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Prediction of channel connectivity and fluvial style in the floodbasin successions of the Upper Permian Rangal Coal Measures (Queensland)

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Abstract

Predicting the presence and connectivity of reservoir-quality facies in otherwise mud-prone fluvial overbank successions is important as such sandbodies can potentially provide connectivity between larger neighboring sandbodies. This paper addresses minor channelized fluvial elements (crevasse splay and distributary channels), and attempts to predict connectivity between such sandbodies in 2 interseam packages of the Upper Permian Rangal Coal measurements. Channel body percent as measured in well logs were 2% in the upper (Aries-Castor) interseam, and 17% in the lower (Castor-Pollux) interseam. Well spacing was too great to allow accurate correlation of channel bodies. The Ob River, Siberia, was used as modern analogue to supply planform geometric measurements of splay and distributary channels, so that stochastic modeling of channel bodies was possible. The resulting models demonstrated that (i) channel-body connectivity is more uniform in distributary river systems than in splay complexes; (ii) relatively good connectivity is seen in proximal positions in splays, but decreases distally from the source as channel elements diverge; (iii) connectivity tends to be greater down the axis of splays, with more isolated channel bodies occurring at the margins.

Keywords: Fluvial, distributary, crevasse, secondary channel, tertiary channel, connectivity, reservoir modeling, Rangal Coal Measures, Bowen Basin, Ob River

Introduction

The distribution of sand bodies in fluvial overbank settings is strongly controlled by processes that dictate the style and frequency of overbank flooding (Benedetti 2003) via the breaching of levees, the generation of crevasse splays (Morozova & Smith 2000), and the development of minor distributary channels (Smith *et al.* 1989). In particular, size, longevity, spatial distribution and style of connection of splays to primary channels governs the distribution of sand-prone elements in overbank successions. The presence of reservoir-quality facies, such as secondary and tertiary splay and distributary channel deposits, in otherwise mud-prone fluvial overbank successions may provide significant connectivity between neighboring major channel elements in avulsion-prone channel belts, as in the Westphalian Coal Measures, Durham, UK (Fielding, 1986).

Although determination of three-dimensional sedimentary architecture and overbank connectivity is crucial for reservoir prediction in low net:gross floodplain settings, the typical km-scale well spacing in some hydrocarbon fields is too great and the total number of wells too few for the development of the appropriate predictive models. Likewise tertiary splay and minor distributary channel elements ($\leq$3 m thickness – Avenell 1998) are typically below the vertical resolution of seismic data (Bridge & Tye 2000; Ethridge & Schumm 2007), and their presence cannot be ascertained, nor their impact on connectivity inferred, from such data.

In low-accommodation fluvial settings, sand-prone channel elements are preferentially preserved as stacked and overlapping multi-story and multi-lateral bodies, whereas in higher accommodation settings, mud-prone overbank elements have greater preservation potential and neighboring channel bodies tend to be spatially isolated (Bristow & Best 1993). An increased rate of accommodation creation is commonly attributed to one or more of the following driving mechanisms: (1) high rates of basin subsidence such as encountered in many foreland basin settings (e.g. Marenessi *et al.* 2005); (2) base-level rise (Bristow *et al.* 1999; Bourquin *et al.* 2006) Most systems are governed by a combination of these factors, although one may be dominant (Ethridge *et al.* 1998).

Facies associations routinely identified in low net:gross, relatively high-accommodation fluvial overbank settings include those associated with mires, levees, secondary and tertiary distributary channels, and splays and splay complexes, including those composed of multiple tertiary splay channels, as well as finer-grained units: floodplain-lake fills and floodplain fines, including palaeosols (Smith & Pérez-Arlucea 1994; Jorgensen & Fielding 1996; Cazanacli & Smith 1998; Farrell 2001). Figure 1 illustrates the typical architecture and internal facies make-up of these depositional elements. Reservoir-quality sandstones are most likely to be present in the overbank setting as networks of secondary and tertiary channel elements, the accumulated deposits of which typically attain thicknesses of up to a few meters, and which may form laterally extensive splay bodies over distances of several kilometers. It is, however, typically difficult to distinguish between deposits of some of the smaller-scale overbank elements, particularly when relying on core or well-logs alone for interpretation (Brierley *et al.* 1997).

The aim of this study is to demonstrate the architecture and connectivity of secondary (distributary) and tertiary (distributary and splay) channelized sand bodies in a low net:gross fluvial setting, to assess the potential for communication between reservoir-quality (sandy) elements in overbank settings. Specific objectives of this study are (i) to document criteria by which minor channelized elements can be identified on wireline logs, (ii) to quantify infill proportions and dimensions of tertiary channels, (iii) to present quantitative data on plan-view geometries of modern tertiary channel elements, and (iv) to stochastically model the predicted lateral and vertical connectivity of tertiary channels. The connectivity of such sand bodies is investigated for two interseam intervals at the South Blackwater Mine, Queensland (Fig. 2), a Permian coal-bearing floodbasin succession.

This work is significant for the following reasons: (i) current models that predict sand-body occurrence in floodbasin settings are overly simplistic and largely qualitative in nature (Bridge & Tye 2000); (ii) current approaches to estimating hydrocarbon reserves in fluvial reservoirs routinely only assess the geometry of major (primary) fluvial sand bodies (e.g. multi-storey channel complexes), and this potentially underestimates the true volume by ignoring the additional significant volume associated with minor secondary and tertiary channel and splay elements; (iii) few models currently exist with which to assess the role of minor secondary and tertiary channel and splay elements in terms of their role in aiding communication and connectivity between primary channel bodies.

Geological Setting

The Permian Rangal Coal Measures of the Bowen Basin, at the South Blackwater Mine, Bowen Basin, Queensland (Fig. 2) are exposed in a series of open cast workings and have been penetrated by a series of shallow boreholes for which well-log and core data are available. The coal measures are widespread throughout the basin and they have been exploited through intensive open-cut mining since the 1970s (Mutton 2003). The Rangal Coal Measures form part of the fill of the Bowen Basin, which evolved – along with several other Eastern Australian Gondwanan basins – as part of the Middle-Late Palaeozoic Tasman Orogen (Fielding *et al.* 1993; Fielding 2001; Fig 3). Three pulses of sedimentation directed southwards along the basin axis occurred during the Late Permian, the last of which was responsible for the accumulation of the Wuchiapingian-Changhsingian age Rangal Coal Measures and equivalents, which represent the preserved deposits of a large scale distributary fluvial system (Fielding *et al.* 1993; Allen & Fielding 2007). The sheet-like nature of primary channel deposits formed in the Rangal Coal measures is indicative of a low-sinuosity system and the Rangal Coal Measures are considered to have formed in a broad alluvial plain setting (Fielding *et al.* 1993)

At the South Blackwater Mine, the Rangal Coal Measures are preserve three mineable coal seams within the study area: Aries (A), Castor (B) and Pollux (C). Within the Rangal Coal Measures, several facies associations have been recognized by previous research. Fielding (1993) identified the following: Sheet-like sandstone channel bodies; laterally accreted, heterolithic channel bodies; proximal overbank; crevasse channel fill; floodbasin; lake floor; mire. Avenell (1998) interpreted wireline and core data as: sheet-like channel sandstone bodies (primary channel elements); heterolithic distributary channel bodies (secondary channel elements); minor crevasse channel bodies (tertiary channel elements); levee; floodbasin; lacustrine and mire. Michaelsen *et al.* (2000) interpreted the interseam deposits as: trunk river channels and crevasse feeder channels; levee bank–proximal crevasse splay; distal splay–overbank; marsh; peat mire and floodbasin lake.

Data and Methods

The study covers a 2km^2 area of the South Blackwater Mine, Queensland. Detailed correlation of a subsurface part of the Rangal Coal Measures succession was undertaken using a high-density subsurface dataset of wireline logs from 63 coal exploration wells. Available well logs included, including gamma-ray (GR), density, caliper and sonic logs were utilized.

High-resolution lithologic logs were made for each well in the dataset using Oilfield Data Manager (ODM) software, primarily via the interpretation of GR and density log responses. For the purpose of lithology interpretation, GR cut-offs were defined as follows: clay/mudstone, >110 API GR; siltstone and silty sandstone, 110-90 API GR; 'clean' sandstone (>60% sand), <90 API GR (Avenell, 1998). Coal was easily identified by its distinctive signature characterized by very low GR values coincident with low density values.

After assigning lithologies to each well, architectural elements (Miall, 1985) were assigned to packages of deposits deemed to have been formed by the same processes. To help achieve this, an extended and refined lithology and facies scheme for the Rangal Coal Measures was developed from a previous core-based study at the South Blackwater Mine (Avenell 1998) and this was used as the basis for the architectural-element scheme developed in this study. Patterns in well-log curves and litholologic cycles were identified and assigned to fluvial and overbank architectural elements. Architectural elements were then correlated between subsurface wells in an attempt to characterize two-dimensional facies changes and, where possible, the likely three-dimensional sedimentary architecture and style of connectivity of secondary and tertiary fluvial channel elements considered to have arisen as a product of crevassing in a distributary system.

Where it was not possible to predict architectural-element type and extent from groups of neighboring well logs, measurements and estimates of likely plan-form geometry were made via the adoption and implementation of geometries of similar elements from analogous modern systems. Study of these modern fluvial systems involved the measurement of channel widths, lengths and sinuosities using NASA Landsat and Google Earth® imagery. These analogue data were integrated into reservoir models of the study area using Reckonnect®, a fluvial stochastic modeling software package. Reckonnect was chosen due to its ability to run multiple iterations of models in a short time period, in order to test the effect on reservoir connectivity of changing the dimensions and other parameters of the channel-element sand bodies.

Interpretations of the depositional sub-environments of the Rangal Coal Measures interseam intervals were then made based on the proportions and distributions of architectural elements observed in each of the two interseam intervals, one between the Aries (A) and Castor (B) seams, and the other between the Castor (B) and Pollux (C) seams.

Architectural Elements

Seven principal architectural elements have been identified in the study area between the Aries (A) and Pollux (C) seams (Fig. 4) using defined GR cut-offs for sand (<90), silty sand (90-110) and mud (>110), together with correlation of wireline log signatures between neighboring well-logs. The architectural element scheme is based on that of Avenell (1998).

(1) <u>Secondary tributary channel elements.</u> The wireline log character of these elements shows a sharp, erosional base, with a fining-up, blocky or bell-shaped gamma response. These deposits are <90 API GR. These elements are greater than 3 m thick and are interpreted as hetrolithic distributary channel-fill deposits (Fielding *et al.* 1993). Distributary channels are typically bounded by levees, are subject to some lateral accretion, and grade laterally into finer-grained floodplain deposits (Avenell, 1998), in places causing local 'washouts' of the Castor (B) seam (Fig. 6).

(2) Tertiary crevasse channel elements. These elements have a GR of <110 API GR, in a succession of <3 m-thickness sandstone. They are typically sharp-based, fining-up to clayey, silty sand. The overall log signature is blocky or bell-shaped. Laterally more extensive tertiary channel elements are interpreted as those of mature crevasse channels, analogous to the stage 3 splay channels of Smith *et al.* (1989). Less extensive, poorly developed tertiary channel elements are interpreted as immature or abruptly abandoned splay channels of a stage 1 or stage 2 crevasse splay (Smith *et al.* 1989).

(3) Channel-margin (including levee) and lake-margin elements. Channel-margin deposits form the finer-grained equivalent to adjoining channelized deposits. They typically exhibit fine-grained (alternating high and low GR) log patterns, corresponding to interbedded sandstones, siltstones and clay drapes. Lake-margin deposits routinely exhibit coarsening-up, progradational log patterns, but are difficult to distinguish from levee channel-margin deposits where observed in wireline borehole logs alone.

(4) Proximal- to medial-floodplain elements. Deposits of these elements consist of interlaminated sandstone, siltstone and clay-rich partings, with a highly variable log pattern attributed to splays and flooding.

(5) Distal floodplain elements. Deposits of these elements are characterized by laminated siltstones and mudstones, with a GR log signatures generally >110 API GR. Minor sandstone intervals identified in these packages likely represent the distal deposits of crevasse splays.

(6) Floodplain lake and frequently inundated floodplain elements. These deposits of interlaminated claystones, mudstones and silty-mudstones, with rare lenses of siltstone and sandstone, have GR log readings generally >110 GR API. They are indicative of a system subject to seasonal flooding.

(7) Mire elements. Within these deposits, a blocky, low GR-log signature is indicative of coals. This 'blocky' GR response, together with a low DENL response distinguishes coal from sandstone. These deposits constitute coal seams and carbonaceous shales formed in peat mires.

