PS Geological Modeling of Outcrop Successions to Assess Analog-Based Predictions of the Sedimentary Heterogeneity in Fluvial Reservoirs*

Luca Colombera[1], Nigel Mountney[1], John Howell[2], Andreas Rittersbacher[3], and Bill McCaffrey[1]

Search and Discovery Article #41771(2016)**
Posted February 22, 2016

*Adapted from poster presentation given at AAPG 2015 Annual Convention and Exhibition, Denver, Colorado, May 31 – June 3, 2015

[1]School of Earth and Environment, University of Leeds, Leeds, United Kingdom (l.colombera@leeds.ac.uk)
[2]Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, United Kingdom
[3]Statoil ASA, Bergen, Norway

Abstract

In the generation of static reservoir models, it is common to apply quantitative information derived from outcrop analogs, especially in techniques for well correlation and stochastic modeling. Sand-body well correlations can be guided by reference to 'correlability' models, which quantify the likelihood of correlation of sand-bodies across well arrays, based on analog sand-body width distributions. Pixel-based geostatistical simulations of reservoir architecture can be conditioned by indicator variograms that are parameterized using empirical relationships based on geologic properties, whereas object-based reservoir models are commonly constrained using analog data on the geometry of sedimentary units. Through application of such geostatistical techniques, analog information also enables the construction of training images for conditioning reservoir models based on multi-point statistics. This study applies these techniques to model large-scale fluvial architecture of extensively exposed outcrops of various successions, as constrained by data from outcrops of analog successions. A typical subsurface workflow has been replicated, the aim being to test the value and limitations of the methods mentioned above, and to assess the impact of analog choice in workflows involving their use. Vertical 'dummy' wells (minimum spacing = 50 m) were placed across outcrop architectural panels representing km-wide exposed sections; the intervening architecture was predicted by correlability models and geostatistical simulations, constrained on outcrop-analog data drawn from an architectural database (FAKTS). The relevant FAKTS output was filtered to obtain composite analogs that match with the outcrop successions being modeled in terms of key system parameters (e.g. river discharge regime) and architectural properties (e.g. net-to-gross ratio). The value of the predictive methods was assessed by quantifying the degree of match between forecasted and known outcrop architecture, in terms of channel-complex correlability and static connectivity. Comparisons of correlability and geostatistical models vs. outcrop observations highlight the effectiveness of the different methods and demonstrate the influence of well density on the confidence assigned to predictions. Results support modeling approaches based on the use of a varied range of analogs as a way to consider uncertainty in analog choice, and on alternative modeling methods to account for potential algorithm-related pitfalls.

FRG Fluvial & Eolian Research Group

UNIVERSITY OF LEEDS

Geologic modeling of outcrop successions to assess analog-based predictions of the sedimentary heterogeneity in fluvial reservoirs

Luca Colombera[1], Nigel Mountney[1], John Howell[2], Andreas Rittersbacher[3], Bill McCaffrey[1]

1) Fluvial & Eolian Research Group, University of Leeds, UK
2) Department of Geology and Petroleum Geology, University of Aberdeen, UK
3) Statoil ASA, Bergen, Norway

Abstract

In the generation of static reservoir models it is common to apply quantitative information derived from outcrop analogs, especially in techniques for well correlation and stochastic modeling. Sand-body well correlations can be guided by reference to 'correlability' models, which quantify the likelihood of correlation of sand-bodies across well arrays, based on analog sand-body width distributions. Pixel-based geostatistical simulations of reservoir architecture can be conditioned by indicator variograms that are parameterized using empirical relationships based on geologic properties, whereas object-based reservoir models are commonly constrained using analog data on the geometry of sedimentary units. Through application of such geostatistical techniques, analog information is also used to establish the constraints on training images for conditioning reservoir models based on multi-point statistics.

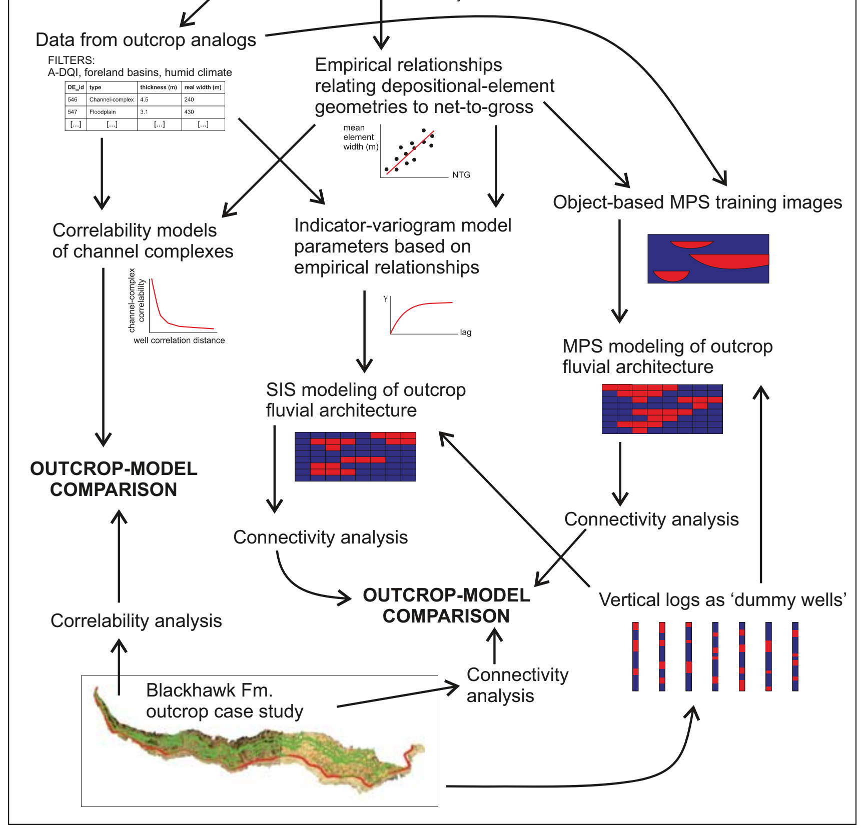
This study applies these techniques to model large-scale fluvial architecture of extensively exposed outcrops of various successions, as constrained by data from outcrops of analog successions. A typical subsurface workflow has been replicated, the aim being to test the value and limitations of the methods mentioned above, and to assess the impact of analog choice in workflows involving their use.

Vertical 'dummy' wells (minimum spacing = 50 m) were placed across outcrop architectural panels representing km-wide exposed sections; the intervening architecture was predicted by correlability models and geostatistical simulations of outcrop-analog data drawn from an architectural database (FAKTS). The relevant FAKTS output was filtered to obtain composite analogs that match with the considered analogs based on system parameters (e.g. river discharge regime) and architectural properties (e.g. net-to-gross ratio).
The value of such predictive methods was assessed by quantifying the degree of match between forecasted and known outcrop architecture, in terms of channel-complex correlability and static connectivity. Comparisons of correlability and geostatistical models vs. outcrop observations highlight the effectiveness of the different methods and demonstrate the influence of well density on the confidence assigned to predictions.
Results support modeling approaches based on the use of a varied range of analogs as a way to consider uncertainty in analog choice, and on alternative modeling methods to account for potential algorithm-related pitfalls.

Workflow

FAKTS database

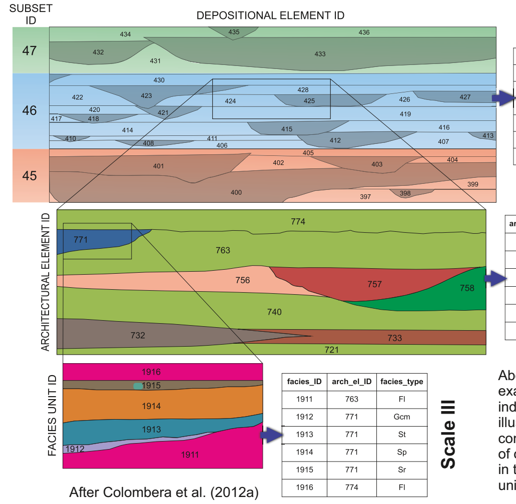
The **Fluvial Architecture Knowledge Transfer System** (FAKTS) is a database that stores data about fluvial sedimentary architecture, derived from both original fieldwork studies and peer-reviewed literature. The database incorporates data from both modern rivers and ancient successions that are considered as potential analogs to hydrocarbon reservoirs hosted in fluvial strata.



FAKTS database overview

FAKTS GENETIC-UNIT HIERARCHY

In FAKTS, **each case study is subdivided into a series of stratigraphic volumes** (subsets) characterized by having the same depo-system attributes. **Each subset is broken down into sedimentary units belonging to multiple scales, recognizable as lithosomes in ancient successions and as geomorphic elements in modern river systems.** The tables associated with these genetic units contain a combination of interpreted soft data (e.g. object type) and measured hard data (e.g. thickness and other dimensional properties). **The hierarchical containment of genetic units within higher scale parent objects is recorded** (depositional elements within subsets, architectural elements within depositional elements, facies units within architectural elements) by using numeric indices (Colombera et al. 2012a).

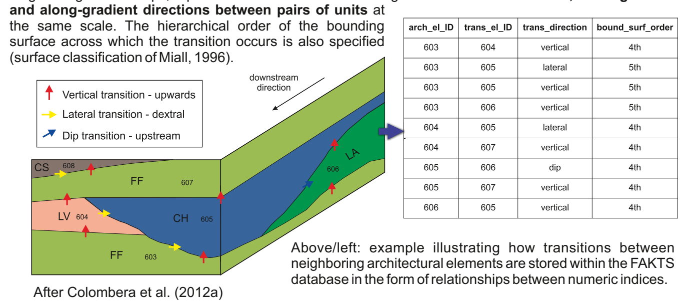


Above/left: example showing object indexing at all scales and illustrating how the nested containment of each order of objects is implemented in the tables by means of unique numeric indices.

