Quantitative empirical relationships for the prediction of subsurface fluvial sedimentary architecture

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ABSTRACT

Realistic prediction of fluvial reservoir geometries and connectivity requires a quantitative description of the sedimentary architecture of potential analogs on which to base deterministic and stochastic reservoir models. To tackle this issue, we propose a novel and innovative database approach to determining quantitative empirical relationships between sedimentary architecture and the boundary conditions that controlled deposition and also between the resultant architectural properties.

Quantitative descriptors are derived by analyzing the sedimentary architecture of many case studies within a database that stores multi-scale information from both ancient and modern depositional systems, together with information on system parameters (e.g. channel pattern) and controls (e.g. subsidence rate). Thus the database permits derivation of quantitative relationships describing the degree of association of different architectural properties; in reservoir-modeling workflows, for example, database-derived descriptive statistics of channel-sandbody dimensions expressed as a function of basin-wide channel-deposit proportions can be used in conjunction with borehole-derived channel-deposit proportions as forecasting tools. The ability to consider lithological heterogeneity at several scales enables external geometries to be linked to internal organization, thereby allowing derivation of quantitative descriptions of geometries related to facies assemblages defined to match known subsurface lithofacies associations.

The database can also be employed to derive empirical relationships between system controls or parameters and architectural properties. Such relationships can be referred to whenever knowledge on the boundary conditions governing the subsurface depositional system is available; for example, vertical channel-sandbody connectivity can be quantified as a function of system aggradation rate, or sandbody geometric parameters can be expressed as functions of the system drainage pattern.

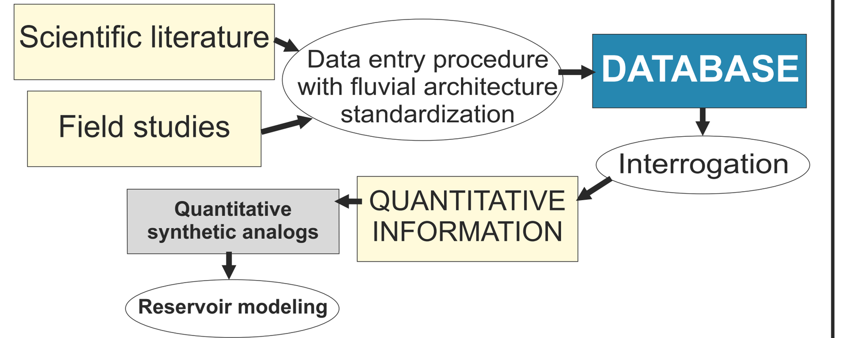
Architectural relationships can be customized to best match the subsurface system being modeled by filtering the knowledge-base to include only data from case studies considered to be appropriate analogs, either in terms of sedimentary architecture or boundary conditions, or both.

Preliminary results demonstrate shortcomings in some qualitative relationships implied by physical stratigraphic models commonly used as predictive tools for subsurface fluvial architecture.

APPROACH

The **Fluvial Architecture Knowledge Transfer System** (FAKTS) is a relational database storing fluvial architecture data populated with literature- and field-derived case studies from modern rivers and ancient successions. The database scheme characterizes fluvial architecture at three different scales of observation, recording style of internal organization, geometries and spatial relationships of genetic units, classifying datasets according to controlling factors and context-descriptive characteristics. The database can therefore be filtered on both architectural features and boundary conditions to yield outputs from case studies that may be equivalent to the one of a subsurface case study of interest, making the model function as a synthetic analog.

