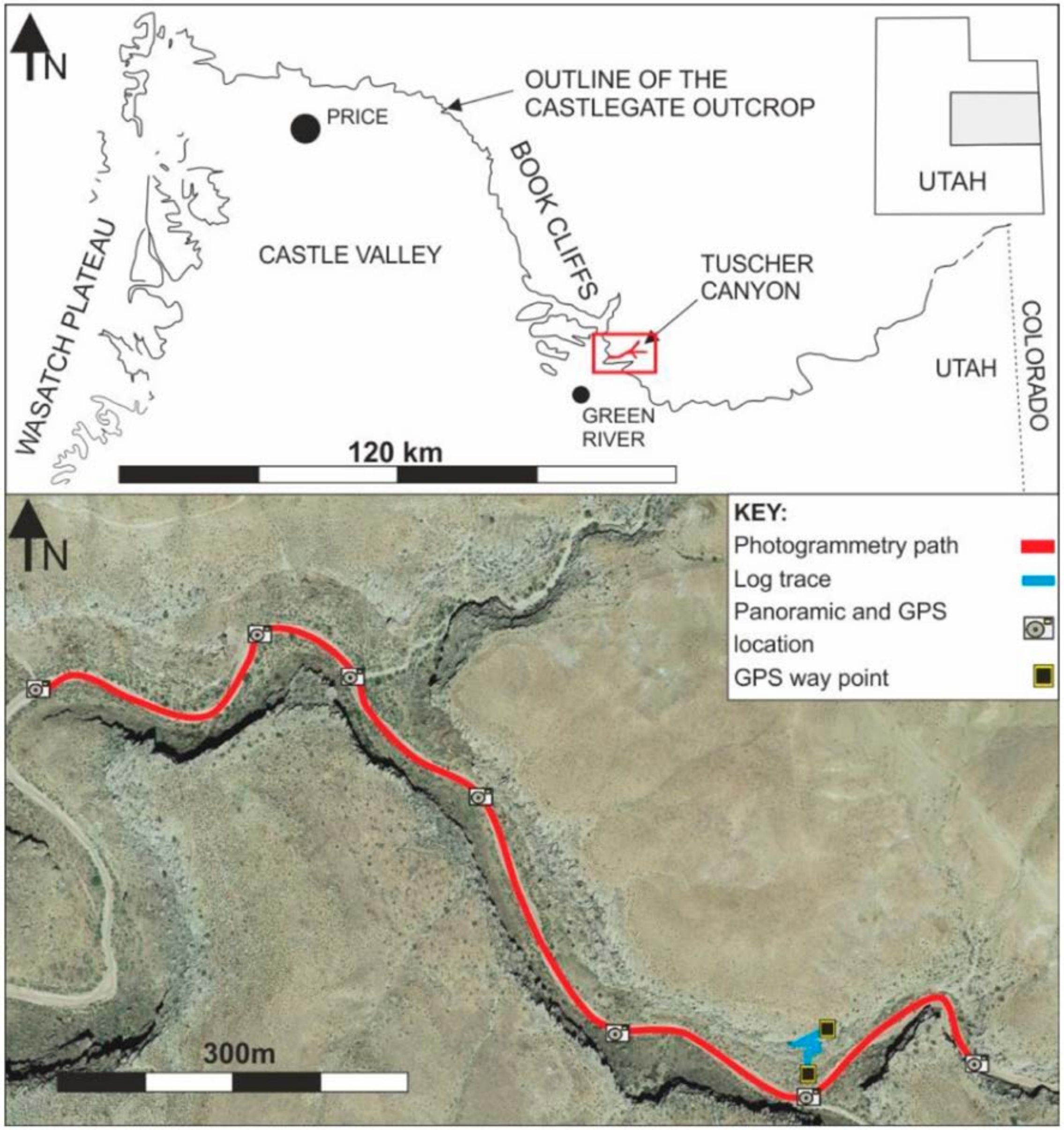


Figure 2. Map showing the outline of the Castlegate Sandstone outcrop (modified from Chan and Pfaff 1991) in east central Utah, with location (insert). The red box and lines indicate the position of the aerial image of Tuscher Canyon (below). The aerial image shows the position of the photogrammetric data collection and the position of the lithological and spectral gamma ray log data.