After Colombera et al. (2012a)

FAKTS GENETIC-UNIT SPATIAL RELATIONSHIPS

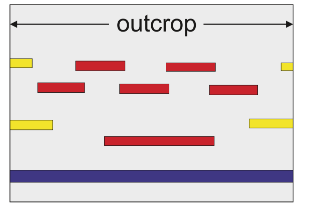
The same numeric indices that are used for representing containment relationships, are also used for object neighboring relationships, represented within tables containing **transitions in the vertical, cross-gradient and along-gradient directions between pairs of units** at the same scale. The hierarchical order of the bounding surface across which the transition occurs is also specified (surface classification of Miall, 1996).



Above/left: example illustrating how transitions between neighboring architectural elements are stored within the FAKTS database in the form of relationships between numeric indices.

After Colombera et al. (2012a)

FAKTS GENETIC-UNIT GEOMETRY



complete lengths
partial lengths
unlimited lengths

The dimensional parameters of each genetic unit can be stored as thicknesses, flow-perpendicular (i.e. cross-gradient) **widths, downstream lengths, cross-sectional areas,** and **planform areas**. Widths and lengths are classified according to the completeness of observations into complete, partial or unlimited categories, as proposed by Geehan & Underwood (1993). Apparent widths are stored whenever only oblique observations with respect to the unit-scale average paleoflow direction are available. Where derived from borehole correlations, widths and lengths are always classified as 'unlimited'.

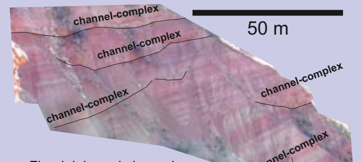
Modified after: Geehan & Underwood (1993)

ANALOG CLASSIFICATION AND QUERY

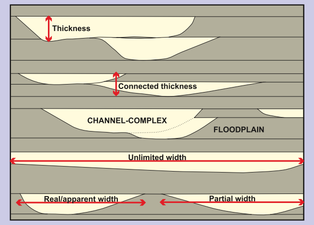
One of the key aspects of the FAKTS database is the **classification of each case study and parts thereof according to controlling factors** and associated dependent variables (e.g. description of climatic and tectonic context, subsidence rates, relative base-level changes, basin vegetation type and abundance, suspended sediment load component) **or intrinsic descriptors** (e.g. dominant transport mechanism, channel/river pattern, relative distality of each stratigraphic volume).
In addition, FAKTS stores **metadata that describe the original source of the data** and information including the methods of acquisition employed, the chronostratigraphy of the studied interval, the geographical location, the names of the basin and river or lithostratigraphic unit, and a dataset **quality index** (DQI), incorporated as a threefold ranking system of perceived dataset quality and reliability based on established criteria.
When FAKTS is interrogated, it is possible to filter the output quantitative information on fluvial architecture on any of the above parameters, so that the **analogy with a subsurface reservoir of interest can be defined on either architectural properties** (e.g. net-to-gross ratio), **or depo-system parameters** (e.g. high-sinuosity river system), or both. This output information can be exported to spreadsheets, and analysed and represented in a variety of forms.

DEPOSITIONAL ELEMENTS

Employed in all following work

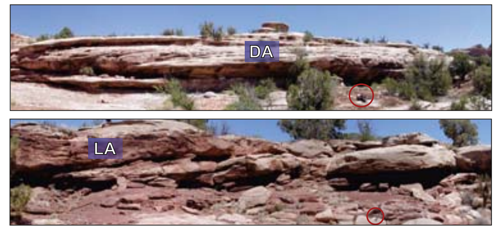


Floodplain and channel-complex depositional elements from the Tremp Group of the Tremp-Graus Basin (Spain).



Depositional elements are classified as channel-complex or floodplain elements. Channel-complexes represent channel-bodies defined on the basis of flexible but unambiguous geometric criteria, and are not related to any particular genetic significance or spatial or temporal scale; they range from the infills of individual channels, to compound, multi-storey valley-fills. This definition facilitates the inclusion of datasets that are poorly characterized in terms of the geological meaning of these objects and their bounding surfaces (especially subsurface datasets – Colombera et al. 2012a; 2013).
Floodplain segmentation into depositional elements is subsequent to channel-complex definition, as floodplain deposits are subdivided according to the lateral arrangement of channel-complexes.

ARCHITECTURAL ELEMENTS

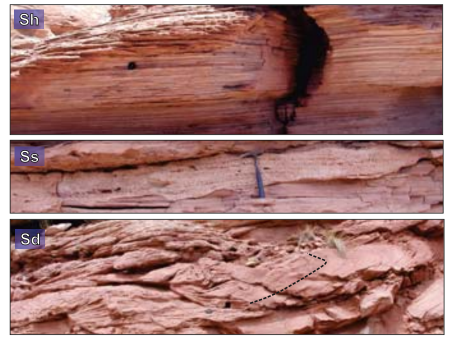


Above: examples of preserved architectural elements (downstream and laterally accreting barforms) from the Lower Jurassic Kayenta Formation (SE Utah, USA).

FAKTS architectural elements are defined as components of a fluvial depositional system with characteristic facies associations and architectural properties that make them interpretable in terms of sub-environments; they typically represent the preserved product of the finite morphodynamic evolution of geomorphic elements. The element nomenclature follows the scheme by Miall (1996), with some additions (cf. Colombera et al. 2013).

FACIES UNITS

FAKTS facies units are defined as sub-bed scale sedimentary units characterized by a single lithofacies type, and bounded by surfaces that record a change in facies type, or a significant change in paleoflow, or erosion (cf. 2nd-order surfaces of Miall, 1996). FAKTS lithofacies types are based on characters of both textural (grain-size, support) and structural (primary or secondary structures) nature. The facies nomenclature follows the scheme by Miall (1996), with some additions (cf. Colombera et al. 2012a; 2013).



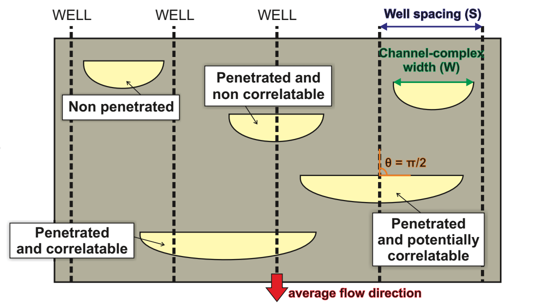
Above: examples of sandstone facies units from the Lower Jurassic Kayenta Formation in SE Utah.

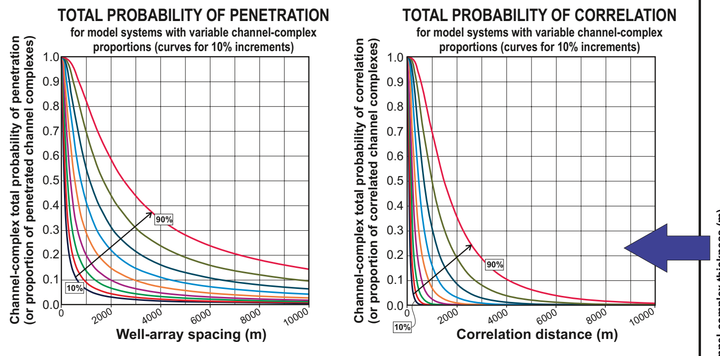
FAKTS applications

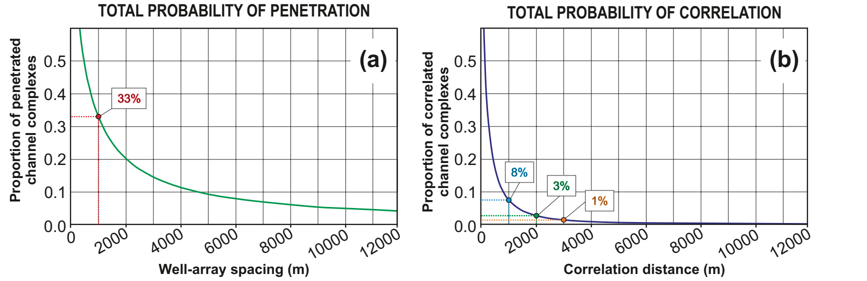
CORRELABILITY MODELS FOR GUIDING WELL-TO-WELL CORRELATIONS OF CHANNEL COMPLEXES

Assuming orthogonal penetration of a well array with constant spacing S into channel complexes, it is possible to combine analytical expressions for the conditional probability of penetration and correlation of a channel complex with width W with FAKTS-derived probability density functions of channel-complex width to **obtain total probabilities of channel-complex penetration and correlation**. Results can be integrated and expressed **as functions of well-spacing and correlation distance** respectively. **From these curves, 'correlability' models** (i.e. functions **that quantify the proportion of penetrated channel complexes that are likely to be correlatable as a function of correlation distance**) **can be obtained** as exemplified below (see Colombera et al. 2014).

Empirical relationships between morphometric parameters of channel and floodplain depositional elements (width and thickness mean, standard deviation) and net-to-gross (see following section) **can be used to compile curves that relate the total probabilities of penetration and correlation that can be expected given a value of net-to-gross**. Again, correlability models can be derived from these curves to match the net-to-gross of any subsurface interval of interest.







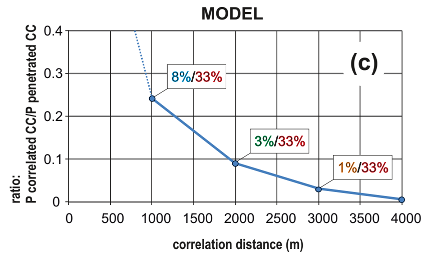
IDEAL EXAMPLE:

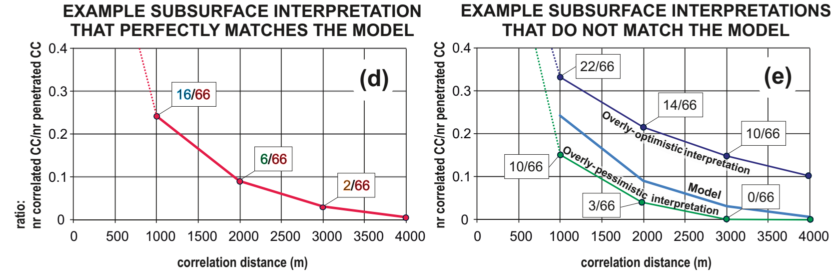
subsurface succession with:
– well spacing = 1000 m
– penetrated channel complexes = 66

model based on FAKTS analogs (c).