Thick and sheet-like primary channel-fill elements are not encountered in the interseam deposits of the study area, though such bodies are identified from some wells beneath the C seam. Most wells stopped at or just beneath the C seam, so correlation of these extensive sand-prone elements has not been possible.

Correlation

Figure 5 details a typical subsurface well correlation, taken from the northeast of the study area (see inset map for location). The correlation utilizes caliper, gamma-ray and density wireline logs to identify the three major coal seams present in the studied interval, to interpret the interseam lithology, and to interpret the architectural elements present in the interseams. Fence diagrams collating key correlation panels were constructed to demonstrate the three-dimensional architecture of the interseam deposits (Fig. 6) and to identify key areas of secondary and tertiary fluvial channel deposition.

Element Proportions

Proportions of the A-B, and B-C interseam intervals infilled by each architectural element were measured from their thicknesses in each interpreted well log (Fig. 7). Net:gross was calculated for each interval (A-C, A-B, B-C), taking only 'clean' (GR <90 API) sandstone as net. The correlation panel and fence diagram (Figs. 5 & 6) demonstrate that the B-C interseam has a greater proportion of channel elements and therefore a higher net:gross than the A-B interseam.

Channel Element Thicknesses and Widths

Channel-element thicknesses were determined from well logs. A frequency plot reveals the distribution of the range of channel thicknesses (Fig. 8), where frequency refers to the number of appearances in well logs. It was not possible to measure channel-element widths using the well correlation data alone because well spacing was greater than the width of the channel elements in most cases, such that estimated widths measured from correlation panels effectively became a function of the well spacing rather than a true indicator of channel-body width.

Interpretation

Analogue Measurements

In cases where it is not possible to directly derive all the information necessary to build accurate reservoir models from available datasets, analogue data may be used to approximate the missing parameters (e.g. plan-form geometry) that cannot be determined from the primary subsurface dataset alone (Alexander, 1993; Lang *et al.* 2002). For overbank depositional systems whose constituent architectural elements (e.g. floodplain and splay) are readily preserved, such as those of the Rangal Coal Measures, modern analogues must be chosen from relatively high-accommodation fluvial/fluvio-deltaic settings in which extensive peat-forming processes are acting and for which frequent flooding, crevassing and deposition occurs on the floodplain.

One modern example is the Ob River, Siberia. The Ob River was selected as a suitable analog as it is set within the large-scale, continental, non-tropical peat-forming depositional system in the West Siberian Plain (Lang *et al.* 2002). The Ob River has a very large primary channel (fig. 9). However it is the numerous secondary and tertiary channels, running roughly perpendicular to the primary channel, that have been identified as likely modern equivalents of the distributary and splay channels present at the time of deposition of the Rangal Coal Measures at the location of the South Blackwater Mine (Lang *et al*. 2002). This analogue is used to link surface geomorphology to subsurface sedimentology in the South Blackwater Mine dataset. The Ob River distributary system floods seasonally (Fig. 9a), with floods emanating from breaches in levees that result in widespread crevassing, the generation and maintenance of secondary and tertiary distributary channels (Fig. 9b) during spring floods. As the floods dry suring summer months, the receding water leaves abundant floodplain lakes across the floodplain (Lang *et al.* 2002). Figure 9c illustrates a typical crevasse splay complex of the Ob River, and this is considered to be similar in both scale and morphology to those envisaged for the South

Blackwater study succession, based on the similarity in scale of the various architectural elements known from the two systems.

Measurement of the dimensions of the planform geometries of tertiary channels of the Ob River (both splay and distributary), including width, length and sinuosity, were taken from Google Earth aerial photographs (Table 1). Mean sinuosity (1.16) and width (41.60 m) of splay channels (N = 43) was less than that of the distributary tertiary channels (sinuosity = 1.27; width = 59.75 m, N = 24).

Modeling

The tertiary channels in the Ob River record little evidence for significant lateral migration via the accretion of point-bar deposits, so preserved sediment geometries assumed to be similar to those on the surface. Measurements of the widths and sinuosities of active channels from the Ob River analogue were therefore used in combination with the subsurface data, to derive estimates of likely infill proportions and channel thickness:width relationships for the Rangal Coal Measures. These were in turn used to define input ranges for stochastic models of the interseams made using Reckonnect (fluvial stochastic modeling software).

Reckonnect is a stochastic, object-based model that quickly models channel bodies to assess the effect of changing channel body dimensions and distributions on connectivity (Collinson & Preater). Models are created using channel body thickness and channel percentage data from wells, and geometric data (e.g. channel body width and sinuosity). Modelled output is simple, treating all channel bodies as reservoir, and all other deposits (model background) as non-reservoir. The models allow quantification of channel body connectivity, as well as connectivity to pseudo-wells.

For each model run, graphic output from a a randomly selected run was generated to illustrate the form of modeled channel geometries, and predicted style of clustering, channel connectivity (where channel connectivity by volume is defined as the mean percentage of sand connected to a random sandy point), and channel-body percentages observed in pseudo-wells. Results demonstrate potential well connectivity to sand bodies in the model, where well connectivity is defined as the probability (%) that pseudo-wells are connected by a continuous sandy path (Fig. 10a).

Reckonnect is not suitable for modeling two types of channel simultaneously (i.e. secondary and tertiary channels), and therefore models were built to represent the distribution of tertiary channels, which make up a greater proportion of interseam infill. In the A-B (Aries-Castor) interseam, infill by minor channels is 2% by tertiary channels and <1% by secondary channels. In the B-C (Castor-Pollux) interseam, the bias towards tertiary channels is greater with 17% infill by tertiary channels and 2% by secondary channels.

As both splay and distributary channels are identified in the South Blackwater Mine (Avenell, 1998) and in the Ob River (Fig. 9), both of these fluvial styles were modeled for the interseam deposits. Figures 10-12 show random replications from modeling runs conducted with 100 replications in each run. As well as the graphic output, Reckonnect also generates statistics covering channel proportion, channel connectivity and sand connectivity to pseudo-wells for each modeling run, summaries of which are given in tables 2-4. Model inputs are listed in Tables 2a, 3a and 4a.

The sand-poor A-B interseam was modeled with a splay (fan-like) geometry (Fig. 10b), whereby all modeled channels were forced to originate from a single point; this is the most likely arrangement to account for the low proportion of channel-infill and interpreted poor channel network development within the modeled interseam volume. The B-C interseam was modeled with both splay and distributary geometries, the latter type being characterized by channels that have no fixed point of origin within the model.

Due to the low proportion (2%) of channel-body infill in the A-B interval, very few channel bodies are modeled, and the majority (on average 87%) of those that are present are isolated (i.e. are not in communication with another channel body within the modeled interval) (Fig. 10b). Channel-body connectivity was low across most of the model (mean channel-body connectivity = 13%). The pseudo-wells demonstrate that, in both proximal and distal locations, wells are likely only to intersect isolated (i.e. non-clustered) channel bodies, if any, with the mean well connectivity being only 1.9%.

The B-C interseam, when modeled as a crevasse splay complex (Fig. 11), displayed the following features compared to the model for the A-B interseam: greater overall channel-body percentage (17%), greater mean channel-body thickness (1.59 m), which resulted in higher mean connectivity of channel bodies (22%) such that they formed multiple clusters of connected channel bodies. As expected in a splay, channel-body connectivity decreased distally and away from the axis of the splay, with isolated channel bodies more commonly occurring towards the splay margins. Figure 11 demonstrates a representative output from the B-C (splay) modeling runs: pseudo-wells demonstrate that, for a proximal location, it is possible for wells to intersect almost all of the channel clusters, whereas for distal locations, a well will intersect fewer channel bodies, the majority of which are likely to be isolated. Mean well connectivity is 46%: i.e. by intersecting channel clusters, a single well would be predicted, on average, to be in communication with 46% of the channel bodies modeled.

When modeled as a distributary system – i.e. where channels have no fixed point of origin (Fig. 12) – the B-C interseam displayed the following features: distributary tertiary channels were modeled with greater widths and sinuosities than crevasse-splay channels, using width and sinuosity measurements provided from the Ob River (Table 1). This resulted in greater amalgamation and stacking of channel bodies and generated fewer but larger channel-body clusters, yielding an average channel-body connectivity of 54% by volume. Channel-body connectivity was distributed more randomly across the modeled interval compared to that predicted by models of the interval that used a splay-type geometry (Fig. 12, '% channels connected' inset figure). As a result, pseudo-wells were, on average, likely to intersect all of the channel clusters, yielding a mean well connectivity of 79.8%.

Discussion

Depositional Models

Typical plan-form geometries of tertiary channel-body assemblages – i.e. elements generated in splay complexes and distributary channel settings – from the Ob River have been combined with channel body distributions resulting from the random replications of stochastic modeling runs in order to propose three-dimensional architectural models of the A-B (Aries-Castor) and B-C (Castor-Pollux) interseam deposits of the Rangal Coal Measures succession.

Upper (A-B interseam) interval: The A-B interseam is a poorly developed crevasse splay complex, with few, poorly connected channel bodies in a very low net:gross, distal floodplain setting (Fig. 13). Negligible connectivity is predicted for this interval. Channel bodies are mostly immature, being poorly developed, thin and isolated. The inset well-logs taken from the South Blackwater Mine dataset demonstrate typical successions from the interval (Fig. 13). Channel bodies present are interpreted as small scale-tertiary channels that abruptly grade laterally into channel-margin levee and lake-margin deposits.

The difference in fluvial style between A-B interseam deposits and the lower B-C interseam deposits may be attributed to a number of factors. The deposits could have formed during an episode of increased rate of accommodation creation, resulting in drowning of mires, splays and more medial floodplain deposits, thereby preferentially preserving distal floodplain deposits, rather than primary channel deposits.

Lower (B-C interseam) interval: The B-C (Castor-Pollux) interseam can be interpreted as large, well-developed crevasse splay complex (Fig. 14), which evolved over time to preserve a network of interconnected splay-channel elements in a medial floodplain setting (similar to those seen in the Ob River). Connectivity likely exhibits a large spatial variation, being significantly greater in proximal positions, where channels are more closely clustered adjacent to the source of the splay. The inset wireline well logs demonstrate typical medial and distal successions from the interval (Fig. 14).

The B-C interseam can alternatively be interpreted as a complex assemblage of bifurcating, meandering distributary channel bodies (Fig. 15). Distributary channel bodies interpreted from this part of the succession are considered to be of low sinuosity (Fielding *et al.* 1993). A network of distributary-channel elements will have a higher overall connectivity, and a more random distribution of connectivity than channel elements modeled as a crevasse-splay morphology.

A network of distributary channels originating at various points along a reach of the larger primary channel might explain the large number of channel bodies observed in the subsurface succession, in contrast to the relatively channel-poor overlying A-B interseam. The inset well-logs demonstrate successions predicted at various locations in such a system. Deposits in the South Blackwater Mine dataset generally grade laterally from channel element, to channel-margin element, to medial floodplain element, and locally to distal floodplain element (Avenell 1998). The B-C interseam is considered to be closely analogous to the floodplain morphology of the modern Ob River.

Limitations of data

The principal limitation for this study is the limited lateral extent of the data, leading to uncertainty as to where the data is situated in the overall depositional system, and how representative of that system it is. A single splay in the Ob River (Fig. 9c) is 4000 m by 5000 m, yet the entire study area at South Blackwater Mine measures only 1000 m by 2000 m. Thus, the predictions of subsurface fluvial architecture arising from this study could represent only a small portion of a much larger distributary system, so care must be taken when extrapolating interpretations made from such small sub-sections of what is overall a much larger fluvial system. This may explain the contrasting styles of deposition interpreted in the A-B and B-C interseams, including the observed differences in the proportions of overall channel bodies – 2% versus 17%, respectively.

Although apparently an extremely low net:gross interval, with negligible reservoir potential, the A-B interseam examined in the study area might represent a low net:gross fluvio-lacustrine environment located in a floodplain setting, at a stratigraphic level which overall has a greater reservoir potential elsewhere within the larger system. Analysis of a larger dataset from a wider spatial area could provide additional insight into the regional variability of such systems.

Conclusions

Subsurface datasets, even those of relatively high resolution such as the closely spaced coal mine wells of the South Blackwater Mine, may still not provide data of sufficient density of coverage to accurately resolve small-scale (tertiary) channel-element dimensions in floodbasin settings. Where the spacing of subsurface wells is greater than the mean width of any channel elements present, modern analogues can be a useful tool in supplementing the primary dataset to yield information regarding likely analogous plan-form geometries.