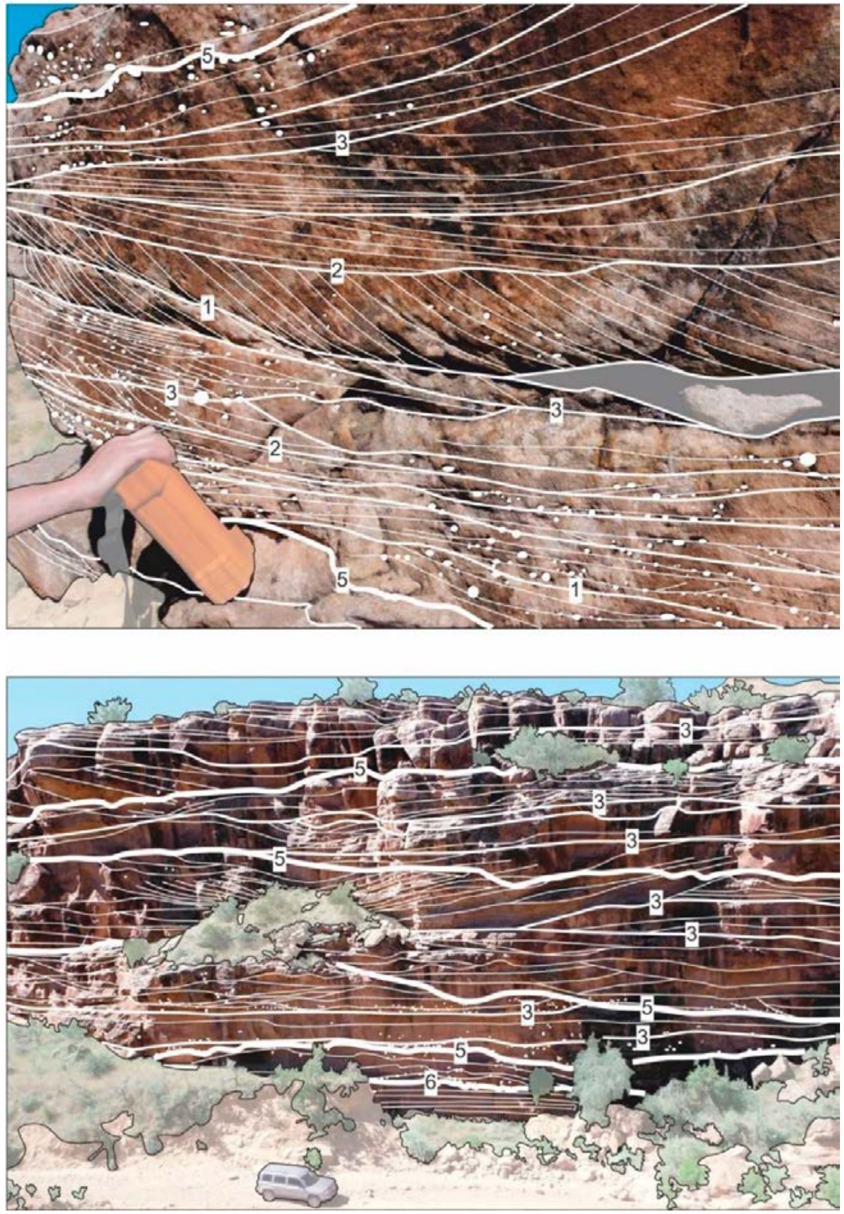


Figure 3. Photopanels showing bounding surface interpretations for the Castlegate Sandstone. The upper figure shows thalweg deposits and sandy bedform development in a channel. The lower image shows the abundance of reactivation and erosional surfaces within the Lower Castlegate. This gives evidence for the suggestion of variable discharge. Bounding surfaces indicated use of the Miall (1985) hierarchy scheme.