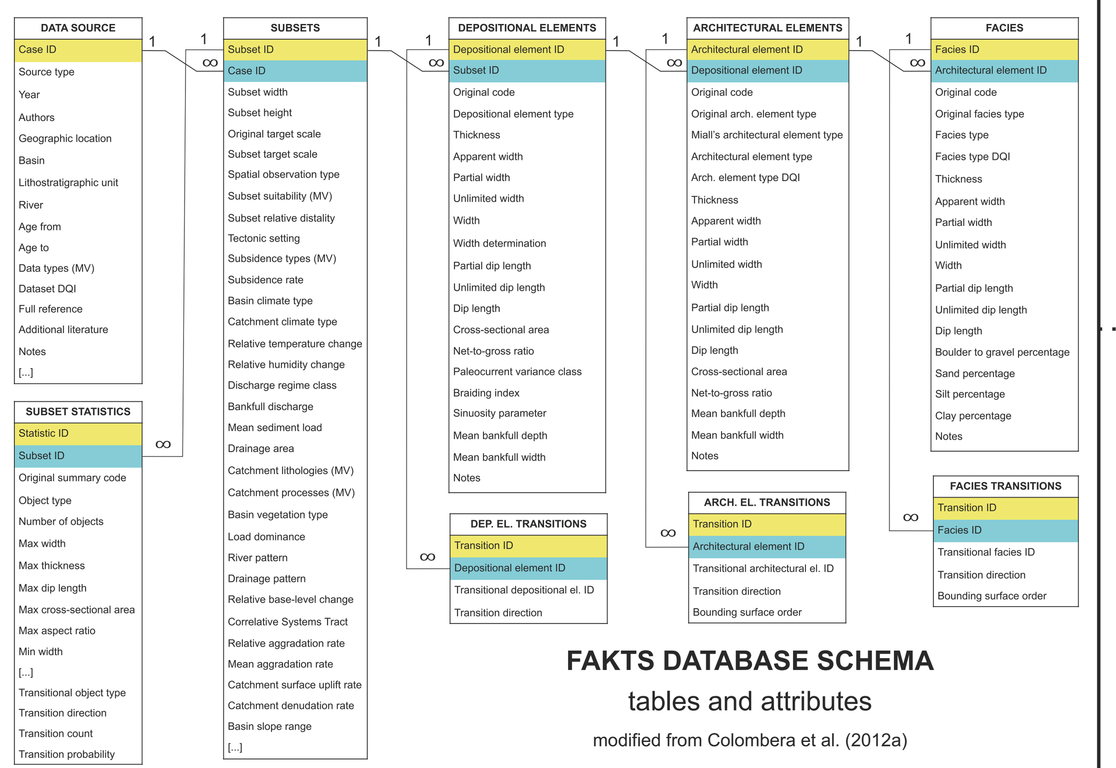
SCOPE Here FAKTS is employed to derive filtered quantitative information for the following purposes: (i) the elaboration of quantitative empirical relationships, which by linking different architectural properties between them and with system parameters describing boundary conditions (e.g. tectonic setting) or architectural motifs (e.g. channel pattern), can be used to guide deterministic or stochastic fluvial-reservoir modeling; (ii) to demonstrate how a probabilistic model of genetic-unit correlability can be applied to rank the geologic realism of well-correlation panels.



FAKTS DATABASE OVERVIEW

CASE STUDY CLASSIFICATION

One of the key aspects of the FAKTS database is the classification of each case study example and parts thereof on the basis of traditional classification schemes or intrinsic environmental descriptors (e.g. dominant transport mechanism, channel/river pattern, relative distality of each stratigraphic volume), external controlling factors (e.g. description of climatic and tectonic context, subsidence rates, relative base-level changes), and associated dependent variables (e.g. basin vegetation type and abundance, suspended sediment load component). Some of these attributes are only expressed as relative changes (=, -, +) in a given variable (e.g. relative humidity) between stratigraphic or geomorphic segments, which are implemented as subsets. In addition, FAKTS stores all the metadata that refer to whole datasets, describing the original source of the data and information including the methods of acquisition employed, the chronostratigraphic stages corresponding to the studied interval, the geographical location, the names of the basin and river or lithostratigraphic unit, and a dataset data quality index (DQI), incorporated as a threefold ranking system of perceived dataset quality and reliability based on established criteria. Moreover, subsets are classified according to their suitability for a given query (i.e. for obtaining dimensional parameters, proportions, transitions or grain-size data) for a specified scale (target scale).