Simple models created using Reckonnect reservoir modeling software demonstrate some characteristic features of channel connectivity in small-scale distributary fluvial systems developed in floodbasin settings, such as those of the Rangal Coal Measures succession: (i) channel-body connectivity is more uniform in distributary river systems than in splay complexes; (ii) relatively good connectivity is seen in proximal positions in splays, but decreases distally from the source as channel elements diverge; (iii) connectivity tends to be greater down the axis of splays, with more isolated channel bodies occurring at the margins.

Good connectivity between channel bodies is expected in some cases (e.g. in the B-C interseam, which has a 17% channel proportion). However, where channel percentage is very low, as in the A-B interseam, connectivity between channel bodies is negligible. It is therefore vital to accurately constrain the proportions of infill by each architectural element in the system, in order to produce models with realistic channel-body distributions and connectivities.

Care must be taken when extrapolating findings from small datasets to a larger scale, as a small dataset may provide a biased, non-representative representation of the subsurface at a regional scale. This may be of particular relevance in petroleum exploration, where seismic datasets typically cannot resolve small-scale channel elements, and where well data are sparse, potentially leading to biased estimations of architectural-element proportions, especially where inappropriate analogues have been used to provide supplementary data.

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Table Captions

Table 1. Summary of tertiary channel dimensions from the Ob River, Siberia.

Table 2. A-B interseam modeling results for a splay-type geometry.

Table 3. B-C interseam modeling results for a splay-type geometry.

Table 4. B-C interseam modeling results for a distributary-type geometry.

Figure Captions

Fig. 1. Schematic diagram illustrating the typical facies associations and architectural elements encountered in a low net:gross fluvial overbank environment.

Fig. 2. Location of the Bowen Basin and South Blackwater Mine. Adapted from Allen & Fielding (2007) and Fielding et al. (1993).

Fig. 3. Tectonostratigraphic chart detailing tectonic phases in the Bowen Basin region and their relationship to corresponding formations. Rangal Coal Measures are highlighted. Adapted from Allen & Fielding (2007).

Fig. 4. Architectural element scheme of the fluvial and overbank deposits of the Rangal Coal Measures present in the interseam packages of the South Blackwater Mine, Queensland (Adapted in part from Avenell 1998). Lithologies and architectural elements assigned using gamma-ray (GRDE) and density (DENL) logs.

Fig. 5. Correlation panel from the NE of the study area (location circled on the inset map), demonstrating negligible net:gross A-B interseam and low-to-moderate net:gross B-C interseam, where both tertiary and secondary channels are present. Location of the correlation is shown in the inset map, as is the location of the fence diagram (Fig. 6). Wireline log abbreviations: GRDE (gamma ray, API units), DENL (density), CADE (caliper).

Fig. 6. Fence diagram demonstrating presumed 3D spatial geometry of elements. Laterally continuous fine-grained floodplain deposits are accurately correlated. Well spacing was too wide (50 m to 250 m) to accurately correlate tertiary channels, which globally are typically less than 250m width (Gibling 2006). Attempts to correlate individual channel bodies has lead to some unrealistic correlations. Negligible net: gross in A-B interseam, 20% net:gross in B-C interseam.

Fig. 7. Well logs provided proportions of infill by each architectural element in both (a) the Aries-Castor (A-B) interseam and (b) the Castor-Pollux (B-C) interseam. Proportions measured by thickness of occurrence in studied well logs. The A-B interseam is dominated by distal deposits, with only 2% tertiary channel infill, whereas the B-C interseam is dominated by medial deposits, with 17% tertiary channel infill.

Fig. 8. Tertiary channel element thickness data taken from well logs in both the A-B and B-C interseams.

Fig. 9. (a) Overview image of the Ob River, Siberia. This large-scale, distributary system has a up to 40 km-wide floodplain. The primary channel is low sinuosity, over 1 km wide, and numerous secondary distributary and tertiary (distributary and crevasse) channels are present. (b) A typical crevasse splay from the Ob River, Siberia, measuring 5 km in length. Green areas represent the raised crevasse complex, and tertiary channel levees. Dark areas of the floodplain are inundated by spring flood waters. (c) Secondary and tertiary distributary channels in the Ob River, Siberia. Channels exhibit a range of sinuosities and bifurcations are common. Splay complexes exhibit a fractal nature, with mini 'splays' often originating from larger splay complexes and tertiary channels.

Fig. 10. (a) Schematic diagram explaining the graphic outputs of Reckonnect modeling runs used in Figs. 10b-12. The graphic output represents one random replication out of 100 iterations made in each modeling run. (b) Graphic output of a random replication from a Reckonnect modeling run, representing the A-B interseam, with a splay geometry. With only 2% channel infill in the interval, the cross-section shows very few channels, the majority of which are isolated (shown in

grey). The depth slice demonstrates channel orientations and geometries (depth slice location shown in light green on the cross-section). The connectivity scale can be used to interpret the channel connectivity and channel percentage outputs: Channel connectivity is negligible across most of the model. Mean channel connectivity is 11%; i.e. 11% of the 2% of the model infilled by channel bodies is connected. In this scenario, only 0.02% of the modeled interval is represented by reservoir-quality sand bodies that are in some way connected. The pseudo wells demonstrate that in both proximal and distal locations, the well is likely only to intersect isolated channels, if any. Table 2c shows the statistical output from this replication.

Fig. 11. Graphic output of a random replication from a Reckonnect modeling run, representing the B-C interval, with a splay geometry. The cross-section shows five main channel clusters. As expected in a crevasse splay setting, isolated (grey) channels occur most commonly towards the margins of the modeled splay complex. The depth slice demonstrates channel orientations and geometries (depth slice location shown in light green on the cross-section). The connectivity scale can be used to interpret the channel connectivity, and channel percentage outputs: Channel connectivity is highest in a proximal location and as it decreases distally, is greater along the axis of the splay than towards the outer margins. Mean channel connectivity is 20%, but is as high as 80% near the source of the splay. The pseudo-wells demonstrate that in a proximal location, it is possible to intersect almost all of the channel clusters. In a distal location, however, the well intersects fewer channels, and is likely to intersect isolated channels. Table 3c shows the statistical output from this replication.

Fig. 12. Graphic output of a random replication from a Reckonnect modeling run, representing the B-C interval, with a distributary geometry (i.e. the channels do not have a fixed point of origin). The cross-section shows three main channel clusters. Only a few isolated (grey) channels are present. The depth slice demonstrates channel orientations and geometries (depth slice location shown in light green on the cross-section). The connectivity scale can be used to interpret the channel connectivity, and channel percentage outputs: The more random orientation of channels allows greater connectivity between channel bodies (45% of channel

bodies are connected). There is also a more random spread of connectivities and channel percentages in the model. Mean channel connectivity is 45%, but is as high as 90-100% in some areas. The pseudo-well demonstrates that it is possible to intersect the two largest channel clusters, so that the pseudo well is in communication with 77% of the channel bodies. Table 4c shows the statistical output from this replication.

Fig. 13. Simplified 3D architectural model of the Aries [A] - Castor [B] seam interval, incorporating planform geometries from modern analogues, and channel element dimensions and distributions from Reckonnect modeling. Analysis of wireline-log data indicates that silty mudstones, mudstones and claystones dominate the interval; typical of distal floodplain and lacustrine deposits. The inset logs are examples of proximal and distal logs from the A-B interseam. Tertiary channel elements present in the interval tend to be isolated, and are interpreted as small-scale, crevasse splay channels, bordered by leveed channel-margin deposits. Channelised elements are attributed to the distributary fluvial system that was responsible for drowning out the B seam peat mire environment.

Fig. 14. Simplified 3D architectural diagram for the B-C interseam, with tertiary channels present as leveed crevasse splay channels. The diagram incorporates planform geometries of the Ob River modern analogue with channel distributions inline with model outputs from Reckonnect. Medial floodplain deposits are dominantly preserved. Isolated channels tend towards the margins of the splay, with connectivity decreasing distally from the splay source. There is overlapping of channels (as demonstrated by the BC1 modeling run, Fig. 11). The connectivity between channel bodies may be further enhanced by potential connectivity through fine sand or silty-sand splay stacks. The inset well log sections illustrate anticipated proximal and distal well logs for such a splay-based system.

Fig. 15. Simplified 3D architectural diagram for the B-C interseam, with tertiary channels present as leveed, meandering, bifurcating distributary channels. The diagram incorporates planform geometries of the Ob River modern analogue with channel distributions inline with model outputs from Reckonnect. Medial floodplain deposits are dominantly preserved. Some channels are isolated, however

connectivity is good where channels overlap. The inset well log sections illustrates relatively high net:gross areas anticipated within the system.

Table 1. Summary of tertiary channel dimensions from the Ob River, Siberia

Channel Type	Mean Width (m)	Mean Length A (km)	Mean Sinuosity
Distributary Tertiary	59.75	11.12	1.27
Splay 1 Tertiary	50.95	5.85	1.23
Splay 2 Tertiary	41.14	1.83	1.06
Splay 3 Tertiary	34.40	3.92	1.18
Splay 4 Tertiary	34.38	2.22	1.21
Splay 5 Tertiary	32.57	1.81	1.12
All Splay Tertiary	41.60	3.13	1.16

Table 2. A-B interseam modeling results, modeled with a splay geometry

Table 2a. Reckonnect model parameters for the A-B (splay) interseam

Reservoir Thickness m	Mean Azimuth deg.	Channel %	Mode Thickness m	Thickness Variation %	Mode Width m	Width Variation %	Sinuosity	Sinuosity Variation %
30	170	2	1.26	53	41.6	50	1.16	28

Table 2b. Output statistics for the A-B (splay) interseam

Run	No. Channels	Channel %	% Single Storey	Channel Connectivity No.	Channel Connectivity %	Well Connectivity
1	13	1	100	9	13	2
2	14	2	100	9	13	1
3	14	2	100	9	12	4
4	14	1	40	9	14	2
5	12	1	50	10	16	2
6	14	1	50	10	13	1
7	14	2	60	9	13	1
8	13	2	95	12	17	1
9	14	1	69	9	13	3
10	13	2	100	10	13	2
Mean	13.5	1.5	76.4	9.6	13.7	1.9

Table 2c. Output statistics for the A-B (splay) random replication (Fig. 10b).

Run	No. Channels	Channel %	Channel Connectivity No.	Channel Connectivity %	Well Connectivity
3	18	2	7	11	1

Table 3. B-C interseam modeling results, modeled with a splay geometry

Table 3a. Reckonnect model parameters for the B-C (splay) interseam

Reservoir Thickness m	Mean Azimuth deg.	Channel %	Mode Thickness m	Thickness Variation %	Mode Width m	Width Variation %	Sinuosity	Sinuosity Variation %
30	170	17	1.59	40	41.6	50	1.2	28

Table 3b. Output statistics for the B-C (splay) interseam

Run	No. Channels	Channel %	% Single Storey	Channel Connectivity No.	Channel Connectivity %	Well Connectivity
1	130	14	14	14	20	44
2	131	16	85	14	20	47
3	130	14	87	14	19	42
4	136	15	84	15	22	51
5	128	14	84	12	20	45
6	132	15	85	18	26	59
7	134	17	82	20	29	47
8	130	15	82	16	24	44
9	123	15	85	14	20	40
10	128	15	83	15	21	42
Mean	130.2	15	77.1	15.2	22.1	46.1

Table 3c. Output statistics for the B-C (splay) random replication (Fig. 11).