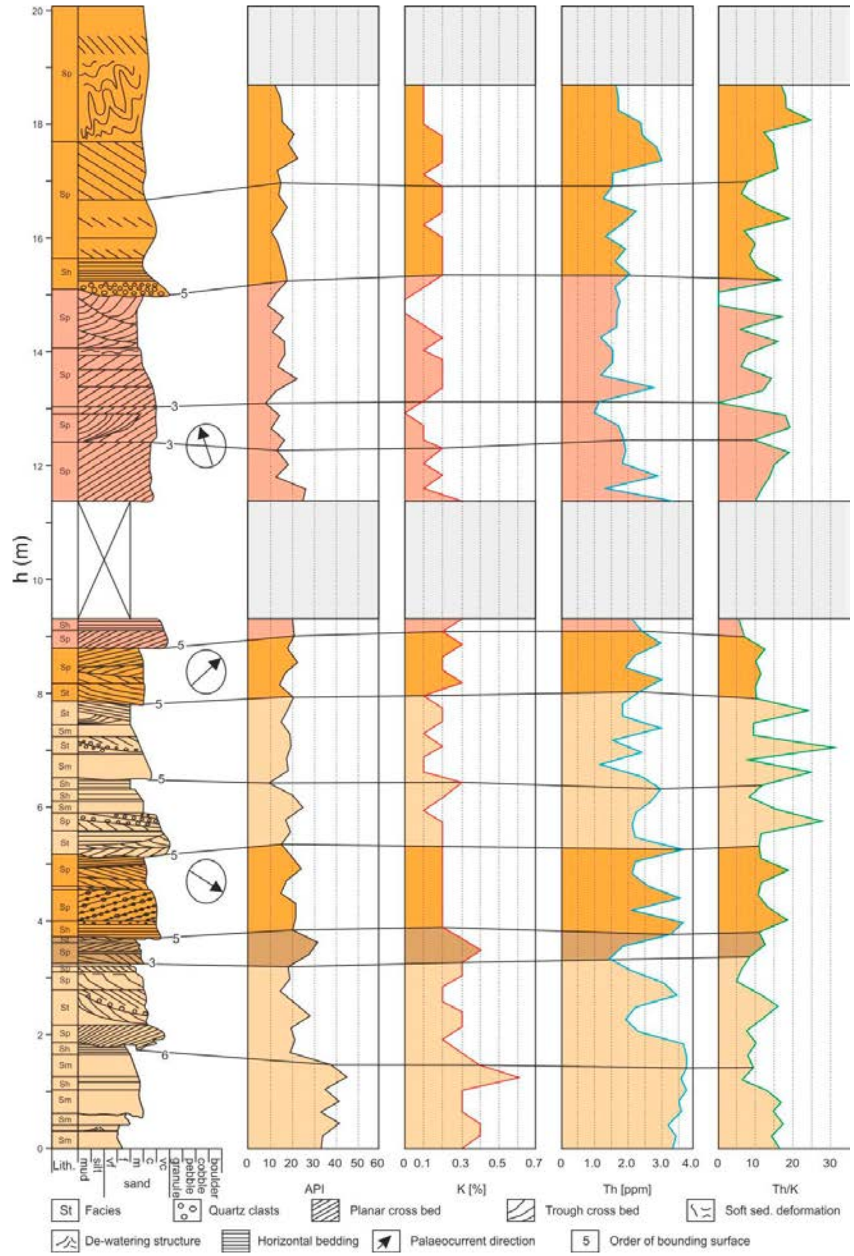


Figure 4. Log data collected from the field showing lithological and spectral gamma ray data. Data is coloured and correlated according to the architectural element interpreted from the data.