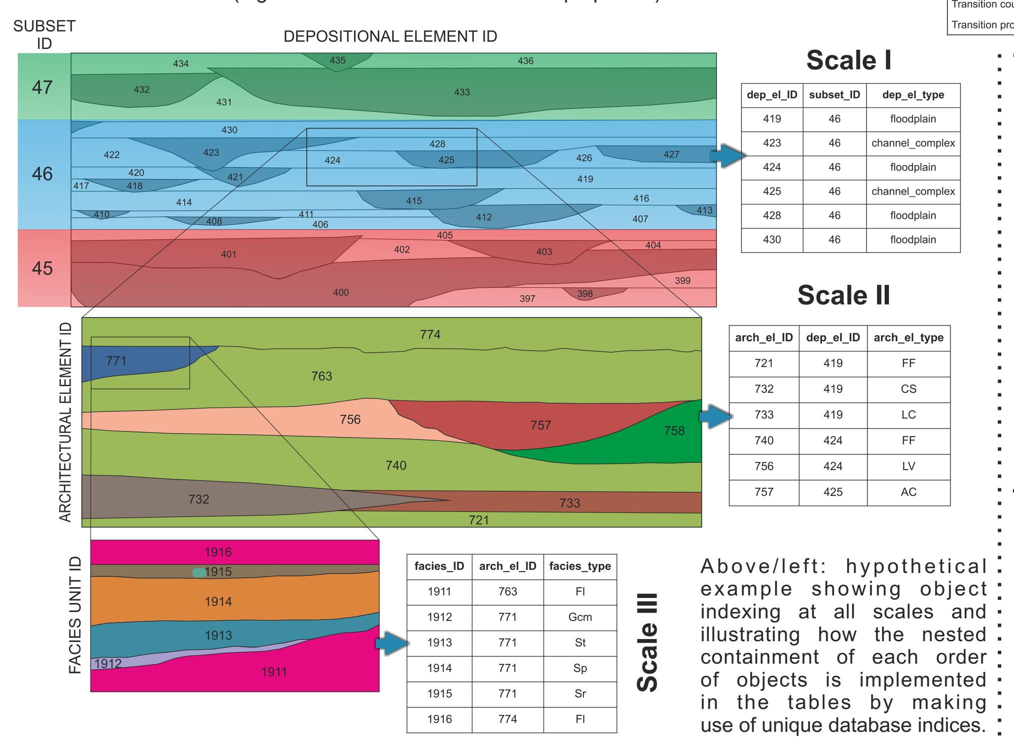
FAKTS DATABASE SCHEMA

tables and attributes

modified from Colombera et al. (2012a)

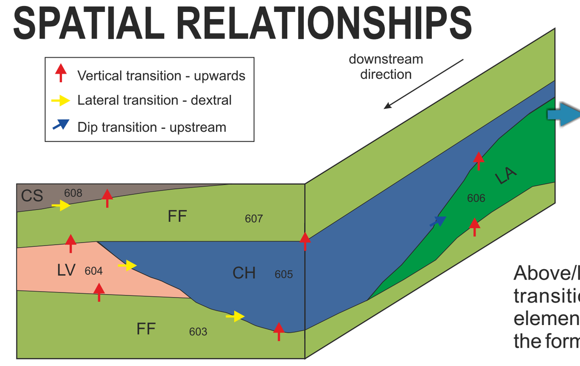
GENETIC-UNIT HIERARCHY

Each case study is subdivided into a series of stratigraphic volumes (subsets) characterized by having the same system attributes. Each subset is broken down into sedimentary building blocks, belonging to the different scales considered, recognizable as lithosomes in ancient successions – in both outcrop and subsurface datasets – 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).



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

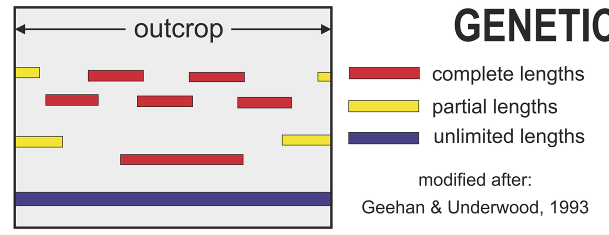
GENETIC-UNIT SPATIAL RELATIONSHIPS



arch_el_ID	trans_el_ID	trans_direction	bound_surf_order
603	604	vertical	4th
603	605	lateral	5th
603	605	vertical	5th
603	606	vertical	5th
604	605	lateral	4th
604	607	vertical	4th
605	606	dip	4th
605	607	vertical	4th
606	605	vertical	4th