3 alternative well-correlation panels are represented: a perfect match (d), and excessively optimistic and conservative interpretations (e).

After Colombera et al. (2014)

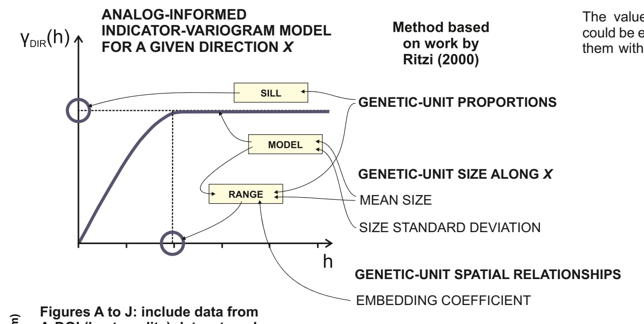




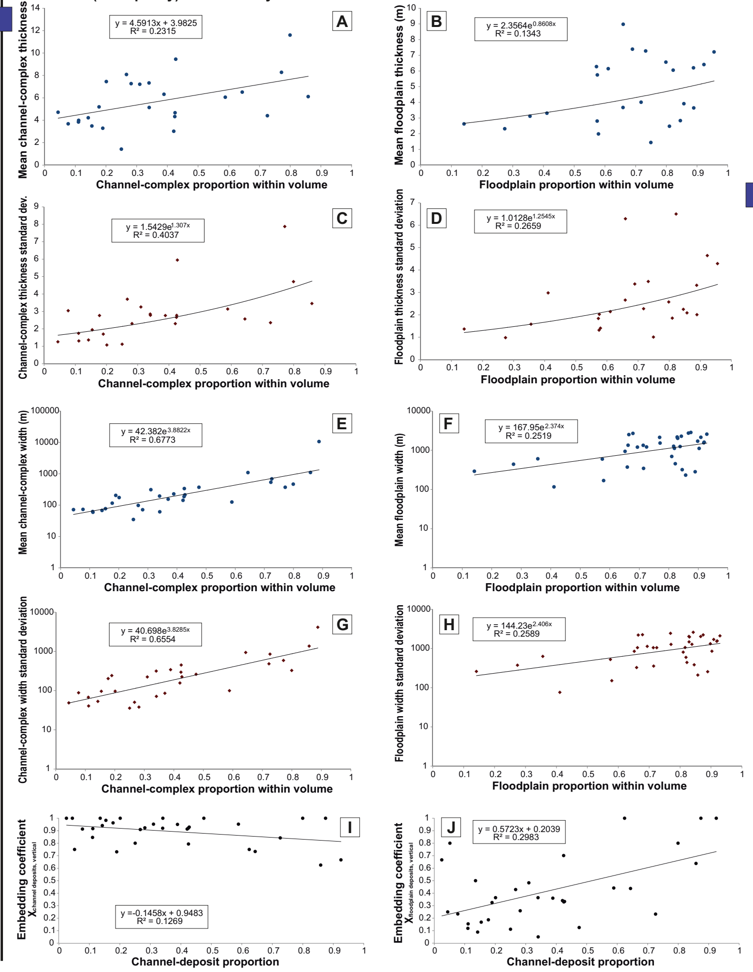
The **ratio between the total probability of correlation and the total probability of penetration** can be **plotted as a function of correlation distance** (see the example on the left, figure c): this function **quantifies the proportion of penetrated channel complexes that are likely to be correlatable as a function of correlation distance**, on the basis of database-derived analog experience. **This curve is dubbed 'correlability model', and represents the model against which to test subsurface interpretations based on well-to-well correlation** across a uniformly spaced well array.

Evaluation of the realism of subsurface well-to-well correlations of the sandbodies is carried out by determining the discrepancy between the correlability model and an analogous curve based on the ratio between correlated and penetrated channel complexes, as represented in **the correlation panel under evaluation** (in the example on the left, figures d and e, representing alternative examples). In effect, this process of quantitative comparison permits **assessment of whether well correlations are too optimistic or too pessimistic, as compared with suitable analogs**, taking into account sampling of variability in sandbody size (cf. Colombera et al. 2014).

EMPIRICALLY CONSTRAINED INDICATOR-VARIOGRAM PARAMETERS



Figures A to J: include data from A-DQI (best quality) datasets only



Experience from **multiple analogs can be used to compile empirical relationships between morphometric parameters of** channel and floodplain **depositional elements** (width and thickness mean, standard deviation) **and net-to-gross**, which can then be **used to parameterize indicator variograms for channel and floodplain deposits** (cf. Colombera et al. 2012b). This approach was taken to derive the range, sill and model for indicator variograms for the vertical and horizontal directions, for channel and floodplain deposits.

The values of horizontal indicator variogram range could be employed in real-world situations by coupling them with indicator variogram ranges for the vertical direction derived through the common curve-fitting of well data, to condition pixel-based models.

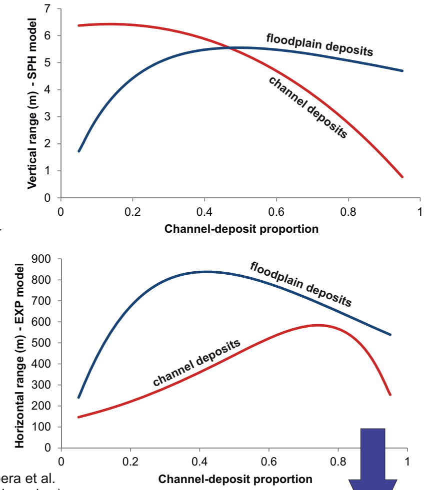
The **value of SIS predictions made on the basis of net-to-gross-based relationships was assessed by evaluating generic unconditional SIS realizations**, constrained on indicator-variogram ranges based on said relationships, and assuming exponential variogram models for both channel and floodplain deposits. Simulations of a 4 km-wide, 200 m-high (horizontal resolution: 4 m; vertical resolution 1 m) fluvial stratigraphy have been run for a 10% net-to-gross scenario. The results are presented below.

- Φ is equal to 1.5 or 3 for a spherical or exponential model respectively
- p_k is the proportion of k
- $\overline{l_{k,x}}$ is its mean size along direction x
- $\chi_{k,x}$ is called 'embedding coefficient' and defined as

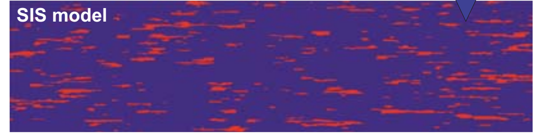
$$\chi_{k,x} = \frac{\text{number of contacts defining a change from category k to category j along x}}{\text{number of occurrences of category k}}$$

$$a_{k,x} = \Phi(1-p_k)\bar{l}_{k,x}\chi_{k,x}^{-1}$$

Indicator variogram range
for category k along direction x (Ritzi 2000)

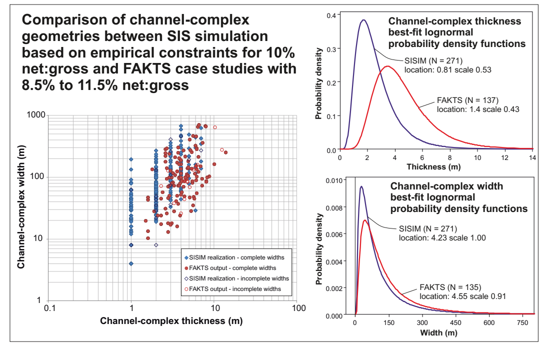


After Colombera et al. (AAPG Bull., in review)



grid size: X = 4000 m, Y = 200 m (vertical exaggeration x5) ● floodplain deposits ● channel deposits

Comparison of channel-complex geometries between SIS simulation based on empirical constraints for 10% net:gross and FAKTS case studies with 8.5% to 11.5% net:gross



PetroleumLeeds

Fluvial & Eolian Research Group
School of Earth and Environment
Leeds LS2 9JT UK

contact: Luca Colombera
email: l.colombera@leeds.ac.uk
URL: http://frg.leeds.ac.uk

AREVA · bhpbilliton · ConocoPhillips · MURPHY OIL CORPORATION · nexen · Saudi Aramco · Shell · Tullow · woodside · YPF

FRG Fluvial & Eolian Research Group

UNIVERSITY OF LEEDS

Geologic modeling of outcrop successions to assess analog-based predictions of the sedimentary heterogeneity in fluvial reservoirs

Luca Colombera[1], Nigel Mountney[1], John Howell[2], Andreas Rittersbacher[3], Bill McCaffrey[1]

1) Fluvial & Eolian Research Group, University of Leeds, UK
2) Department of Geology and Petroleum Geology, University of Aberdeen, UK
3) Statoil ASA, Bergen, Norway

Case study 1: Blackhawk Formation (Campanian, Utah, USA)

Given that this work aims to assess the proposed predictive tools through their employment in **modeling outcropping fluvial architecture by adopting subsurface practice**, it is essential that the fluvial successions considered as real-world tests are extensively exposed both vertically and laterally. For this study, a **laterally extensive outcrop exposing the continental interval of the Upper Cretaceous (Campanian) Blackhawk Formation along a steep cliff in the central part of the Wasatch Plateau** (Utah, USA) has been considered. This outcrop forms part of the dataset discussed by Rittersbacher et al. (2014).

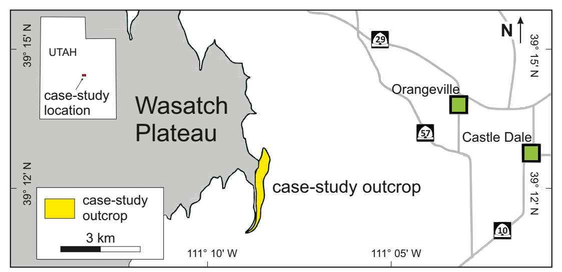
The non-marine Blackhawk Formation consists of a ca. 200 to 300 m-thick succession of mudstone, sandstone and coal that is interpreted to have accumulated in an alluvial to coastal plain setting (cf. Flores et al. 1984; Adams & Bhattacharya 2005; Hampson et al. 2012) as part of a clastic wedge that prograded eastward from the Sevier Orogen into a retroarc foreland basin on the western margin of the Western Interior Seaway.