Run	No. Channels	Channel %	Channel Connectivity No.	Channel Connectivity %	Well Connectivity
2	141	15	15	20	53

Table 4. B-C interseam modeling results, modeled with a distributary geometry

Table 4a. Reckonnect model parameters for the B-C (distributary) interseam

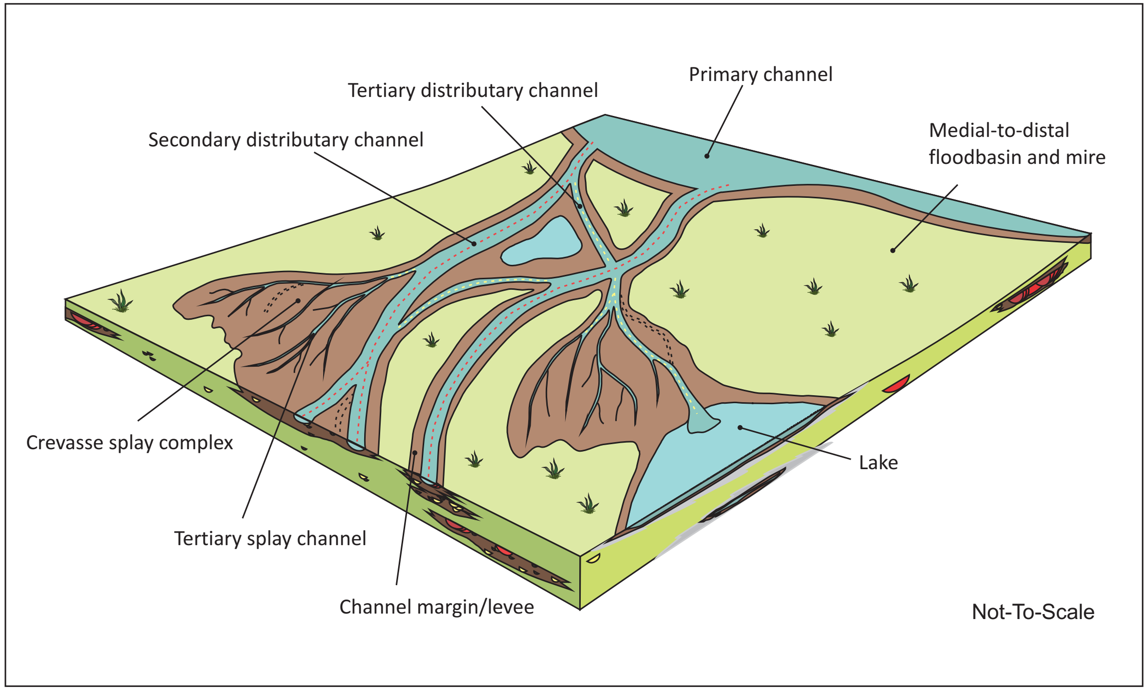
Reservoir Thickness m	Mean Azimuth deg.	Channel %	Mode Thickness m	Thickness Variation %	Mode Width m	Width Variation %	Sinuosity	Sinuosity Variation %
30	170	17	1.59	40	59.8	50	1.3	28

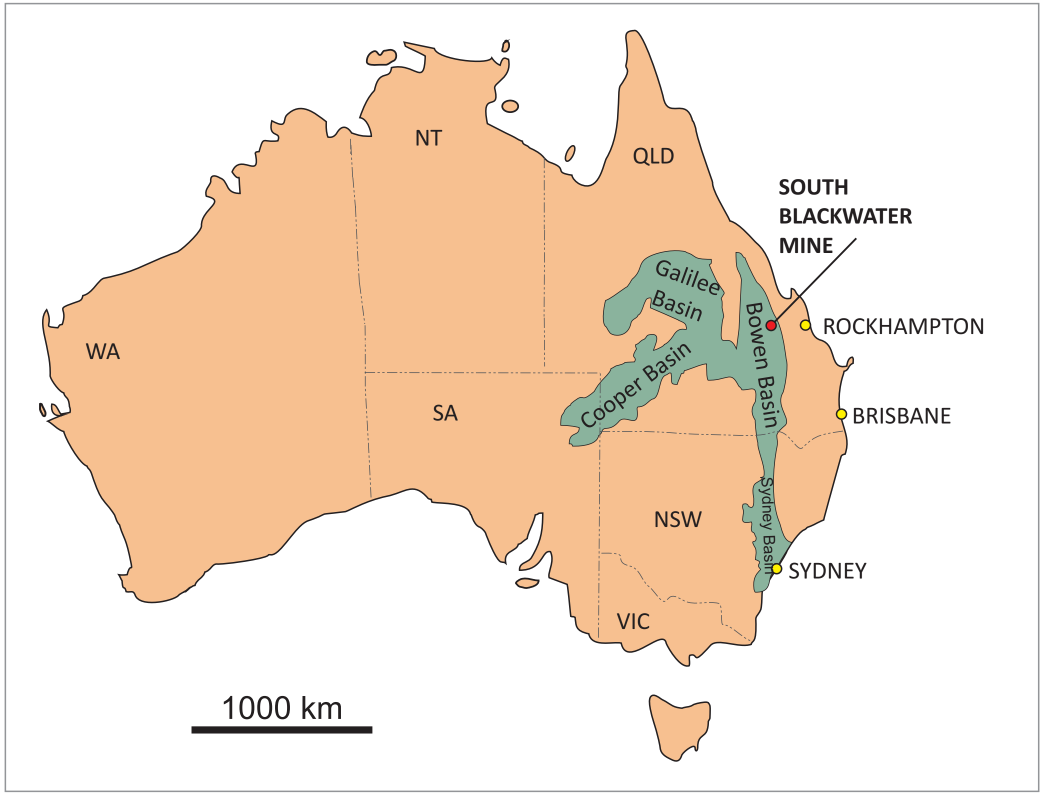
Table 4b. Output statistics for the B-C (distributary) interseam

Run	No. Channels	Channel %	% Single Storey	Channel Connectivity No.	Channel Connectivity %	Well Connectivity
1	90	15	86	38	43	83
2	94	17	84	63	68	88
3	89	15	84	51	57	80
4	89	14	90	42	48	74
5	96	17	83	51	54	83
6	90	16	86	43	45	71
7	87	16	85	43	47	80
8	98	17	79	64	70	85
9	94	15	83	45	52	77
10	93	16	82	52	59	77
Mean	92	15.8	84.2	49.2	54.3	79.8

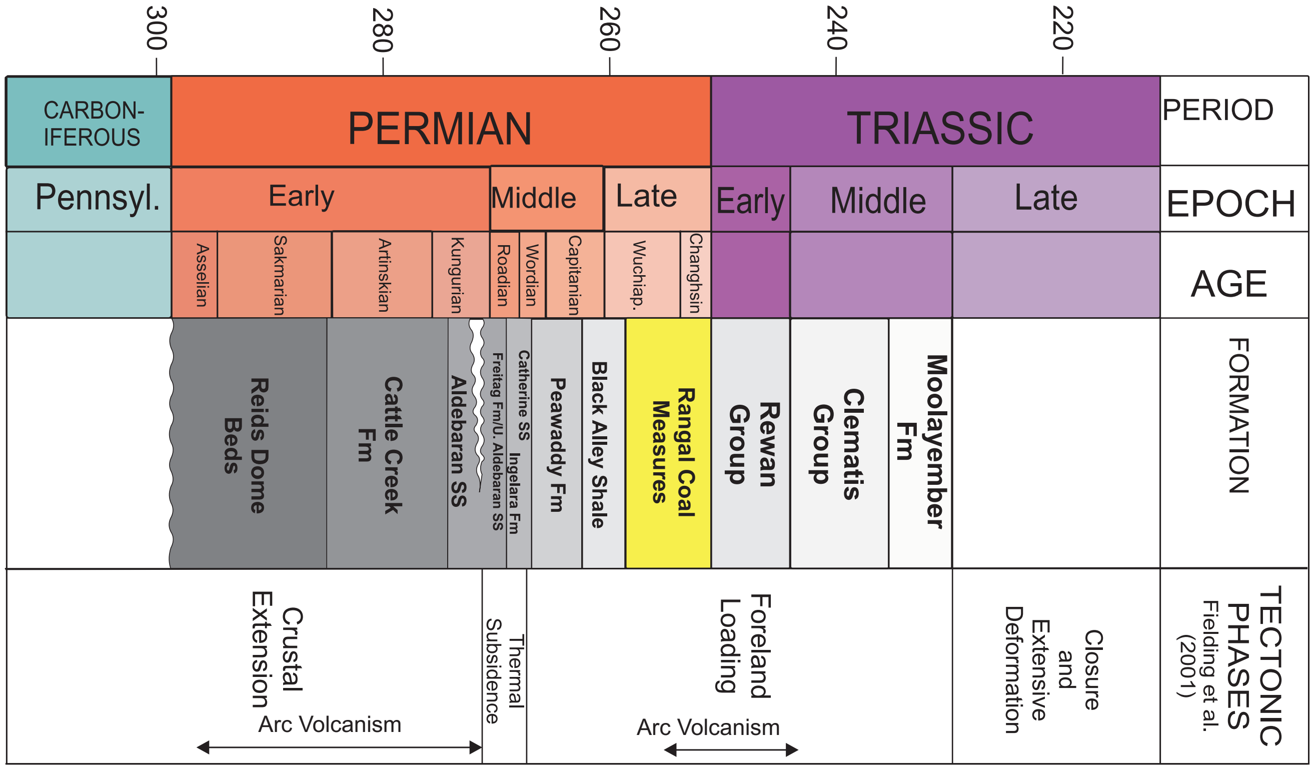
Table 4c. Output statistics for the B-C (distributary) random replication (Fig. 12).

Run	No. Channels	Channel %	Channel Connectivity No.	Channel Connectivity %	Well Connectivity
1	92	12	39	45	77


Tertiary distributary channel
Primary channel
Secondary distributary channel
Medial-to-distal
floodbasin and mire
Crevasse splay complex
Lake
Tertiary splay channel
Channel margin/levee
Not-To-Scale

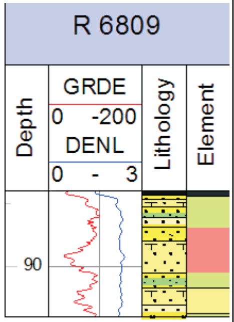


NT
QLD
WA
SA
NSW
VIC
SOUTH BLACKWATER MINE
ROCKHAMPTON
BRISBANE
SYDNEY
Galilee Basin
Cooper Basin
Bowen Basin
Sydney Basin
1000 km


300
280
260
240
220
CARBON-IFEROUS
PERMIAN
TRIASSIC
PERIOD
Pennsyl.
Early
Middle
Late
Early
Middle
Late
EPOCH
Asselian
Sakmarian
Artinskian
Kungurian
Roadian
Wordian
Capitanian
Wuchiap.
Changhsin
AGE
Reids Dome Beds
Cattle Creek Fm
Aldebaran SS
Freitag Fm/U. Aldebaran SS
Catherine SS
Ingelara Fm
Peawaddy Fm
Black Alley Shale
Rangal Coal Measures
Rewan Group
Clematis Group
Moolayember Fm
FORMATION
Crustal Extension
Arc Volcanism
Thermal Subsidence
Foreland Loading
Arc Volcanism
Closure and Extensive Deformation
TECTONIC PHASES
Fielding et al. (2001)

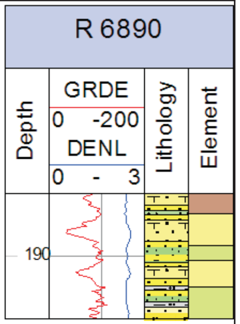
Secondary Channel

- >3 m-thickness sandstone
- Sharp/erosional base
- Fining-up
- Blocky or bell-shaped gamma response
- <90 API GR



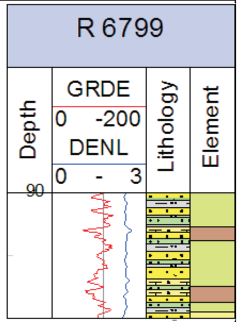
Tertiary Channel

- <3 m-thickness sandstone
- Typically sharp-based
- Fining-up to clayey, silty-sandstone
- Squat, blocky or bell-shaped gamma response
- <110 API GR



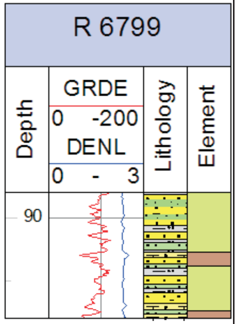
Channel/Lake Margin

- Interbedded sandstones and siltstones with claystone drapes
- Prograding (coarsening-up) log signature attributed to levees and crevasse splay deposits



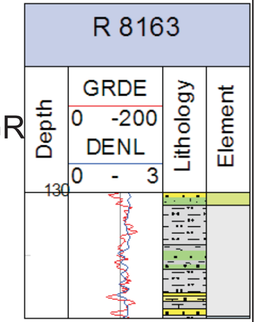
Proximal-Medial Floodplain

- Interlaminated sandstone, claystone and clay-rich partings
- Highly variable log pattern attributed to splays and flooding



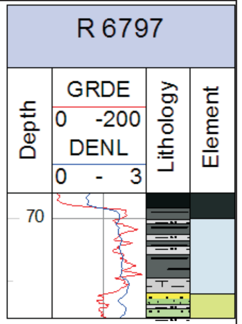
Distal Floodplain

- Laminated siltstones and mudstones
- GR log signature generally >110 API GR
- Minor sandstones attributed to distal crevasse splays



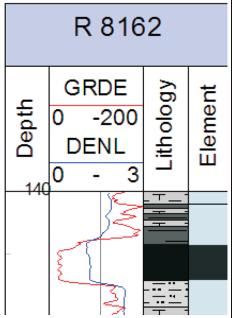
Lake

- Interlaminated claystones, mudstones and silty mudstones
- Occasional lenses of siltstone and sandstone
- >110 API GR