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

GENETIC-UNIT GEOMETRY



modified after: Geehan & Underwood, 1993

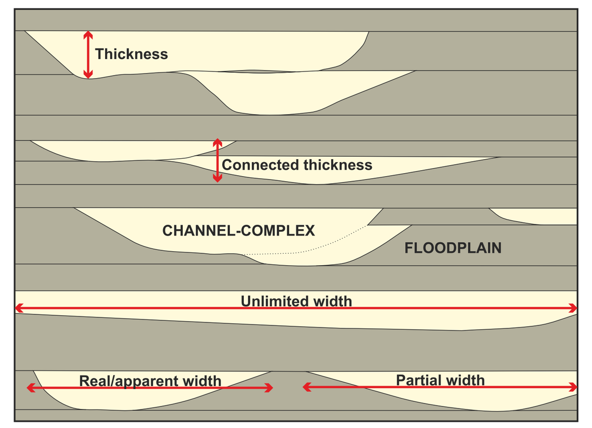
Left: representation of categories of completeness (after Geehan & Underwood 1993) of observed/sampled dimensional parameters. Correlated genetic-unit dimensions are stored as unlimited.

FAKTS GENETIC UNITS

DEPOSITIONAL ELEMENTS

Depositional elements are classified as channel-complex or floodplain elements. Channel-complexes represent channel-bodies defined on the basis of flexible but unambiguous geometrical 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 (mainly subsurface datasets).
Floodplain segmentation into depositional elements is subsequent to channel-complex definition, as floodplain deposits are subdivided according to the lateral arrangement of channel-complexes.

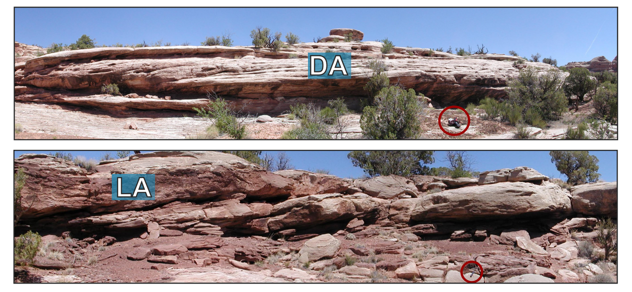
IDEALIZED PANEL EXEMPLIFYING GEOMETRICAL DEFINITION OF DEPOSITIONAL ELEMENTS AND DIMENSIONAL-PARAMETER TERMINOLOGY



ARCHITECTURAL ELEMENTS

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

Following Miall's (1985, 1996) concepts, architectural elements are defined as components of a fluvial depositional system with the characteristic facies associations that compose individual elements interpretable in terms of sub-environments.
FAKTS is designed for storing architectural element types classified according to both Miall's (1996) classification and also to a classification derived by modifying some of Miall's classes in order to make them more consistent in terms of their geomorphological expression, so that working with datasets from modern rivers is easier. Architectural elements described according to any other alternative scheme are translated into both classifications following the criteria outlined by Miall (1996) for their definition.

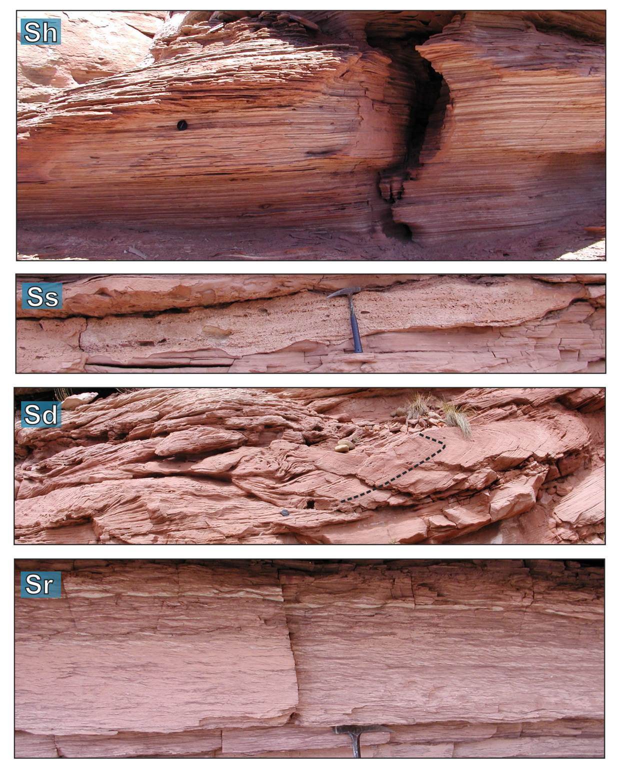


Above: examples of preserved architectural elements (DA and LA barforms) from the Lower Jurassic Kayenta Formation at Sevenmile Canyon (SE Utah, USA).