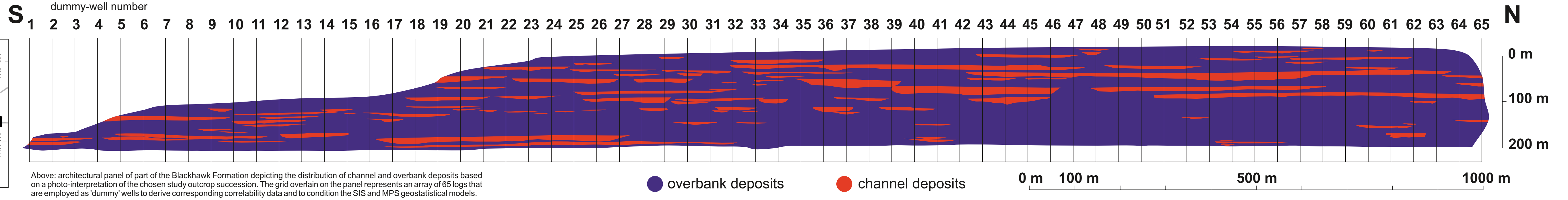
Architecturally, the non-marine Blackhawk Formation consists of **isolated channel sandstone bodies encased in fine-grained mudstones and thin sandstones of overbank origin that are themselves locally interbedded with coal bodies**. The mud-prone character of the Blackhawk Formation makes the **current study particularly relevant to low net-to-gross subsurface fluvial depositional systems**, in which predictions regarding sand-body distribution are typically very important.

The dataset used in this work takes the form of an **architectural panel that depicts a section that is 3.2 km wide and 200 m high**. The panel has been constructed via the photo-interpretation of a LIDAR-acquired 'virtual outcrop model' (*sensu* Pringle et al. 2006), resulting in the generation of a 'map' of the **distribution of the sand-prone channel-bodies in a background of dominantly fine-grained floodplain deposits**. The outcrop is conveniently oriented ca. north-south, i.e. close to orthogonal to the mean drainage direction of the Blackhawk Formation paleo-river systems (Rittersbacher et al. 2014).

The photo-interpreted architecture has been projected onto a vertical plane, and a series of **65 vertical logs, each spaced 50 m apart, have been constructed across the panel to serve as 'dummy' wells** (see below), permitting the derivation of outcrop channel-complex correlability data and the conditioning the SIS and MPS geostatistical models.

Below: location map showing the position of the outcropping study succession in the central Wasatch Plateau area (Utah, USA).





Above: architectural panel of part of the Blackhawk Formation depicting the distribution of channel and overbank deposits based on a photo-interpretation of the chosen study outcrop succession. The grid overlain on the panel represents an array of 65 logs that are employed as 'dummy' wells to derive corresponding correlability data and to condition the SIS and MPS geostatistical models.

overbank deposits
channel deposits

FAKTS analog selection

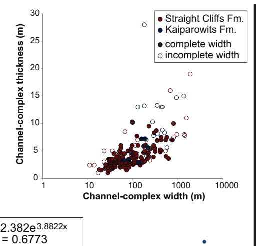
FAKTS was queried to derive filtered depositional-element data with which to model the Blackhawk Formation architecture. Data filtering on system parameters helps narrow down variability (i.e. uncertainty).

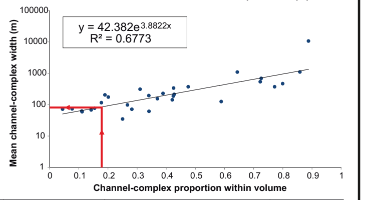
Two types of analogy were considered:

- analogs that partially match with the Blackhawk Formation in terms of **system classification** (datasets with highest – i.e. A – DQI and relating to successions accumulated under the influence of humid/sub-humid climates in foreland basins;
- empirical relationships relating depositional-element width statistics to **channel-deposit proportion** (18% for the Blackhawk Formation panel).

A summary of analog depositional-element width and thickness descriptive statistics (inclusive of data from partial and unlimited widths) is given in the table below for channel complexes, together with corresponding statistics derived from the Blackhawk Formation panel. Corresponding data were also derived for floodplain depositional elements.

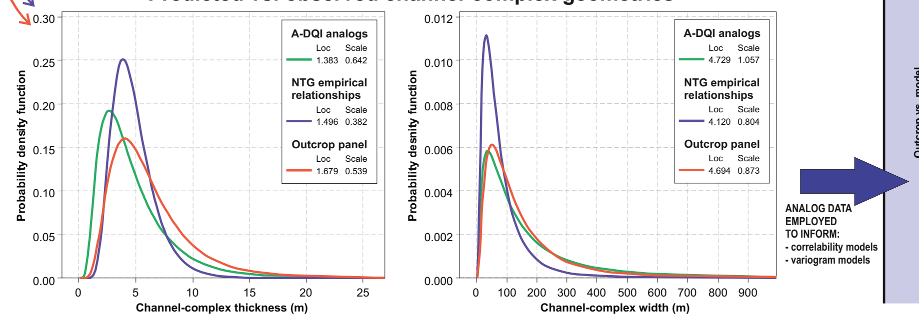
The average width of the channel complexes is overestimated by the A-DQI synthetic analog and underestimated by the corresponding net-to-gross-based empirical relationship. The average width of the floodplain elements is underestimated by the A-DQI synthetic analog and overestimated by the corresponding net-to-gross-based empirical relationship. Thus **the A-DQI synthetic analog is slightly optimistic, and the net-to-gross-based empirical relationships overly pessimistic** with respect to lateral continuity and separation of the channel sandstone bodies.





Dataset	Mean CC thickness (m)	CC thickness standard deviation	N	Mean CC width (m)	CC width standard deviation	N
Outcrop panel	6.2	3.6	99	160	171	99
Analogy on net-to-gross	**Predicted mean CC thickness (m)**	**Predicted CC thickness standard deviation**		**Predicted mean CC width (m)**	**Predicted CC width standard deviation**	
0.18 NTG (all panel)	4.8	1.9		85	81	
Synthetic analog	**Mean CC thickness (m)**	**CC thickness standard deviation**	**N**	**Mean CC width (m)**	**CC width standard deviation**	**N**
Humid/subhumid system in foreland basin	4.9	3.3	460	540	1061	460
A-DQI (best quality) humid/subhumid system in foreland basin	4.9	3.5	268	198	284	191
Control analog	**Mean CC thickness (m)**	**CC thickness standard deviation**	**N**	**Mean CC width (m)**	**CC width standard deviation**	**N**
Blackhawk Fm. in FAKTS (Hampson et al. 2012)	6.2	3.2	707	356	495	707

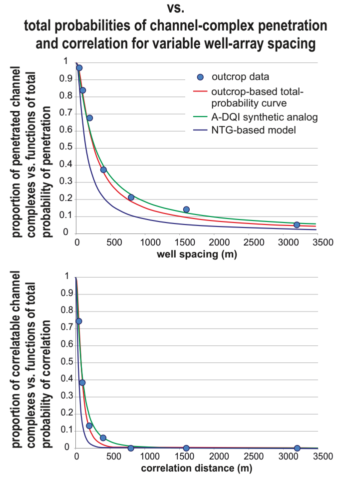
Predicted vs. observed channel-complex geometries



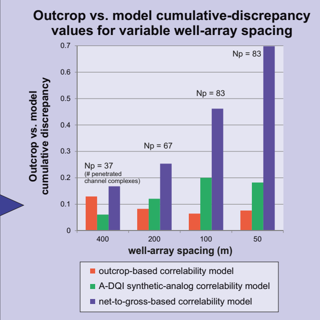
Correlability analysis

The Blackhawk Formation outcrop panel was treated as a correlation panel by considering as 'correlations' the traceability of channel complexes across the dummy-well array. In this way it was possible to quantify the proportions of channel complexes penetrated by different well-arrays and 'correlated' across different values of well spacing (3200 m, 1600 m, 800 m, 400 m, 200 m, 100 m, 50 m). These proportions correspond to what is predicted by the curves of total probability of penetration and correlation.

Proportions of dummy-well intersected (penetrated) and dummy-well correlatable outcrop channel complexes vs. total probabilities of channel-complex penetration and correlation for variable well-array spacing



Outcrop vs. model cumulative-discrepancy values for variable well-array spacing

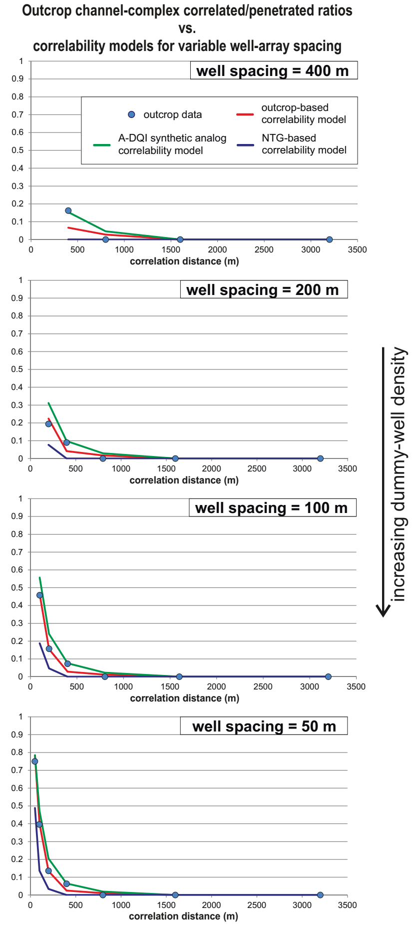


Total-probability curves were compiled based on (i) channel-complex width statistics (inclusive of partial widths) derived from the Blackhawk Formation panel itself, and (ii) channel-complex width statistics associated with the two types of analogs selected.

This allows evaluation of the total-probability curves that underpin the correlability models, through observation of the deviation between the curves and the proportion of penetrated or 'correlated' channel complexes expressed as a function of well spacing and correlation distance (figures on the left).
Both sets of total-probability curves were then employed to construct correlability models, which can be used to determine the error inherent in a typical application of the method. Four different sets of correlability models have been constructed for four different values of well spacing (on the right).