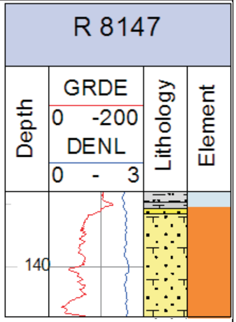
Mire

- Coals formed in peat mires
- Blocky, low GR log signature in good quality coals
- Low DENL response distinguishes coal from sandstone



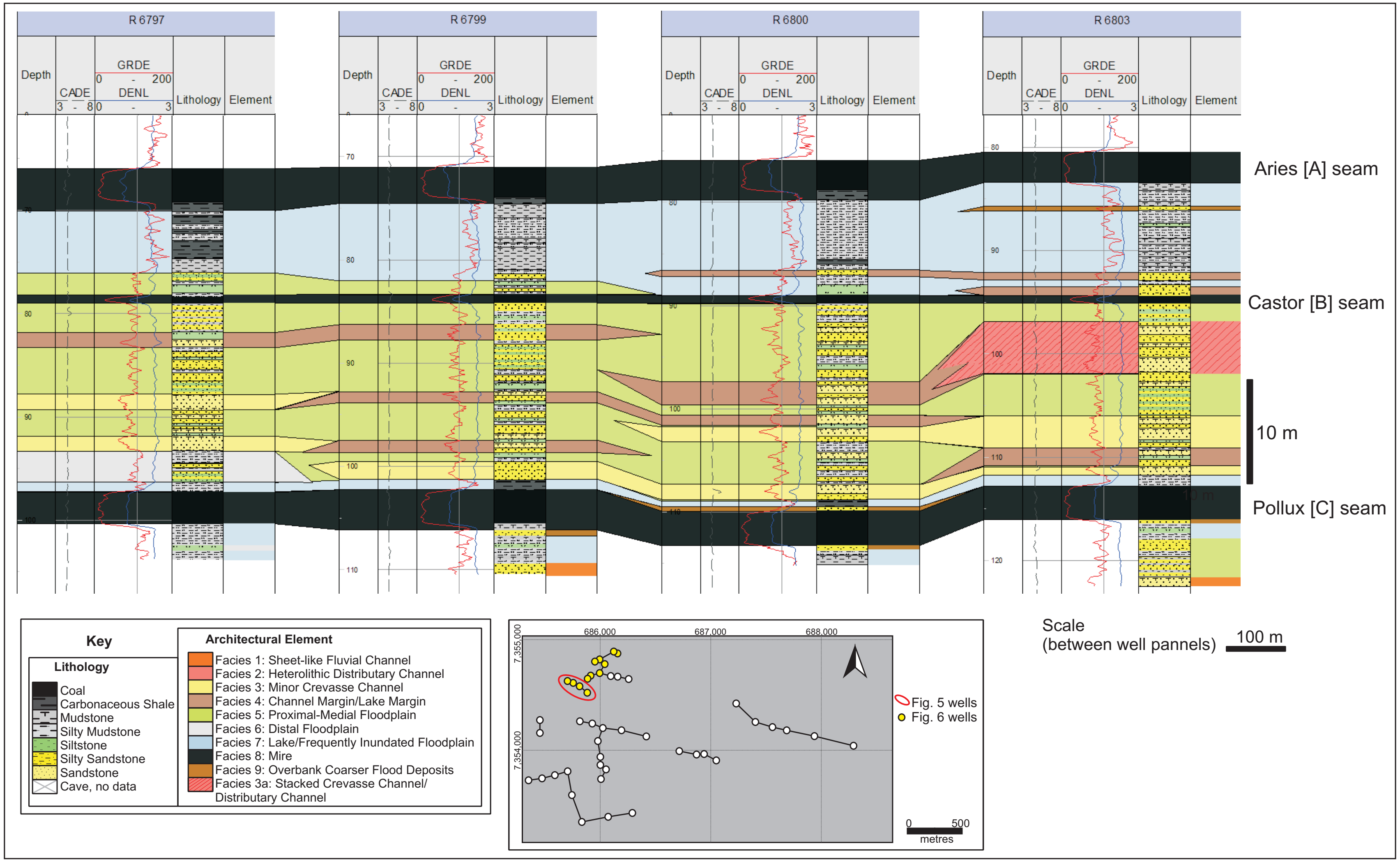
Primary Channel

- Not seen in the A-C interseam
- Blocky, fining-up log signature
- <90 API GR
- >6 m-thickness sandstone

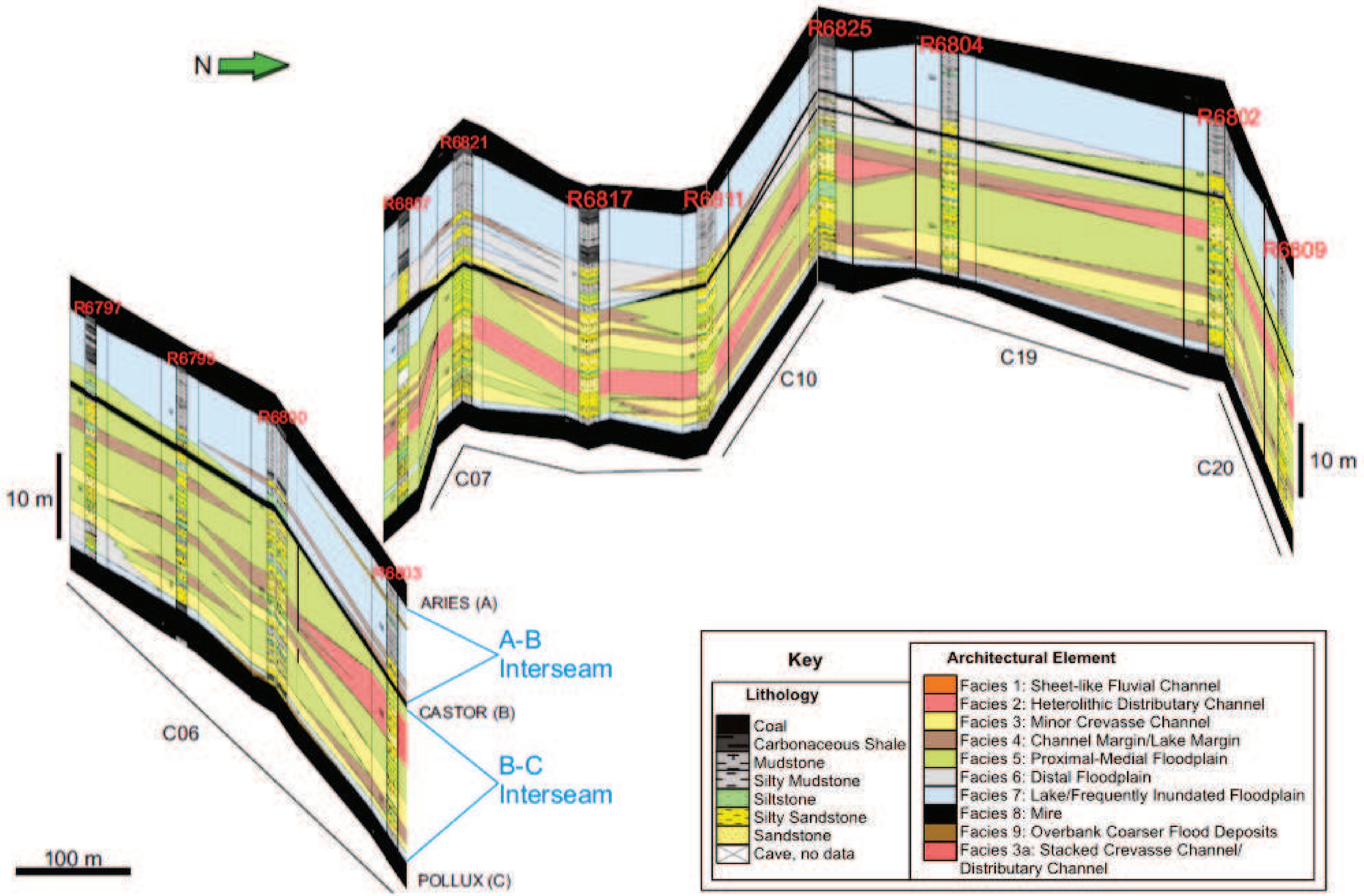


Key

- Secondary Distributary Channel
- Tertiary Crevasse/Distributary Channel
- Channel Margin/Lake Margin
- Proximal-Medial Floodplain
- Distal Floodplain
- Lake/Frequently Inundated Floodbasin
- Mire
- Sheet-like Fluvial Channel

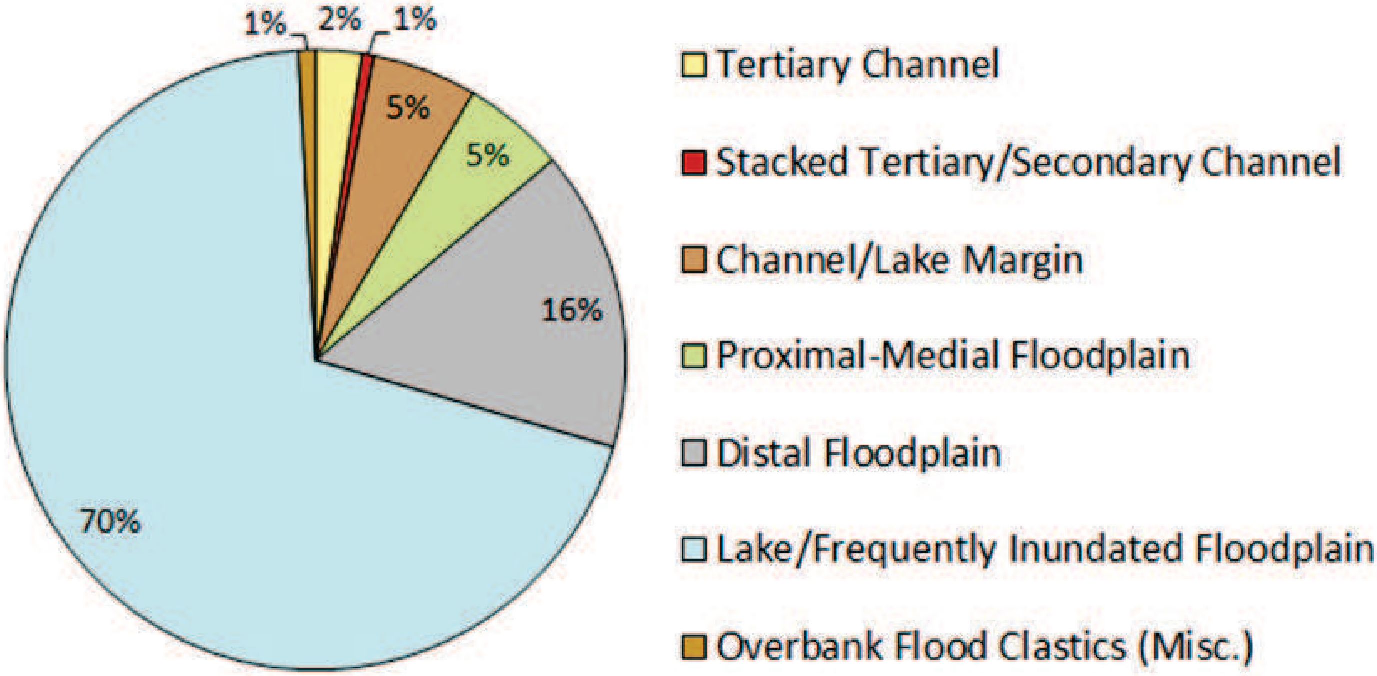


R 6797
R 6799
R 6800
R 6803
Depth
CADE
3 - 8
GRDE
0 - 200
DENL
0 - 3
Lithology
Element
Aries [A] seam
Castor [B] seam
Pollux [C] seam
10 m
Key
Lithology
Coal
Carbonaceous Shale
Mudstone
Silty Mudstone
Siltstone
Silty Sandstone
Sandstone
Cave, no data
Architectural Element
Facies 1: Sheet-like Fluvial Channel
Facies 2: Heterolithic Distributary Channel
Facies 3: Minor Crevasse Channel
Facies 4: Channel Margin/Lake Margin
Facies 5: Proximal-Medial Floodplain
Facies 6: Distal Floodplain
Facies 7: Lake/Frequently Inundated Floodplain
Facies 8: Mire
Facies 9: Overbank Coarser Flood Deposits
Facies 3a: Stacked Crevasse Channel/ Distributary Channel
686,000
687,000
688,000
7,355,000
7,354,000
Fig. 5 wells
Fig. 6 wells
0
500
metres
Scale
(between well pannels)
100 m