FACIES UNITS

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

In FAKTS, facies units are defined as genetic bodies characterized by homogeneous lithofacies type down to the decimetre scale, bounded by second- or higher-order (Miall 1996) bounding surfaces. Lithofacies types are based on textural and structural characters; facies classification follows Miall's (1996) scheme, with minor additions (e.g. texture-only classes – gravel to boulder, sand, fines – for cases where information regarding sedimentary structure is not provided).



Above: examples of sandtone facies units from the Lower Jurassic Kayenta Formation in the Moab area (SE Utah, USA).

CHARACTERIZATION OF LARGE-SCALE ARCHITECTURAL STYLES OF FLUVIAL DEPOSITIONAL SYSTEMS BASED ON CHANNEL-COMPLEX WIDTH-TO-THICKNESS ASPECT RATIO VARIABILITY

Channel complexes are recorded in FAKTS as objects whose geometry can be satisfactorily described by maximum thickness and cross-gradient width, and which are suitable for characterizing the geometry of channelized flow units that build fluvial reservoirs.
Here primary data relating to channel-complex width, thickness and width-to-thickness aspect ratio are presented from the 16 largest and highest-quality literature-derived FAKTS case studies, which collectively provide analog information that can be employed to infer the sedimentary architecture of fluvial hydrocarbon-bearing successions.

Traditional width vs. thickness scatterplots have been coupled with graphs of the width-to-thickness aspect ratio plotted against channel-complex thickness. This allows for recognition – either graphically or numerically – of three different architectural styles depending on whether or not aspect ratios show a relationship with channel-complex thickness, and on whether this relationship is positive or negative. Information on channel-complex W/T vs. T should be taken into account when choosing a fluvial reservoir analog: such information can be used to place an additional constraint on reservoir geometry or to consider how different scenarios embodied by different analogs affect static reservoir models.

Where there exists a negative or positive relationship between T and W/T, such trends likely represent the record of the interplay between allogenic controls and autogenic dynamics in governing channel geometries and clustering. For example, in the Escanilla Fm. (see Case 51 below), syndepositional compressive tectonics may have been the active control on cross-system topographic gradients that ultimately determined a dominantly vertical stacking of channel bodies, which likely resulted in the observed negative relationship between channel-complex T and W/T aspect ratio.

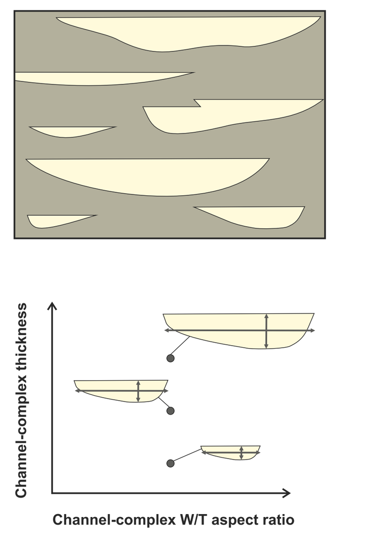
CHANNEL-COMPLEX WIDTH VS. THICKNESS
- Channel-complex real/apparent width
- Channel-complex unlimited/partial width