Appraisal of the correlability models was undertaken by quantifying the deviation between the curves and the ratios between proportions of 'correlated' channel complexes for variable correlation distances (multiples of well spacing) and the proportion of channel complexes penetrated by the well array (i.e. **the architectural-panel correlability**). This deviation is measured by a value called cumulative discrepancy (sum of the absolute values of panel-model difference in correlability at each correlation distance), a measure of how well the correlation panel matches the model. Here, this quantity is used as a measure of how well the model matches the 'correlation' panel (i.e. the architectural panel).

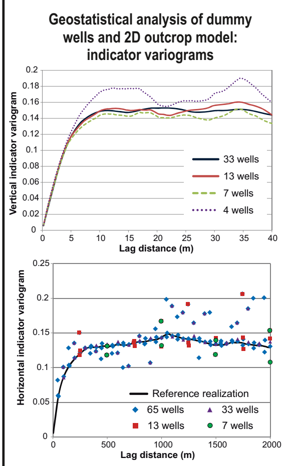
Outcrop channel-complex correlated/penetrated ratios vs. correlability models for variable well-array spacing



The correlability model based on Blackhawk Formation channel-complex width statistics provides a control of common values of panel-to-analog discrepancy over which correlability is meaningful (i.e. operated correlations can be considered as requiring revisions to match the analog).
Over the 4 sets, the correlability models based on analog data are consistent with what expected from channel-complex width statistics (over-optimistic A-DQI analog; over-pessimistic NTG-based analogy).
For the 4 different sets of correlability models, values of their cumulative discrepancy from the architectural-panel correlability are reported and compared. The results of the 400-m well-spacing scenario show the **importance of sampling a statistically significant number of bodies** for the method to be most useful.
For all the denser well-array scenarios, the values of cumulative discrepancy are all consistent with how well channel-complex width statistics on which the models are based approximate the architectural panel.
Overall, results suggest the significance of **considering alternative analogs as a way to handle uncertainty** connected with analog selection.

SIS outcrop models

Geostatistical analysis of dummy wells and 2D outcrop model: indicator variograms



METHODS

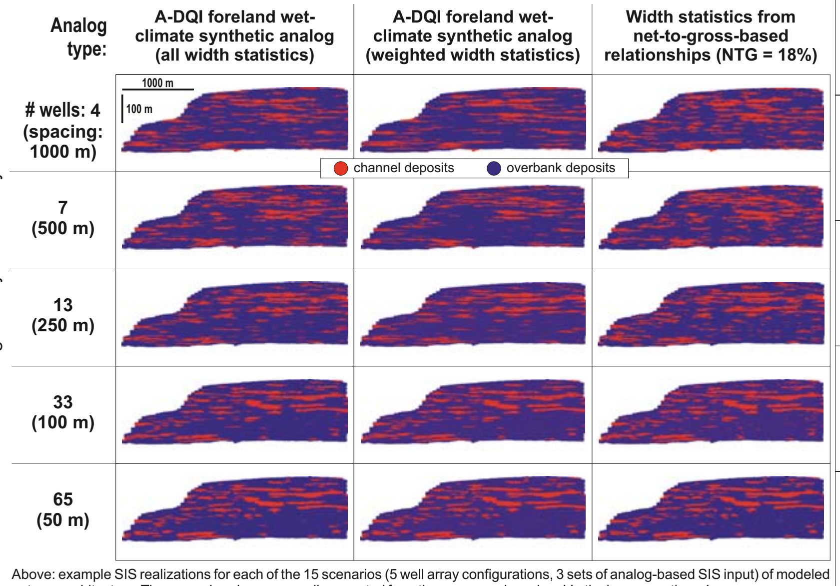
The **Blackhawk Formation outcrop architecture was modeled by means of SIS constrained on the selected analogs** (resolution of 0.2 m x 1 m).
A value of **indicator variogram range (10 m) for the vertical direction has been computed from geostatistical analysis** of dummy-well lithological data. **Horizontal indicator-variogram range values are based on the relationship by Ritzi (2000), applied using depositional-element attributes from the two types of analogs**. Additionally, a third set of simulations was constrained on **indicator-variogram parameters based on weighted depositional-element width statistics for the A-DQI synthetic analog**, by taking into account the variable thickness of the depositional elements in a way that thicker elements contribute more to the statistics, which is sensible in a pixel-based framework. Sets of 20 SIS runs were performed for each of 15 scenarios, given by three analog constraint sets and 5 different well arrays (spacing: 1000 m, 500 m, 250 m, 100 m, 50 m) for hard-data conditioning.
To **further assess model sensitivity to input parameters, 3 different sets of control simulations were run** as constrained on the following: (i) indicator-variogram parameters entirely based on variography of a geocellular model of the Blackhawk Formation outcrop; (ii) well-derived vertical variogram range combined with horizontal variogram range based on the relationship by Ritzi (2000), making use of depositional-element width statistics from the Blackhawk Formation outcrop; (iii) indicator-variogram parameters entirely based on the relationship by Ritzi (2000), applied to depositional-element attributes from the A-DQI synthetic analog, so that values of vertical variogram range are based on corresponding FAKTS output (i.e. depositional-element thicknesses and embedding coefficients for the A-DQI analog). These simulations were conditioned on a single well-array (1 km spacing).

All input indicator-variogram parameters are summarized in the table on the right.

Input indicator variogram ranges (exponential models)

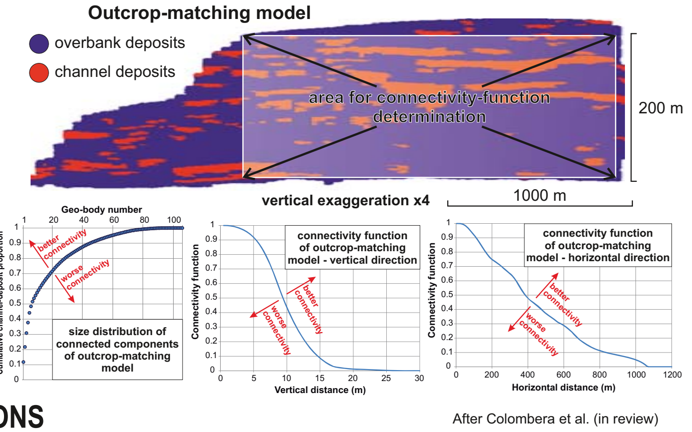
Geostatistical analysis	Vertical range (m)		Horizontal range (m)	
Outcrop panel indicator variogram (Control 1)	10		320	
Analog-based SIS input	**Channel-deposit vertical range (m)**	**Floodplain-deposit vertical range (m)**	**Channel-deposit horiz. range (m)**	**Floodplain-deposit horiz. range (m)**
0.18 NTG	10 (curve fitting)	10 (curve fitting)	210	633
A-DQI analog	10 (curve fitting)	10 (curve fitting)	488	310
A- DQI analog – thickness-weighted width statistics	10 (curve fitting)	10 (curve fitting)	774	342
Control 2: Panel width statistics	10 (curve fitting)	10 (curve fitting)	395	357
Control 3: A-DQI analog – thickness statistics included	13	5	488	310

Analog type:	A-DQI foreland wet-climate synthetic analog (all width statistics)	A-DQI foreland wet-climate synthetic analog (weighted width statistics)	Width statistics from net-to-gross-based relationships (NTG = 18%)
# wells: 4 (spacing: 1000 m)			
7 (500 m)			
13 (250 m)			
33 (100 m)			
65 (50 m)			



Above: example SIS realizations for each of the 15 scenarios (5 well array configurations, 3 sets of analog-based SIS input) of modeled outcrop architecture. The examples shown were all generated from the same seed number. Vertical exaggeration x4.

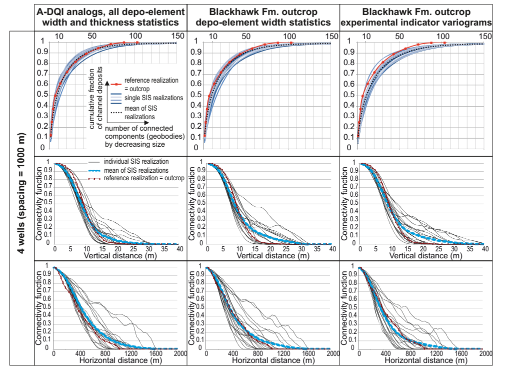
Outcrop-matching model



After Colombera et al. (in review)

ASSESSMENT OF GEOSTATISTICAL MODELS

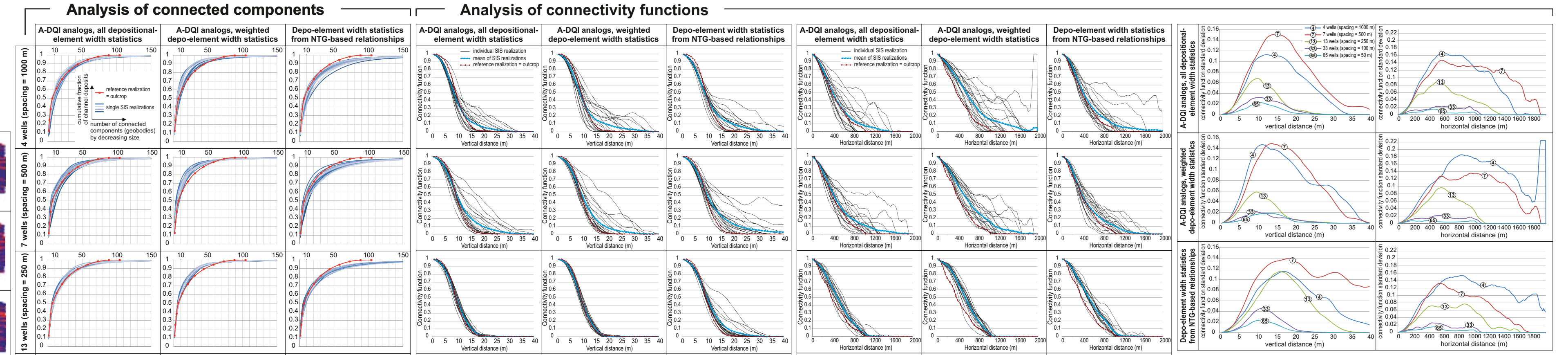
The forecasting method was tested through **quantification of the mismatch between the predicted inter-well architecture and the observed outcrop architecture**. The degree of similarity between the outcrop and the realizations is evaluated **in terms of 2D static connectivity metrics of channel deposits**, employing a geocellular model of the outcrop (left) as a reference. Two types of connectivity metrics have been considered: (i) **size** (x-section area) **distribution of the connected components** (geo-bodies) of channel deposits, i.e. clusters of cells modeled as channel deposit and connected in two dimensions, computed using GEO_OBJ (Deutsch 1998); (ii) **vertical and horizontal connectivity functions** of channel deposits, computed using CONNEC3D (Pardo-Igúzquiza & Dowd 2003); the connectivity function is defined as the probability that two points belonging to a given phase (channel deposits) are connected, expressed as a function of their separation in a given direction (Allard 1993; Renard & Allard 2012). Connectivity functions have been calculated for a rectangular subset of the grid (2 km x 192 m; see left).