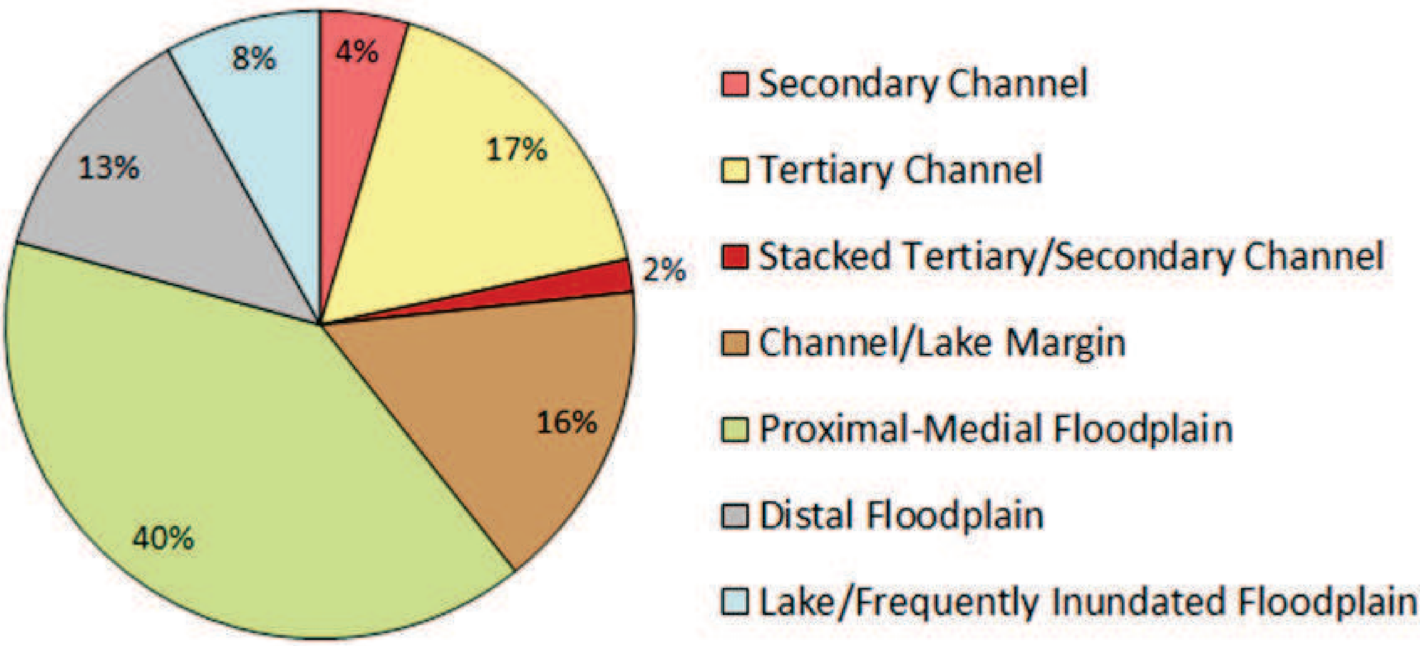


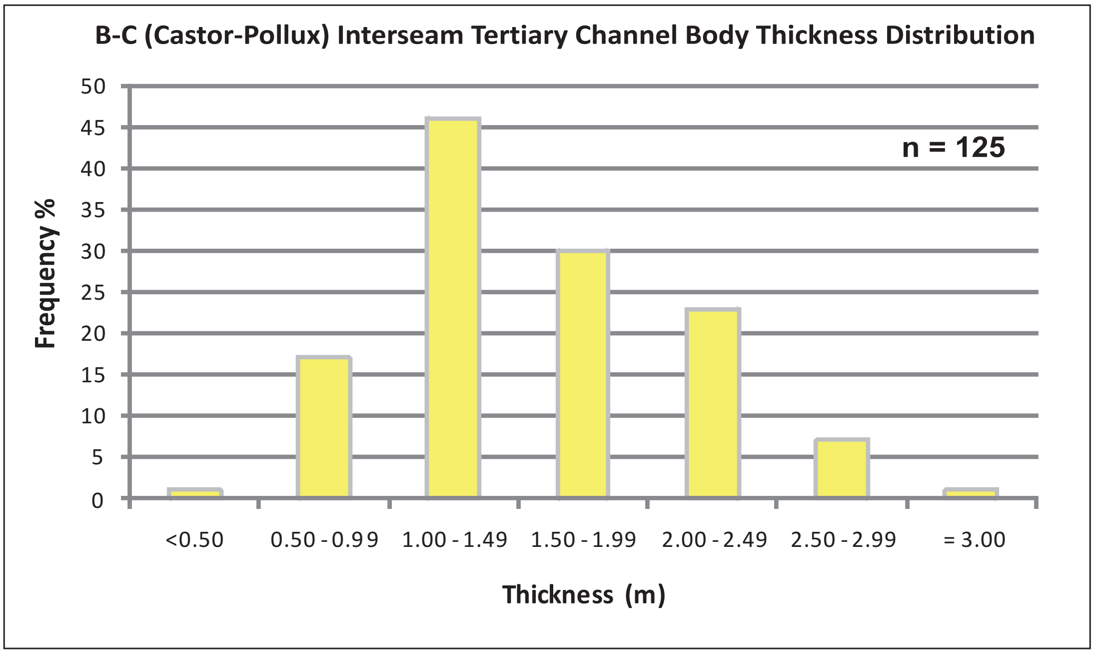
N
R6825
R6804
R6821
R6817
R6811
R6807
R6802
R6809
R6797
R6799
R6800
R6803
C06
C07
C10
C19
C20
10 m
10 m
100 m
ARIES (A)
A-B Interseam
CASTOR (B)
B-C Interseam
POLLUX (C)
Key
Lithology
Coal
Carbonaceous Shale
Mudstone
Silty Mudstone
Siltstone
Silty Sandstone
Sandstone
Cave, no data
Architectural Element
Facies 1: Sheet-like Fluvial Channel
Facies 2: Heterolithic Distributary Channel
Facies 3: Minor Crevasse Channel
Facies 4: Channel Margin/Lake Margin
Facies 5: Proximal-Medial Floodplain
Facies 6: Distal Floodplain
Facies 7: Lake/Frequently Inundated Floodplain
Facies 8: Mire
Facies 9: Overbank Coarser Flood Deposits
Facies 3a: Stacked Crevasse Channel/ Distributary Channel

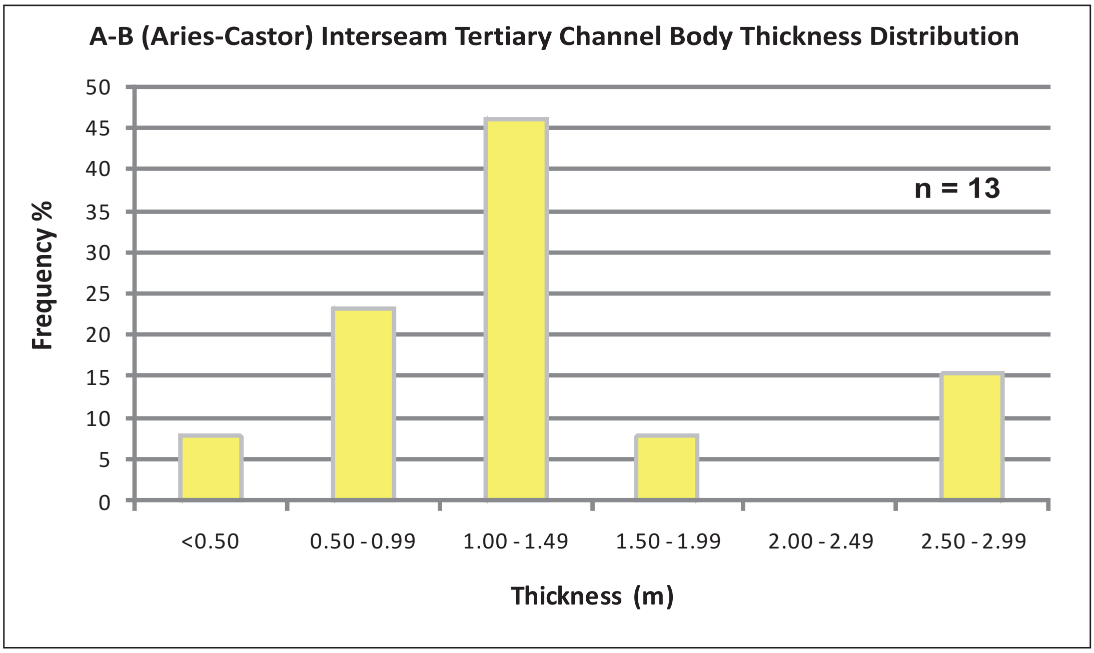
a. Proportions of Architectural Elements in the A-B interseam interval of the Rangal Coal Measures



b. Proportions of Architectural Elements in the B-C interseam interval of the Rangal Coal Measures




B-C (Castor-Pollux) Interseam Tertiary Channel Body Thickness Distribution
n = 125
Frequency %
50
45
40
35
30
25
20
15
10
5
0
<0.50
0.50 - 0.99
1.00 - 1.49
1.50 - 1.99
2.00 - 2.49
2.50 - 2.99
= 3.00
Thickness (m)


A-B (Aries-Castor) Interseam Tertiary Channel Body Thickness Distribution
n = 13
Frequency %
50
45
40
35
30
25
20
15
10
5
0
<0.50
0.50 - 0.99
1.00 - 1.49
1.50 - 1.99
2.00 - 2.49
2.50 - 2.99
Thickness (m)