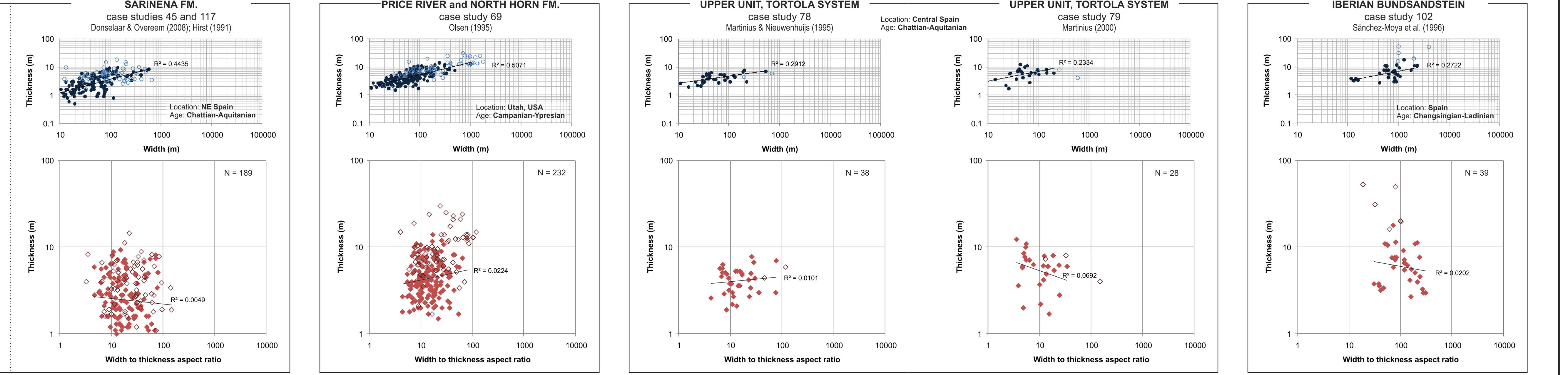
CHANNEL-COMPLEX W/T ASPECT RATIO VS. THICKNESS
- Channel-complex real/apparent width
- Channel-complex unlimited/partial width

TYPE-1 ARCHITECTURAL STYLE

The largest-scale architectural style of most of the systems is characterized by the lack of any clear correlation between the width-to-thickness aspect ratio and the thickness of the channel-complexes occurring in them.

Channel complexes from the Miocene Sariñena Fm. (Ebro Basin, Spain) best exemplify this situation (data from: Donselaar & Overeem 2008; Hirst 1991).

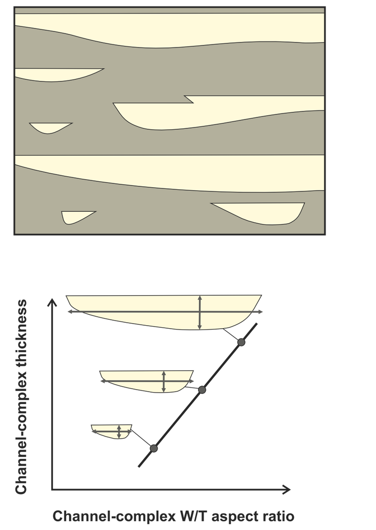


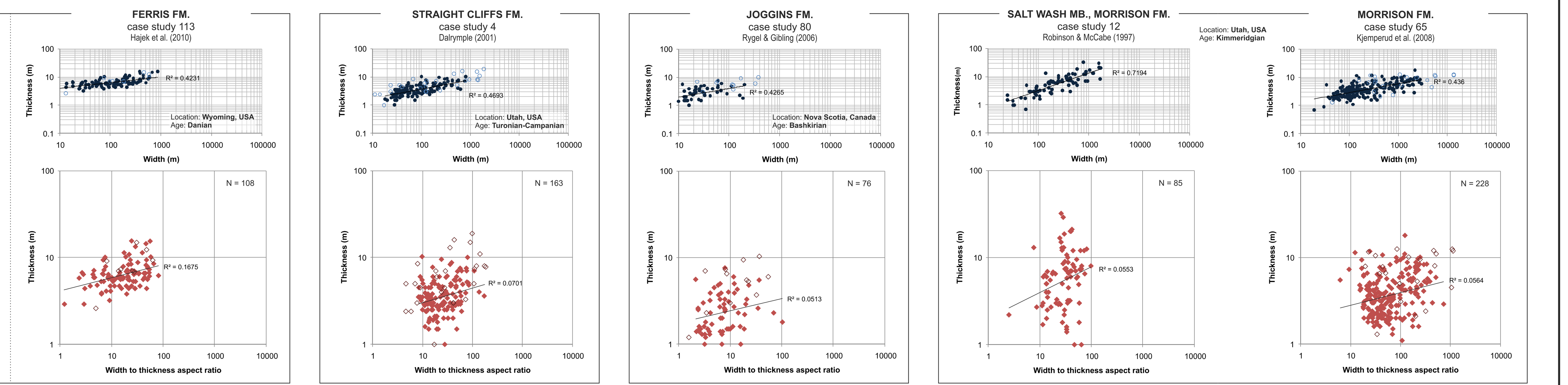


TYPE-2 ARCHITECTURAL STYLE

Few systems/stratigraphic volumes display a large-scale architectural style characterized by a weak positive relationship between channel-complex thickness and their width-to-thickness aspect ratio, resulting in channel complexes with a subtle tendency to display higher aspect ratios when thicker.