OUTCROP vs MODELS COMPARISONS

Analysis of connected components

Analysis of connectivity functions



- In terms of static-connectivity metrics, **indicator-variogram parameters based on analog data resulted in geo-models that are as good as realizations based on experimental variography**. This observation supports this approach in transferring outcrop-analog experience to geostatistical modeling.
- Different **simulation groups display channel-deposit connectivity that do not match with what expected from the channel-complex morphometry statistics of corresponding analogs**. This fact should be born in mind when applying multiple analogs to SIS as a way to account for uncertainty in analog selection.
- An **increase in the number of wells**, which are therefore more closely spaced, **does not necessarily result in a reduction in connectivity variability** within each group of realizations.

PetroleumLeeds

Fluvial & Eolian Research Group
School of Earth and Environment
Leeds LS2 9JT UK

contact: Luca Colombera
email: l.colombera@leeds.ac.uk
URL: http://frg.leeds.ac.uk

AREVA bhpbilliton ConocoPhillips MURPHY OIL CORPORATION nexen Saudi Aramco TULLOW woodside YPF

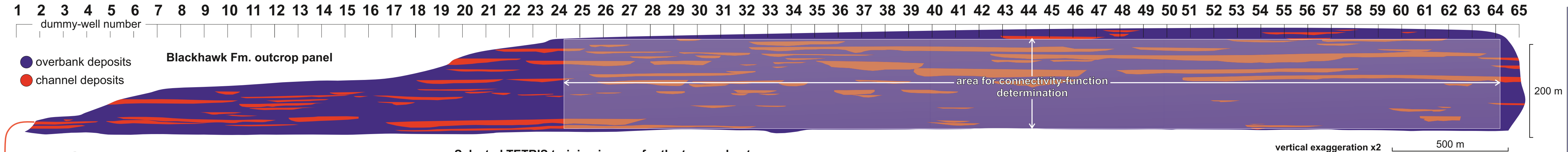
FRG Fluvial & Eolian Research Group

UNIVERSITY OF LEEDS

Geologic modeling of outcrop successions to assess analog-based predictions of the sedimentary heterogeneity in fluvial reservoirs

Luca Colombera[1], Nigel Mountney[1], John Howell[2], Andreas Rittersbacher[3], Bill McCaffrey[1]

1) Fluvial & Eolian Research Group, University of Leeds, UK
2) Department of Geology and Petroleum Geology, University of Aberdeen, UK
3) Statoil ASA, Bergen, Norway



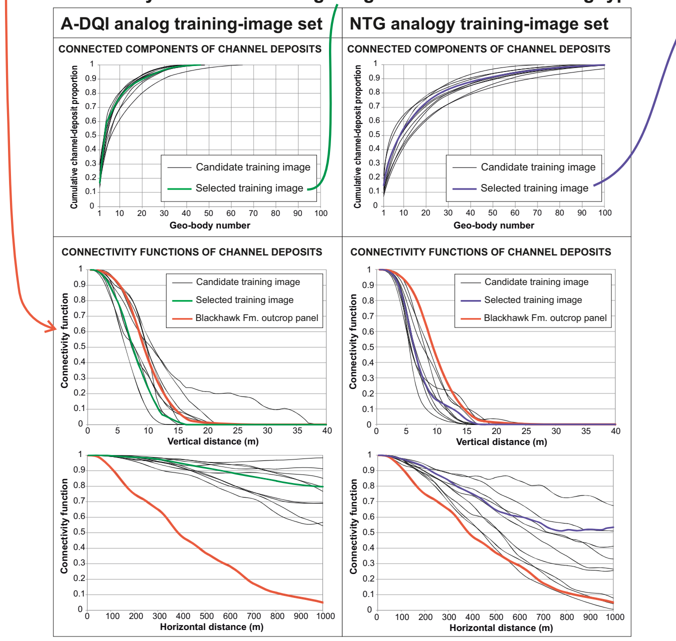
MPS outcrop models

TRAINING-IMAGE CREATION

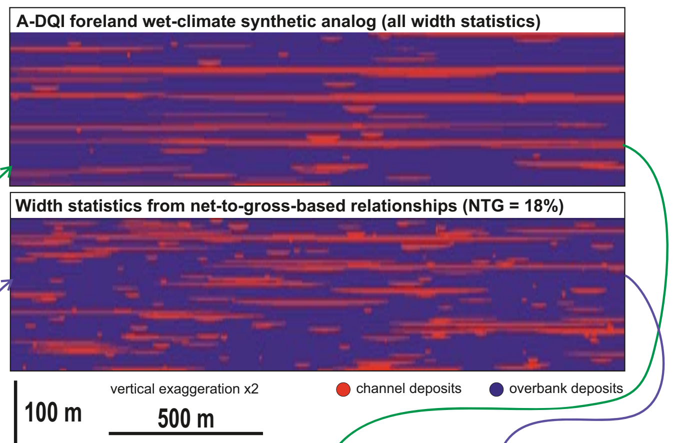
Object-based training images were created for both FAKTS analogy types: 1) A-DQI (i.e. best 'quality') humid/subhumid climate, foreland basin fluvial systems, 2) empirical relationships relating depositional-element geometries and proportions.

Using TETRIS (Boucher et al. 2010), two corresponding sets of 10 training images were created, which consist of 2D cross-strike sections that incorporate channel-complex depositional elements distributed in a floodplain background. The proportions of channel and floodplain deposits match with the proportions observed in the Blackhawk Fm. panel to be modeled. The thickness and width of the channel complexes were parameterized as lognormal distributions with mean and variance as in the chosen analogs. The TI's are 2 km wide and 250 m high. The vertical resolution of the TI's is 0.5 m; the horizontal resolution is 2 m.

Connectivity of TETRIS training-image sets for the two analog types



Selected TETRIS training images for the two analog types



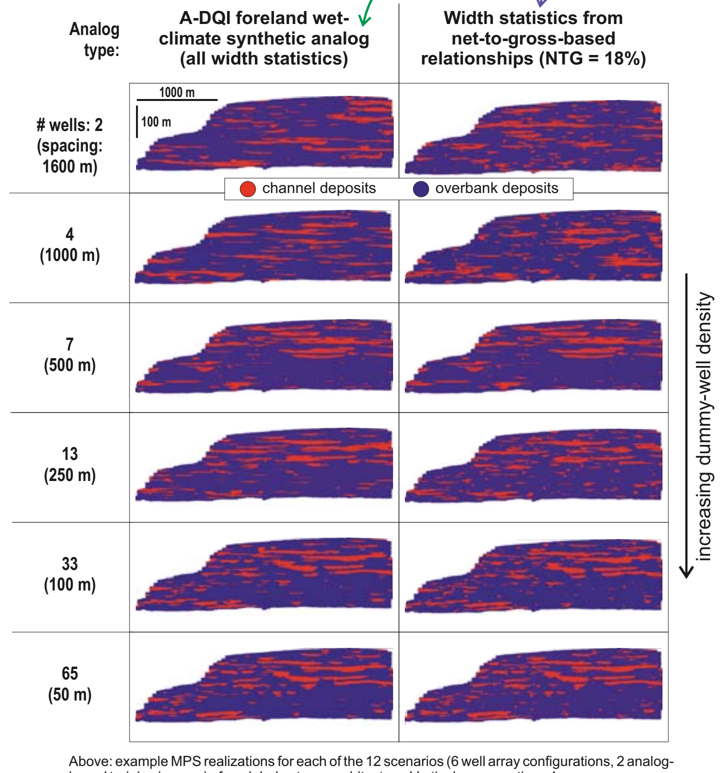
MPS SIMULATIONS

A single training image was chosen for each of the two sets. The two chosen realizations were selected on the basis of the recognition of their connectivity metrics (geo-body size distribution, vertical and horizontal connectivity functions), which could be **deemed as representative of the average of their respective set** (see above).

The two chosen training images have been employed to **simulate the large-scale fluvial architecture of the Blackhawk Fm. panel by means of the multiple-point geostatistical modeling algorithm SNESIM** (Strebelle 2000; Liu 2006). Sets of 20 MPS realizations were performed for each of 12 scenarios, given by the two analog-based training images and 6 different well arrays (spacing: 1600 m, 1000 m, 500 m, 250 m, 100 m, 50 m) for hard-data conditioning.

On the basis of unconditional runs and guidelines given in Liu (2006), the following set of parameters were selected: isotropic search radius (100 m), 100 nodes for conditioning data, and 5 multi-grids.

Example MPS realizations for each of the 12 scenarios are presented on the right.