Ob River, Overview

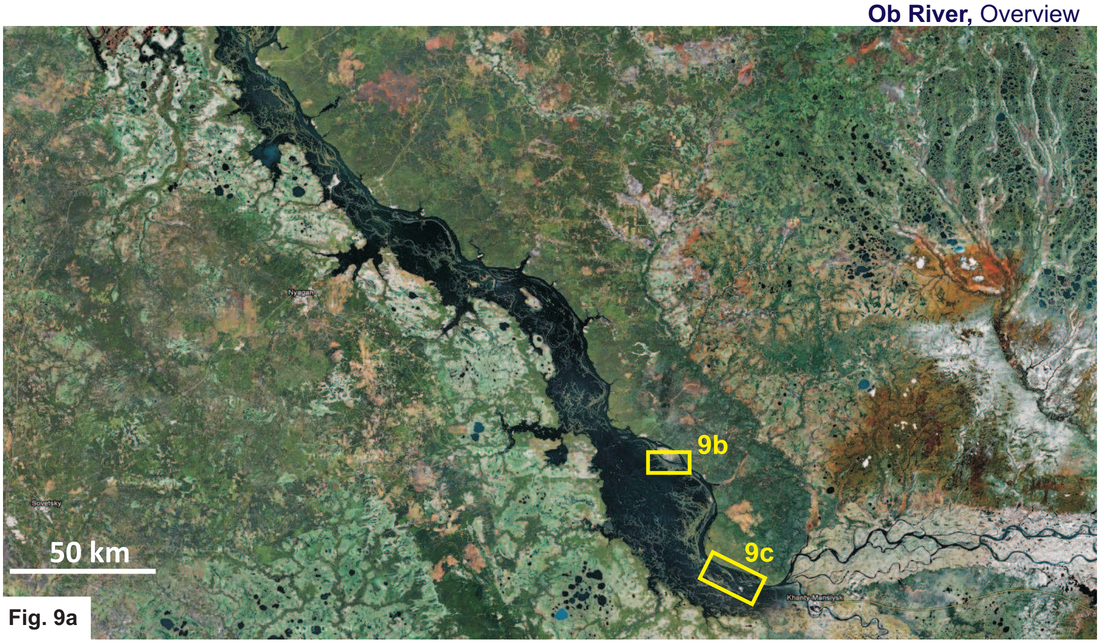


Fig. 9a

Ob River, Splay Analogue

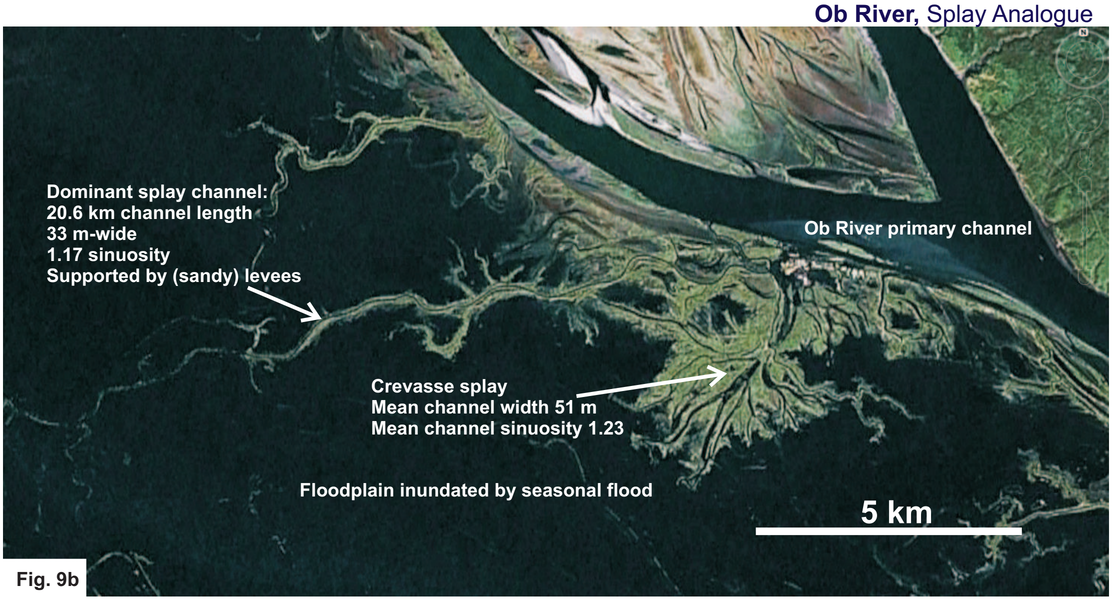


Fig. 9b

Ob River, Distributary Analogue

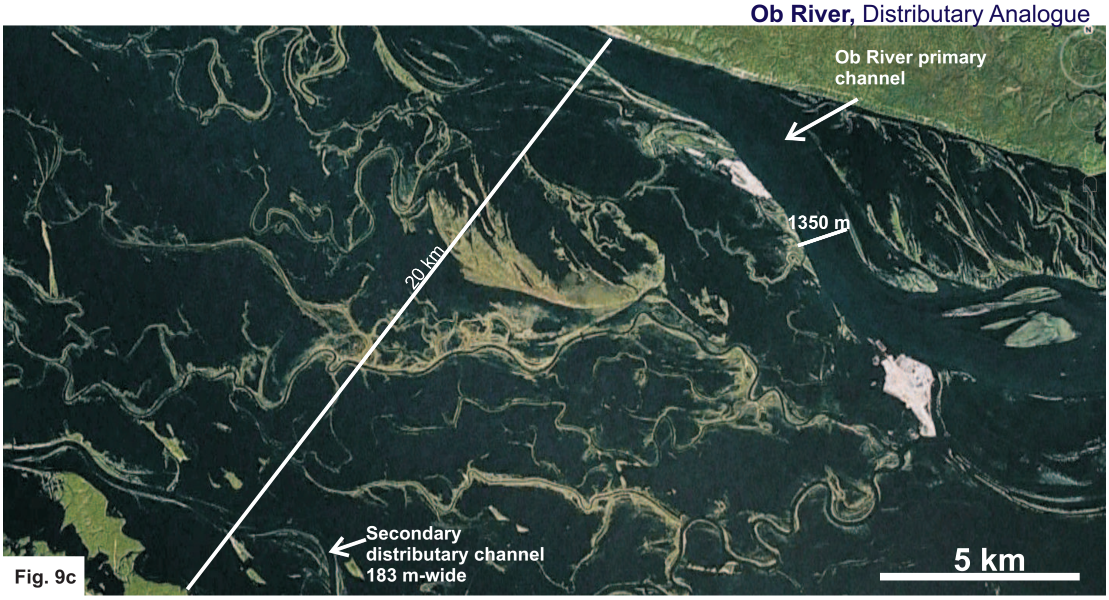


Fig. 9c

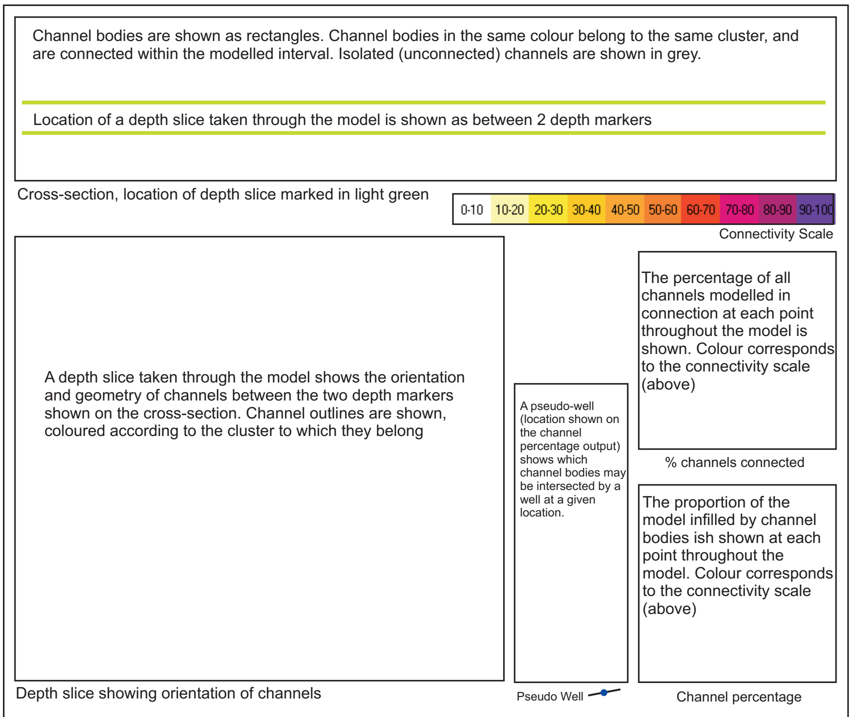


Fig. 10a

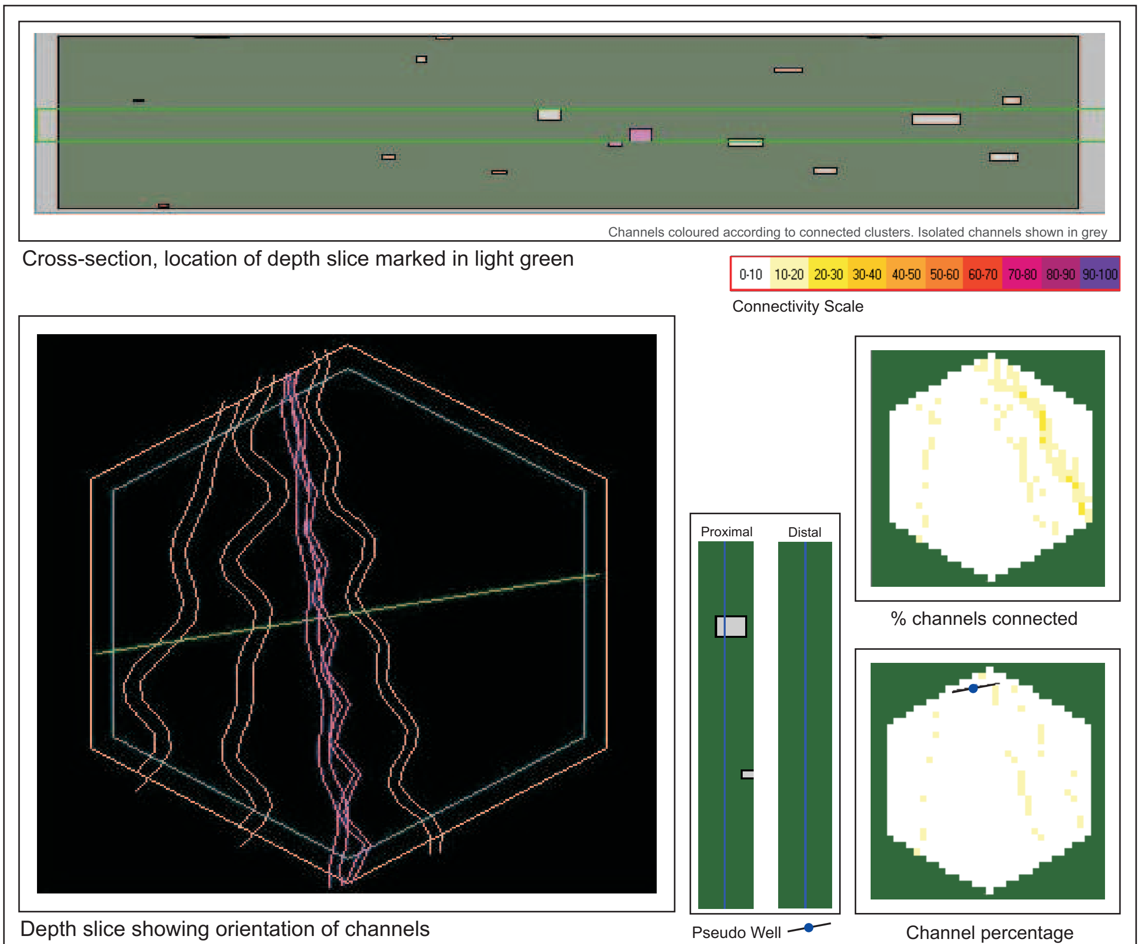
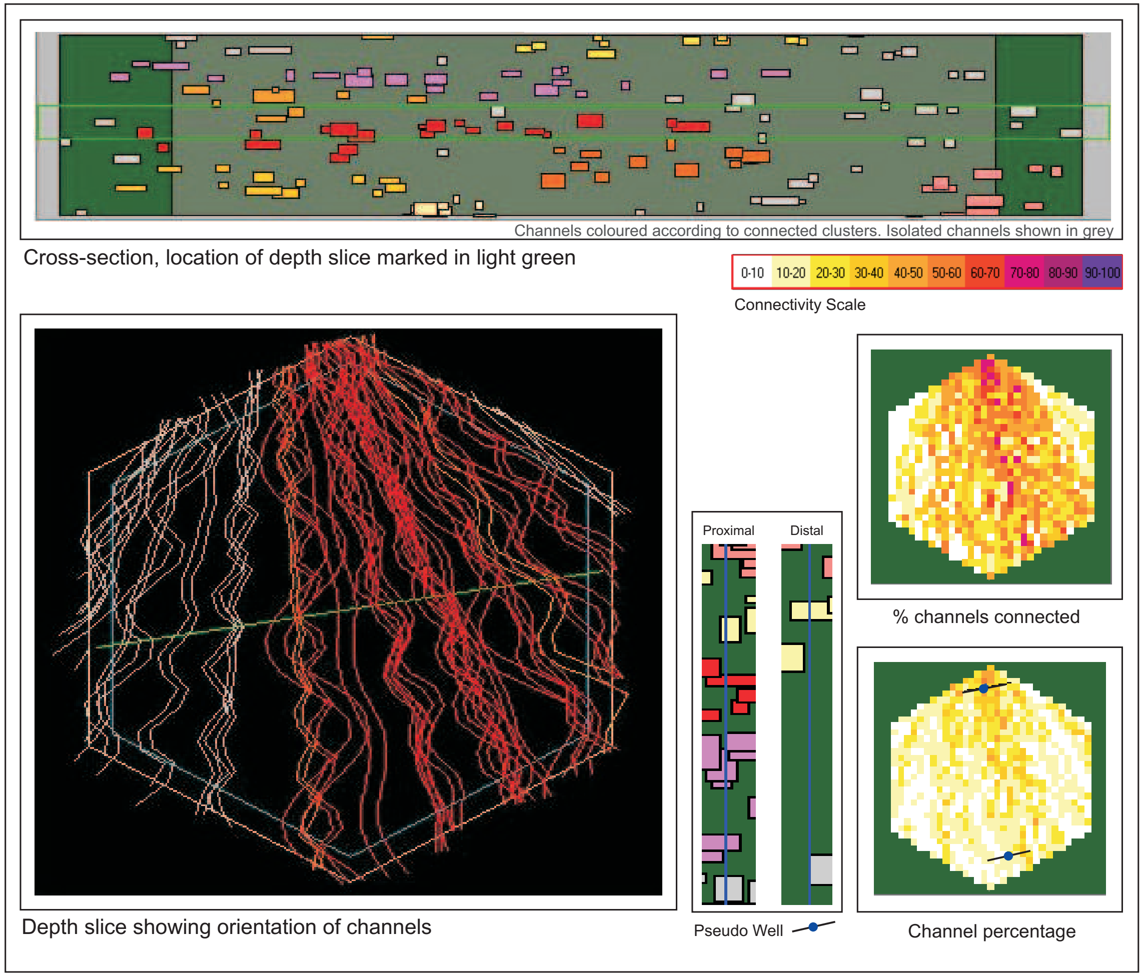
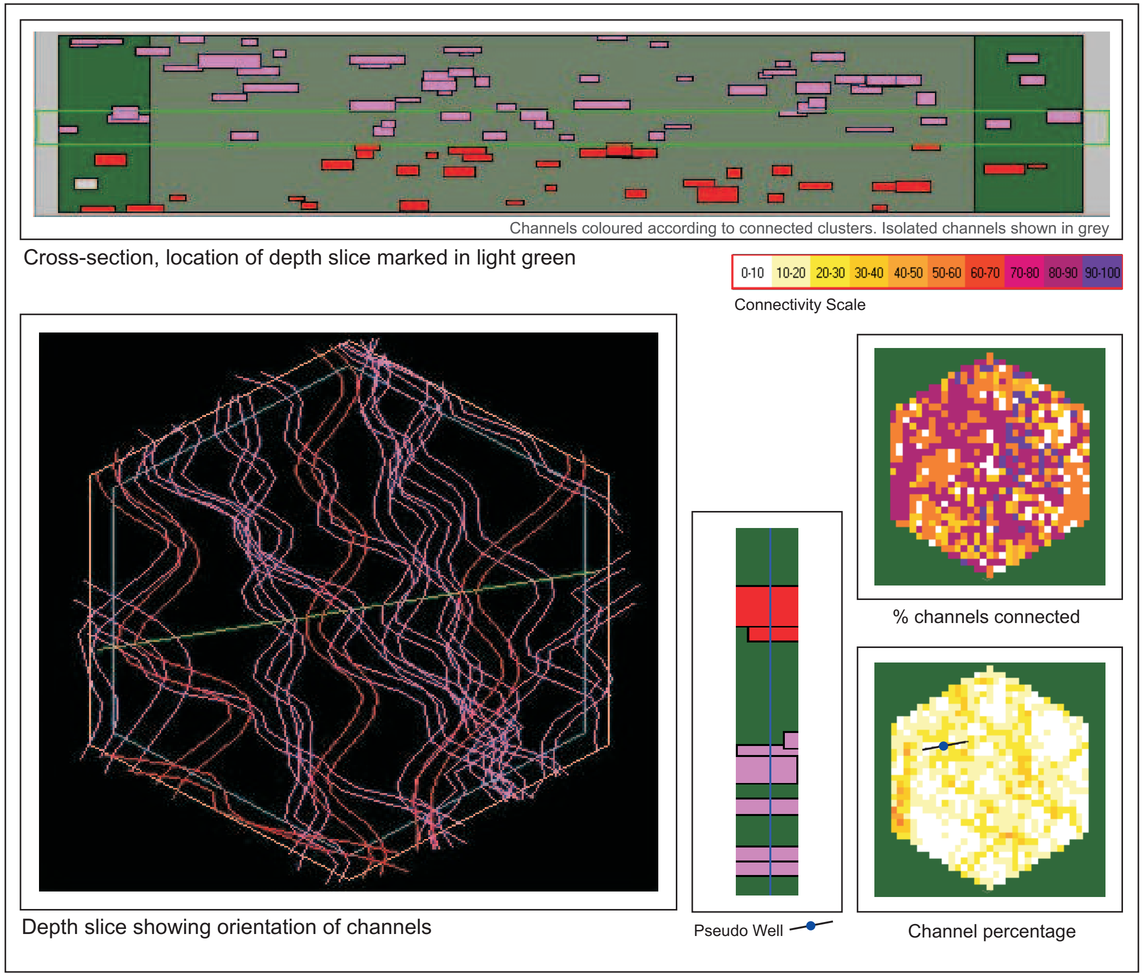