Channel complexes from the Paleocene Ferris Fm. (Hanna Basin, USA) best exemplify this situation (data from: Hajek et al. 2010).

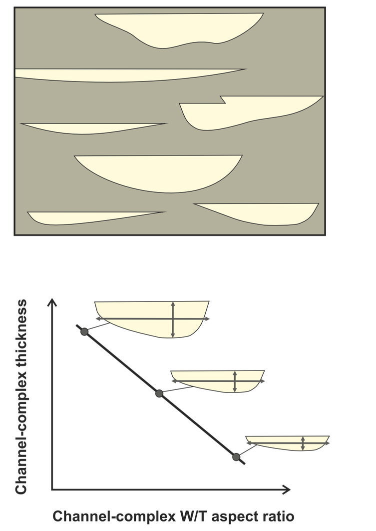


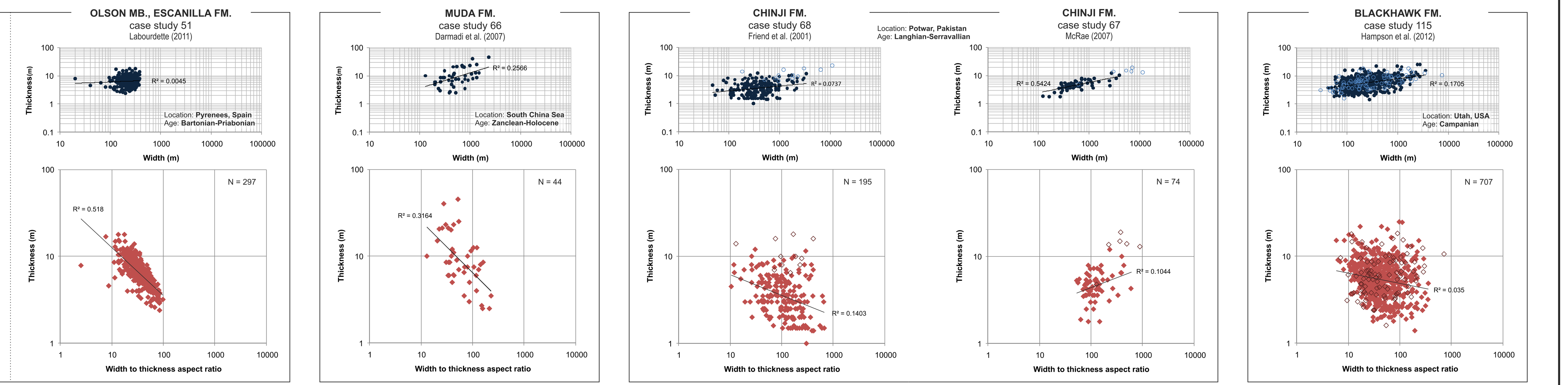


TYPE-3 ARCHITECTURAL STYLE

An alternative architectural style showing a negative correlation between the width-to-thickness aspect ratio and the thickness of the channel complexes is observed in few systems, therefore characterized by channel complexes with a tendency to display smaller aspect ratios when thicker.

Channel complexes from the Eocene Olson Mb. of the Escanilla Fm. (Ainsa Basin, Spain) best exemplify this situation (data from: Labourdette 2011).