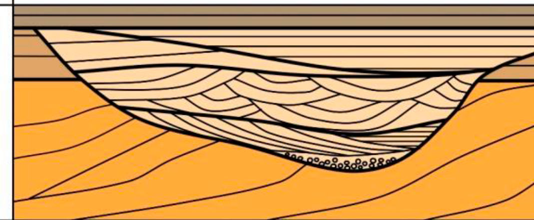
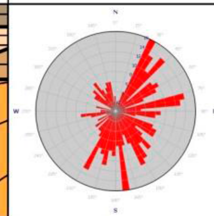
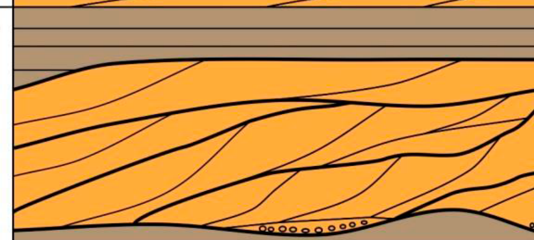
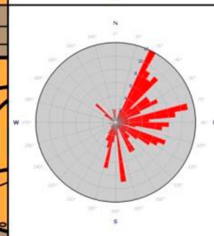
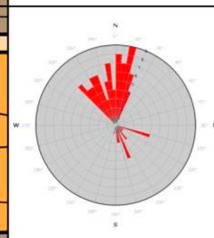
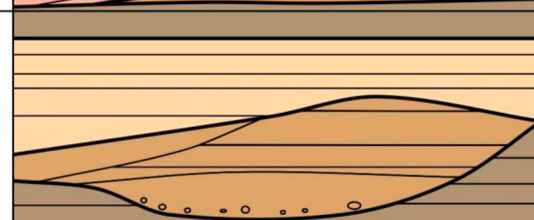
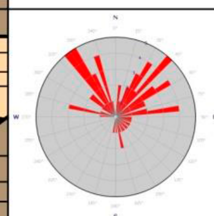
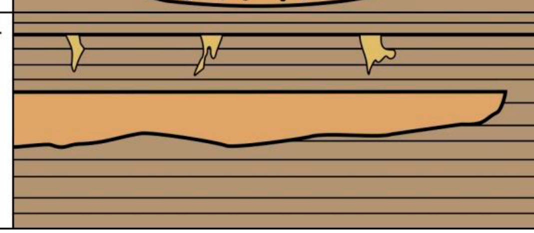
Arch. Element	Desciption	Bounding Surfaces	Facies		Palaeocurrent	
CH	Bedload dominated low-sinuosity sandy channel bodies with undultory down-cutting “U-shaped” basal bounding surfaces. Filled with simple upper flow regime to lower flow regime deposits. Show thalweg migration and bedform train deposition. Channel archiecture can be simple or complex. Simple as described above, or complex, in which channel forms accommodate multiple barform elements.	Basal surface: 5th/6th order. Top surface: 5th if discordant; 4th if concordant.	St, Sp, Sh, Sm, Sr.			N = 446 vm = 80.16
DA	Lenticular to tabular geometry within complex channel forms. Overlying channel lag material above erosive basal bounding surface. Internal foreset geometries are commonly trough cross-bedded, and show reactivation surfaces. Reactivation indicates autogenic migration of thalweg and variable discharge.	Basal surface: 5th/6th order. Top surface: 5th if discordant; 4th if concordant. Internal structure: 3rd reactivation punctuate 1st and 2nd order bedform trains.	St, Sp, Sm, Sr.			N = 209 vm = 76.48
LA	Lenticular inclined heterolithic element. Always confined and overlies basally confining surface, most commonly found close to the margins of a palaeo-topographical confinement. Internal foreset geometries are planar in the majority of occurances, set and coset surfaces are often asymptotic.	Basal surface: 5th/6th order. Top surface: 5th if discordant; 4th if concordant. Internal structure: 3rd reactivation punctuate dominant lateral accretion surfaces.	St, Sp, Sm, Sh, Sr.			N = 103 vm = 2.01
SB	Bedform trains not forming complex barform morphologies. Most commonly observed within wide thalweg migration elements. Lateral confinement is not always obvious. Foreset geometries are less commonly observable indicating poorer preservation. When observed foresets are commonly of trough cross bedding. Always overlies an erosional base, complete element is never preserved.	Basal surface: 3rd/5th/6th order. Top surface: 5th/3rd order Internal structure: 1st order climbing bedforms	St, Sm, Sh, Sr.			N = 82 vm = 46.88
OB	Laterally extensive sheets of fine grained material. Always eroded at its top and sides, basal surface is gradational at every observable interval. Sandstone bodies are commonly present in a limited lateral extent and limited to 50cm thinkness.	Basal surface: 2nd order. Top surface: 5th order.	Fl, Fm, Sm.			

Figure 5. Summary of the architectural elements interpreted from the Lower Castlegate Sandstone in Tuscher Canyon, bounding surfaces are described as Miall’s (1996) hierarchical scheme. Palaeocurrent readings were taken from the photogrammetric data set; N = number of palaeocurrent readings, vm = vector mean (as defined by Curray 1956). Depictions of architectural elements are idealised and schematic.

	Ga1		Gb1		Gb2	
	m	SD	m	SD	m	SD
API	24.26	8.41	17.52	3.38	14.77	3.91
K [%]	0.29	0.11	0.18	0.07	0.15	0.08
Th [ppm]	2.86	0.83	2.37	0.55	1.83	0.56
Th/K	10.59	3.54	15.36	6.63	12.30	4.50

Table 1. Summary statistics for API, potassium (K [%]), thorium (Th [ppm]) and the ratio of thorium to potassium (Th/K) collected at Tuscher Canyon. Note, m is the mean value of the electro-facies and SD is the standard deviation.