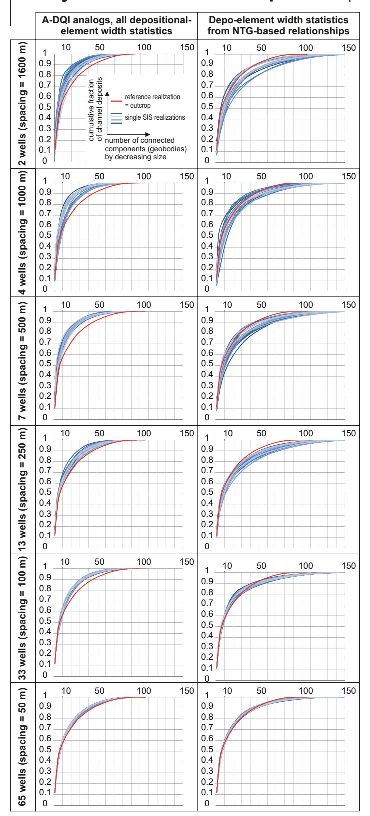
Above: example MPS realizations for each of the 12 scenarios (6 well array configurations, 2 analog-based training images) of modeled outcrop architecture. Vertical exaggeration x4.

OUTCROP vs MODELS COMPARISONS

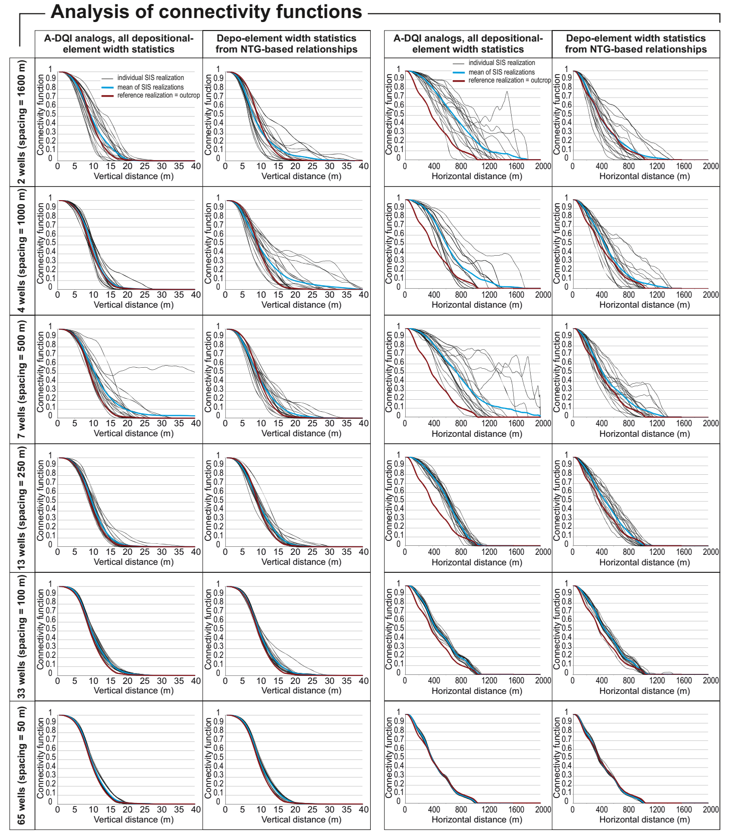
To test the predictive method, a **quantification of the mismatch between the predicted inter-well architecture and the observed outcrop architecture was carried out in terms of 2D static connectivity** metrics of channel deposits: 1) size distribution of the connected components of channel deposits (graphs below), 2) vertical and horizontal connectivity functions of channel deposits (graphs on the right) for a rectangular subset of the outcrop (see frame on panel above).

This assessment permits a direct comparison between the results of the MPS modeling with (i) the previously simulated SIS realizations of the same outcrop panel, and partly with (ii) the training images on which the MPS realizations were constrained (only connectivity functions can be compared).

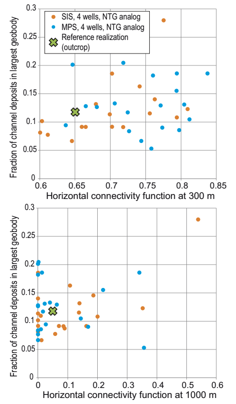
Analysis of connected components



Analysis of connectivity functions



- In relative terms, **the static-connectivity metrics of channel deposits in the MPS simulations reflect the descriptive statistics of channel-complex size** incorporated in the training images from the analogs.
- However, **when the comparison is extended to the outcrop panel**, only the geobody size distributions appear to relate to the size of the channel complexes, as both vertical and horizontal **average connectivity functions for each realization group are consistently overestimated**. This fact appears to be **related to the input training images**, which display channel-complex stacking patterns that favor lateral over vertical juxtaposition. However, even for the widest well-array spacing, MPS runs return connectivity functions more similar to the actual outcrop, compared to the training images.
- Whereas horizontal connectivity functions in the 300-1000 m range seem to be controlled by the size of the largest connected component in the SIS simulations, no evident relationship is seen between maximum geobody size and the connectivity function in the MPS models (see right), possibly suggesting a control exerted by noise in the SIS run.
- Again, an **increase in the number of wells does not necessarily result in a reduction in connectivity variability** within each group of realizations.



Case study 2: Straight Cliffs Formation (Turonian-Campanian, Utah, USA)

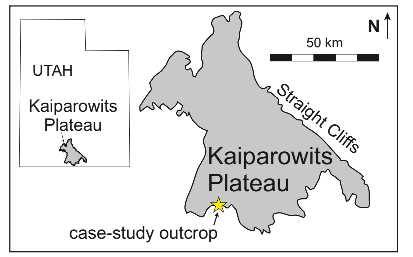
This part of the work deals with the use of empirical relationships that relate depositional-element geometries to their proportion – as obtained through the analysis of many FAKTS analogs – in **application to subsurface fluvial successions that display marked vertical variations in net-to-gross**. To test the value of the approach it is essential to consider a test outcrop succession that is extensively exposed both vertically and laterally. The chosen case study consists in a **published interpreted architectural panel of an outcrop of continental strata from the Upper Cretaceous (Turonian-Campanian) Straight Cliffs Formation, exposed along a steep cliff in the Blue Cove area of the Kaiparowits Plateau** (Utah, USA). This outcrop dataset was originally presented by Dalrymple (2001).

The non-marine part of the Straight Cliffs Formation consists of a ca. 300 to 400 m-thick succession of mudstone, sandstone and coal that is interpreted to have accumulated in an alluvial to coastal plain setting (cf. Peterson 1969; Shanley & McCabe 1993) as part of a clastic wedge that prograded eastward from the Sevier Orogen into the Western Interior Seaway.

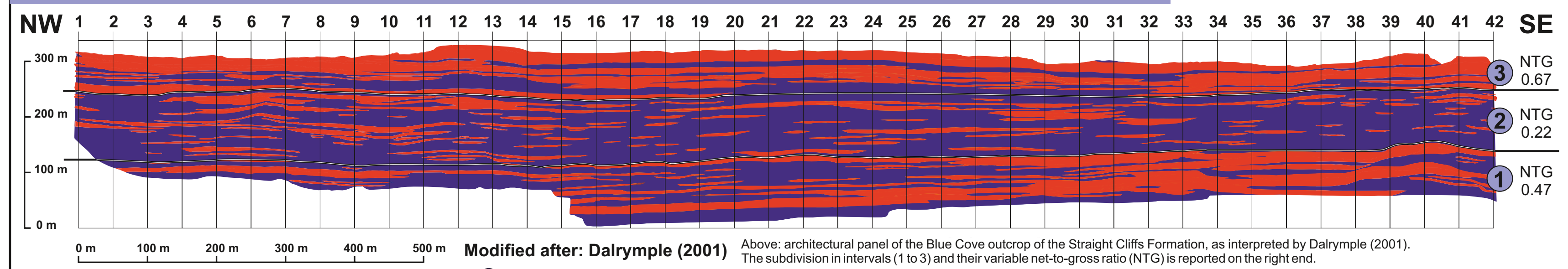
The overall architectural motif of the non-marine Straight Cliffs Formation consists of **isolated or amalgamated channel sandstone bodies encased in fine-grained mudstones interbedded with overbank sandstones and coal bodies**. Significant variations in architectural styles are displayed vertically through the stratigraphy.

The dataset used in this work takes the form of an **architectural panel that depicts a section that is ca. 2.1 km wide and 300 m high**, and consists in a 'map' of the **distribution of the sand-prone channel-bodies in a background of dominantly fine-grained floodplain deposits**, as based on the interpretation by Dalrymple (2001). The outcrop is conveniently oriented close to orthogonal to the mean drainage direction of the Straight Cliffs Formation paleo-river systems (Dalrymple 2001).

Across the interpreted architectural panel, a series of **42 vertical logs, each spaced 50 m apart, have been constructed to serve as 'dummy' wells** (see below), applicable to derive outcrop channel-complex correlability data and to condition the SIS geostatistical models.

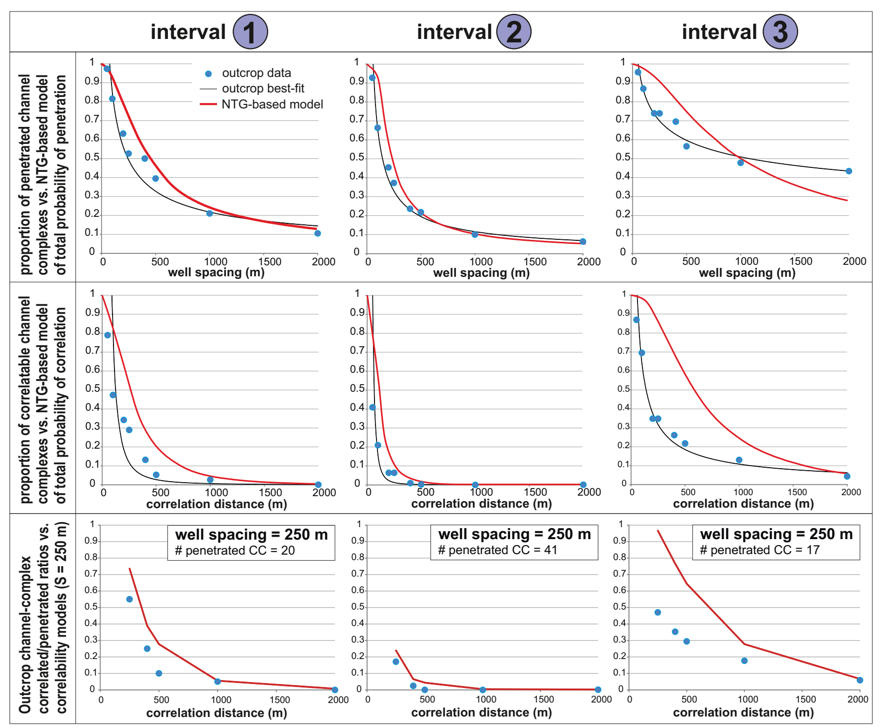


Above: location of the Blue Cove area (Kaiparowits Plateau, southern Utah, USA), where the case-study outcrop of the Straight Cliffs Formation is situated. Modified after Dalrymple (2001).