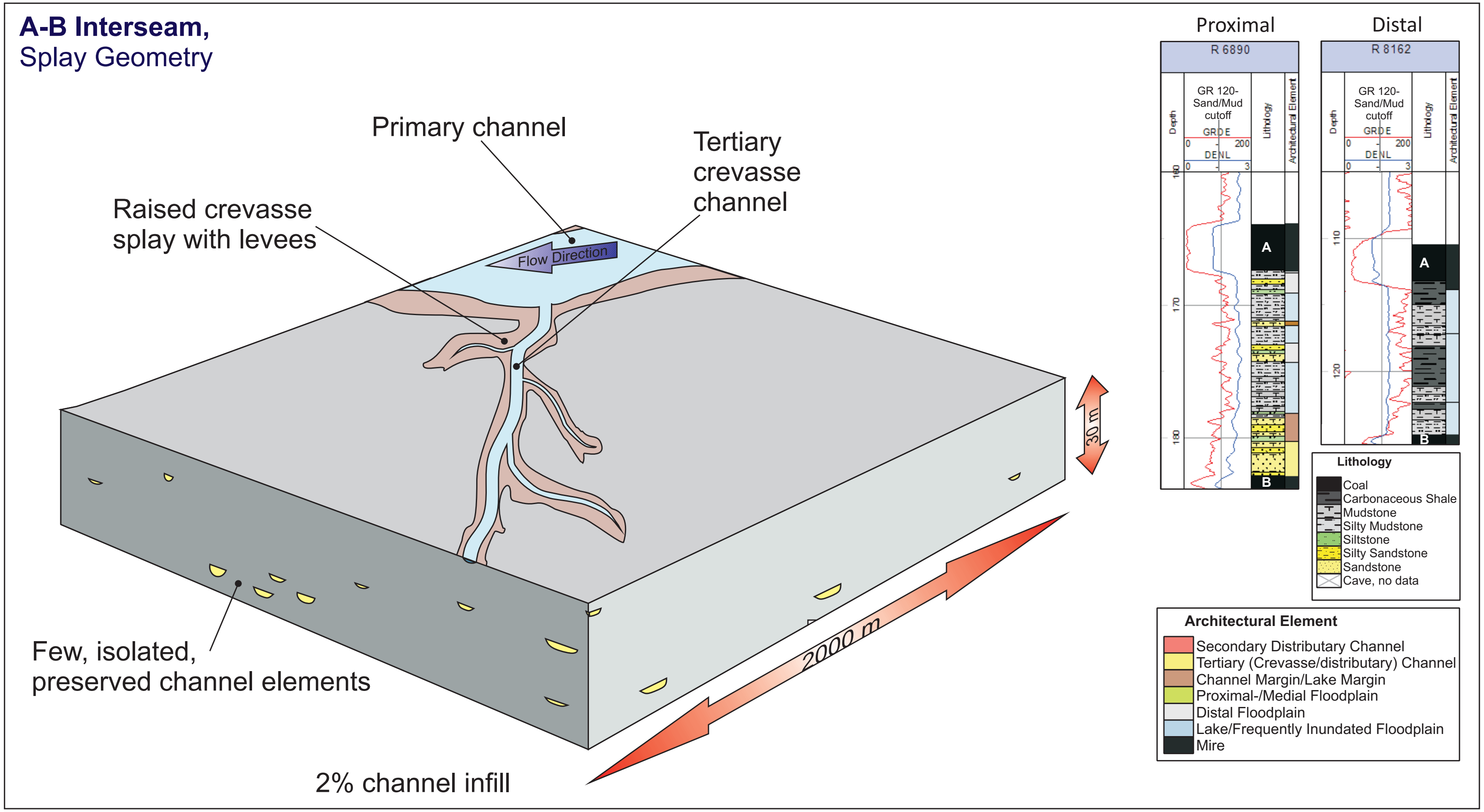
Fig. 10b



Channels coloured according to connected clusters. Isolated channels shown in grey
Cross-section, location of depth slice marked in light green
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
Connectivity Scale
% channels connected
Proximal
Distal
Depth slice showing orientation of channels
Pseudo Well
Channel percentage

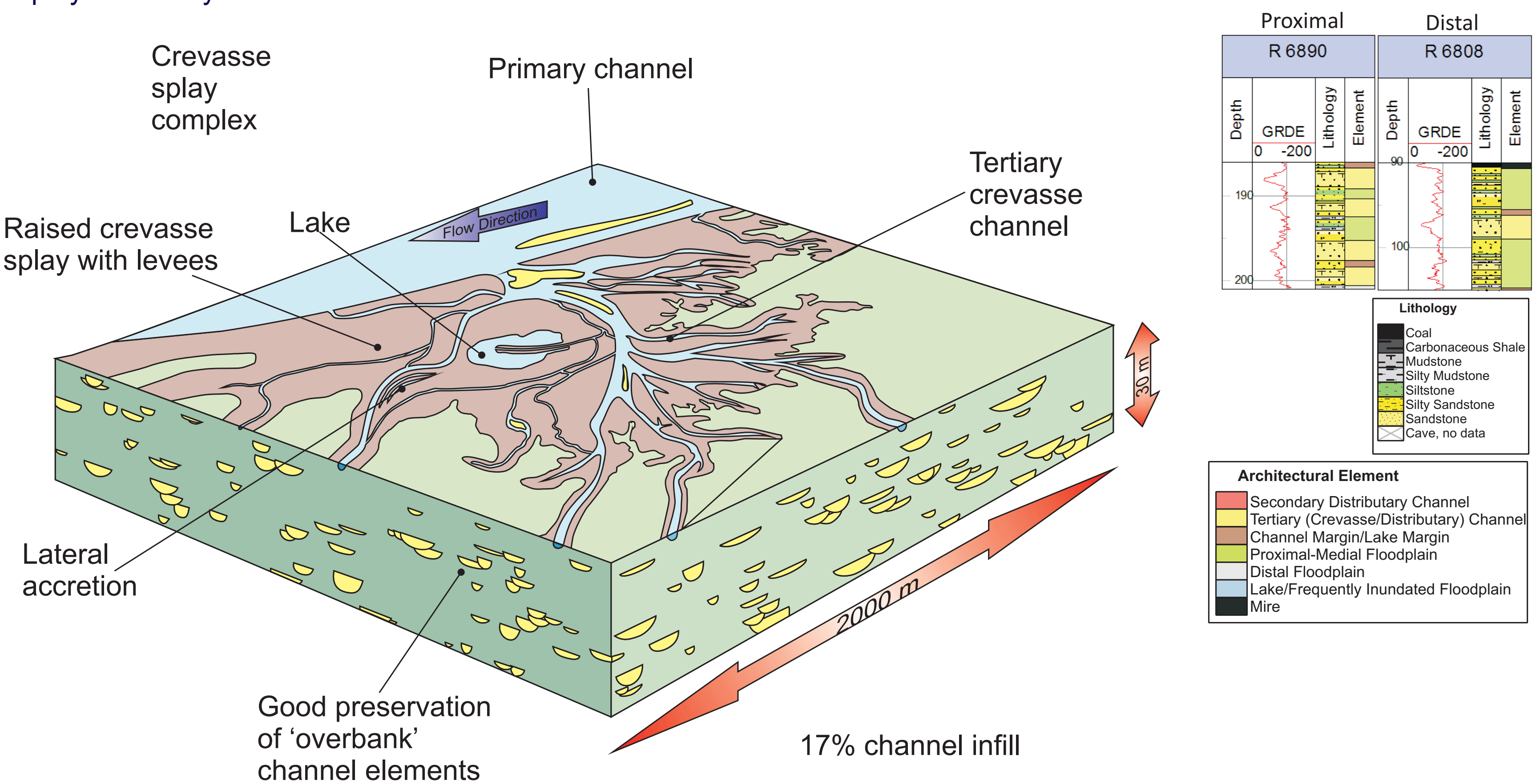


Channels coloured according to connected clusters. Isolated channels shown in grey
Cross-section, location of depth slice marked in light green
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
Connectivity Scale
% channels connected
Depth slice showing orientation of channels
Pseudo Well
Channel percentage



A-B Interseam,
Splay Geometry
Primary channel
Tertiary crevasse channel
Raised crevasse splay with levees
Flow Direction
30 m
2000 m
Few, isolated, preserved channel elements
2% channel infill
Proximal
Distal
R 6890
R 8162
Depth
GR 120-Sand/Mud cutoff
GRDE
DENL
Lithology
Architectural Element
A
B
Lithology
Coal
Carbonaceous Shale
Mudstone
Silty Mudstone
Siltstone
Silty Sandstone
Sandstone
Cave, no data
Architectural Element
Secondary Distributary Channel
Tertiary (Crevasse/distributary) Channel
Channel Margin/Lake Margin
Proximal-/Medial Floodplain
Distal Floodplain
Lake/Frequently Inundated Floodplain
Mire

B-C Interseam,
Splay Geometry



B-C Interseam,
Meandering, Bifurcating Distributary Channels