Above: architectural panel of the Blue Cove outcrop of the Straight Cliffs Formation, as interpreted by Dalrymple (2001). The subdivision in intervals (1 to 3) and their variable net-to-gross ratio (NTG) is reported on the right end.

Correlability analysis



Curves that quantify the total probability of channel-complex penetration and correlation were compiled on the basis of values of channel-complex width mean and standard deviation that were derived from the relationships that relate depositional-element width statistics to proportions (see table on the right for comparison between outcrop and predictions).

The discrepancy between the outcrop architecture and correlability-model predictions was assessed for the 3 stratigraphic intervals (see panel above), by quantifying: 1) the deviation between the total-probability curves that underpin the model, and the proportion of penetrated or correlated channel complexes expressed as a function of well spacing and correlation distance; 2) the deviation between the correlability models and the outcrop correlability for a scenario of well-array spacing of 250 m.

The results show the **importance of sampling a statistically significant number of bodies** for the method to work best, and this has implications on the chosen resolution in stratigraphic subdivision when applying this type of analysis in subsurface studies.

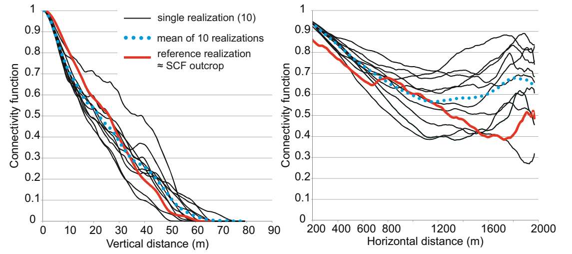
Dataset	Mean CC width (m)	CC width standard deviation	N
Outcrop panel	190	296	174
Interval 1	284	320	38
Interval 2	103	106	113
Interval 3	461	561	23
NTG analogy	**Predicted mean CC width (m)**	**Predicted CC width standard deviation**	
0.49 NTG (all panel)	282	264	
0.47 NTG (interval 1)	260	243	
0.22 NTG (interval 2)	98	93	
0.67 NTG (interval 3)	571	530	

Connectivity of SIS outcrop models

Multiple sequential indicator simulations have been run with SISIM (Deutsch & Journel 1998), as conditioned by 3 dummy wells (spacing 1 km – well #: 2, 22, 42 on panel above) to model the fluvial architecture observed on the Straight Cliffs Formation architectural panel.

The SIS models were constrained on indicator variograms parameterized in part on the basis of geostatistical analysis of the dummy wells (vertical indicator-variogram range), and partly based on the use of Ritzi's (2000) relationships in combination with the same net-to-gross-based empirical relationships employed in the correlability analysis (horizontal indicator variogram range). **SIS was employed to simulate the distribution of channel-complex and floodplain deposits, and the 3 stratigraphic volumes** (see above) **were independently constrained on the basis of their different net-to-gross values**.

The SIS realizations were assessed in terms of vertical and horizontal channel-deposit connectivity functions of a 2 km x 200 m sample area (see results below).



Conclusions

The current study has demonstrated the two-fold application of outcrop analogs for informing and validating predictive tools for forecasting the architecture of subsurface fluvial successions. Results support the use of outcrop-analog experience to build corresponding subsurface models.

Some guidelines can be drawn for ensuring best practice in the application of analogs to subsurface modeling problems:

- **Correlability models have been shown to serve as realistic templates for comparing the geologic sensibility of sandbody well-to-well correlations against outcrop analogs**. Results also demonstrate that, if well arrays offer sufficient sampling of the sandbodies, different **correlability models based on alternative analogs can be usefully applied to the same panel to account for uncertainty** regarding the suitability of any particular analog.
- Although there is imprecision inherent in the process of transferring outcrop-analog knowledge to variogram-based reservoir models, and results suggest that existing empirical relationships could be improved, **the use of analog information in the compilation of indicator-variogram models for channel and overbank deposits has been demonstrated to be effective**: sequential indicator simulations conditioned on such variogram models display a comparable degree of realism relative to equivalent simulations conditioned on variograms based on the outcrop two-point statistics.
- Results of both SIS and MPS modeling of the outcrop architecture demonstrate that both **FAKTS-informed indicator variograms and training images translate in** outcrop models that display **size distributions of the connected components of channel deposits that are directly scaled to the input channel-complex size distribution**.
- However, it appears evident that **there may not be a straightforward correspondence between channel-deposit connectivity functions in a set of models and the analog dimensional parameters used for building them**, when considering multiple analogs as representative of pessimistic or optimistic scenarios on the basis of their geometric properties. This consideration applies to models obtained through application of both SIS and MPS methods, although it is drawn from results limited to a two-dimensional evaluation.
- It has been observed that **an increase in the number of wells (closer spacing) used to condition geostatistical models does not necessarily result in a reduction in the variability in connectivity functions** seen within each set of realizations, and this is especially evident for the widest well arrays; this is counter to the expectation that an increase in the number of wells should necessarily result in a decrease in model uncertainty.

REFERENCES

Adams M.M., Bhattacharya J.P. (2005) No change in fluvial style across a sequence boundary, Cretaceous Blackhawk and Castlegate Formations of central Utah, USA. J. Sed. Res. 75, 1038-1051.

Allard D. (1993) On the connectivity of two random set models: the truncated Gaussian and the Boolean. Geostatistics Tróia'92, 467-478.

Boucher A., Gupta R., Caers J., Satija A. (2010) Tetris: a training image generator for SGeMS. Stanford Center for Reservoir Forecasting.

Colombera L., Mountney N.P., McCaffrey W.D. (2012a) A relational database for the digitization of fluvial architecture concepts and example applications. Petrol. Geosc. 18, 129-140.

Colombera L., Felletti F., Mountney N.P., McCaffrey W.D. (2012b) A database approach for constraining stochastic simulations of the sedimentary heterogeneity of fluvial reservoirs. AAPG Bull. 96, 2143-2166.

Colombera L., Mountney N.P., McCaffrey W.D. (2013) A quantitative approach to fluvial facies models: Methods and example results. Sedimentology 60, 1526-1558.

Colombera L., Mountney N.P., Felletti F., McCaffrey W.D. (2014) Models for guiding and ranking well-to-well correlations of channel bodies in fluvial reservoirs. AAPG Bull. 98, 1943-1965.

Colombera L., Mountney N.P., Howell J.A., Rittersbacher A., Felletti F., McCaffrey W.D. (in review) A test of analog-based tools for quantitative prediction of large-scale fluvial architecture. AAPG Bull.

Dalrymple M. (2001) Fluvial reservoir architecture in the Statfjord Formation (northern North Sea) augmented by outcrop analogue statistics. Petrol. Geosc. 7, 115-122.

Deutsch C.V. (1998) Fortran programs for calculating connectivity of three-dimensional numerical models and for ranking multiple realizations. Comp. & Geosc. 24, 69-76.

Deutsch C.V., Journel A.G. (1998) GSLib. Geostatistical software library and user's guide.

Flores R.M., Blanchard L.F., Sanchez J.D., Marley W.E., Muldoon W.J. (1984) Paleogeographic controls of coal accumulation, Cretaceous Blackhawk Formation and Star Point Sandstone, Wasatch Plateau, Utah. GSA Bull. 95, 540-550.

Geehan G., Underwood J. (1993) The use of length distributions in geological modelling. IAS Spec. Publ. 15, 205-215.

Hampson G.J., Royhan Gani M., Sahoo H., Rittersbacher A., et al. (2012) Controls on large-scale patterns of fluvial sandbody distribution in alluvial to coastal plain strata: Upper Cretaceous Blackhawk Formation, Wasatch Plateau, Central Utah, USA. Sedimentology 59, 2226-2258.

Liu Y. (2006) Using the Snesim program for multiple-point statistical simulation. Comp. & Geosc. 32, 1544-1563.

Miall A.D. (1996) The geology of fluvial deposits: sedimentary facies, basin analysis, and petroleum geology.

Pardo-Igúzquiza E., Dowd P.A. (2003) CONNEC3D: a computer program for connectivity analysis of 3D random set models. Comp. & Geosc. 29, 775-785.

Peterson F. (1969) Cretaceous sedimentation and tectonism in the southeastern Kaiparowits region, Utah. USGS Open File Report 69-202.

Pringle J.K., Howell J.A., Hodgetts D., Westerman A.R., Hodgson D.M. (2006) Virtual outcrop models of petroleum reservoir analogues: a review of the current state-of-the-art. First Break 24, 33-42.

Renard P., Allard D. (2013) Connectivity metrics for subsurface flow and transport. Adv. Water Res. 51, 168-196.

Rittersbacher A., Howell J.A., Buckley S.J. (2014) Analysis of fluvial architecture in the Blackhawk Formation, Wasatch Plateau, Utah, USA, using large 3D photorealistic models. J. Sed. Res. 84, 72-87.

Ritzi R.W. (2000) Behavior of indicator variograms and transition probabilities in relation to the variance in lengths of hydrofacies. Water Res. Res. 36, 3375-3381.

Shanley K.W., McCabe P.J. (1993) Alluvial architecture in a sequence stratigraphic framework: a case history from the Upper Cretaceous of southern Utah, USA. IAS Spec. Publ. 15, 21-55.

Strebelle S. (2000) Sequential simulation drawing structures from training images. Unpublished PhD Thesis. Stanford University.

PetroleumLeeds

Fluvial & Eolian Research Group
School of Earth and Environment
Leeds LS2 9JT UK

contact: Luca Colombera
email: l.colombera@leeds.ac.uk
URL: http://frg.leeds.ac.uk

AREVA bhpbilliton ConocoPhillips MURPHY OIL CORPORATION nexen Saudi Aramco Shell TULLOW woodside YPF