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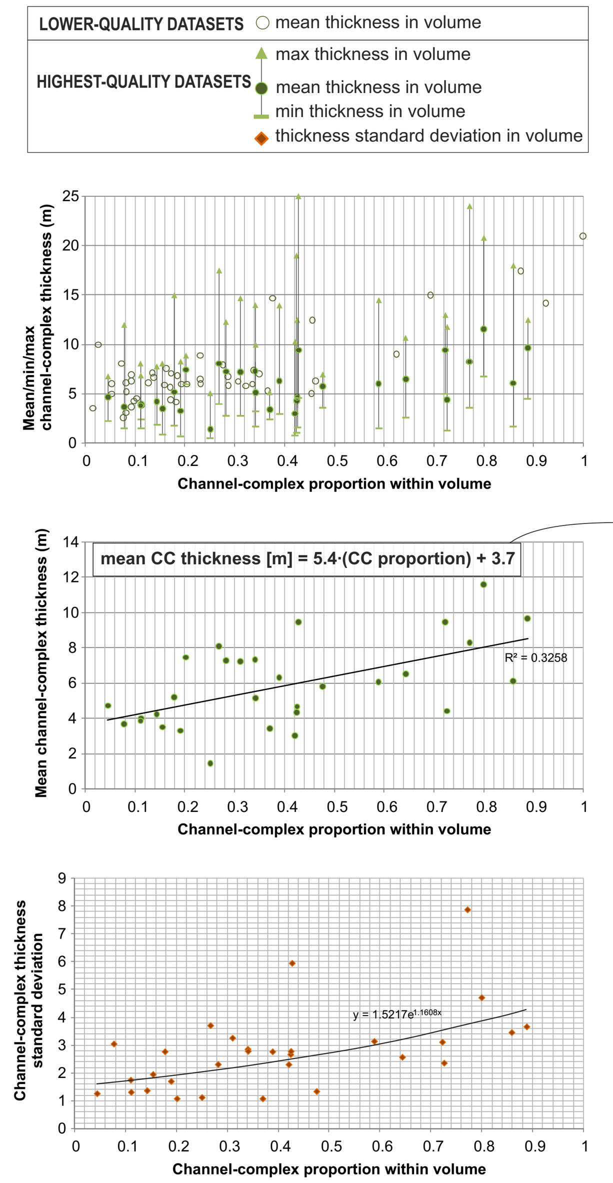
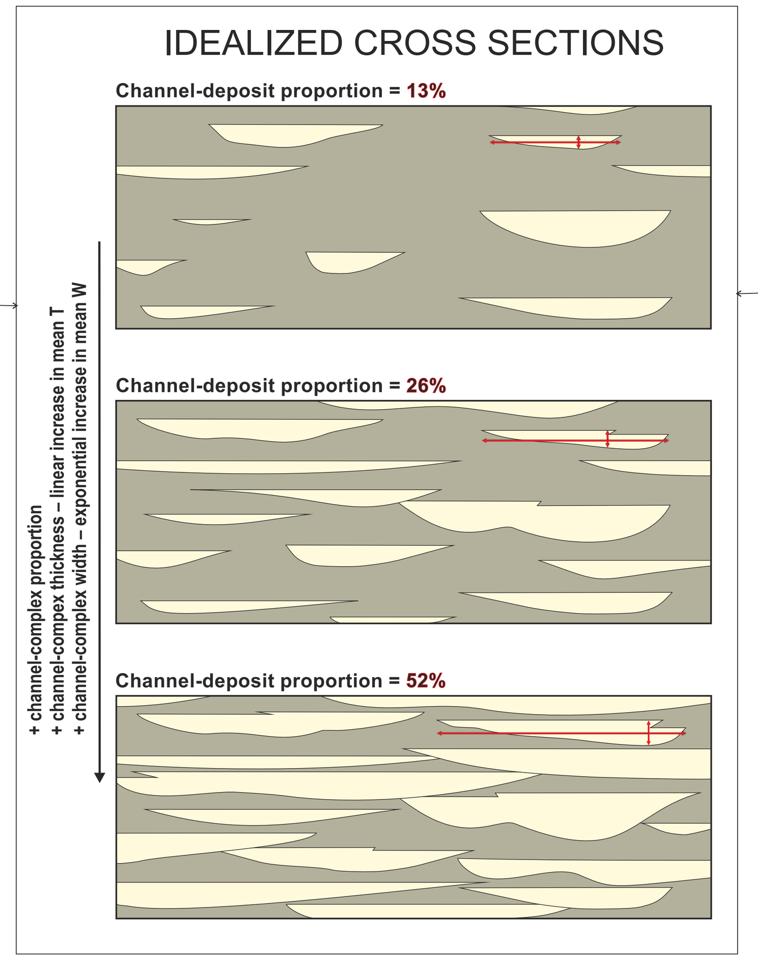
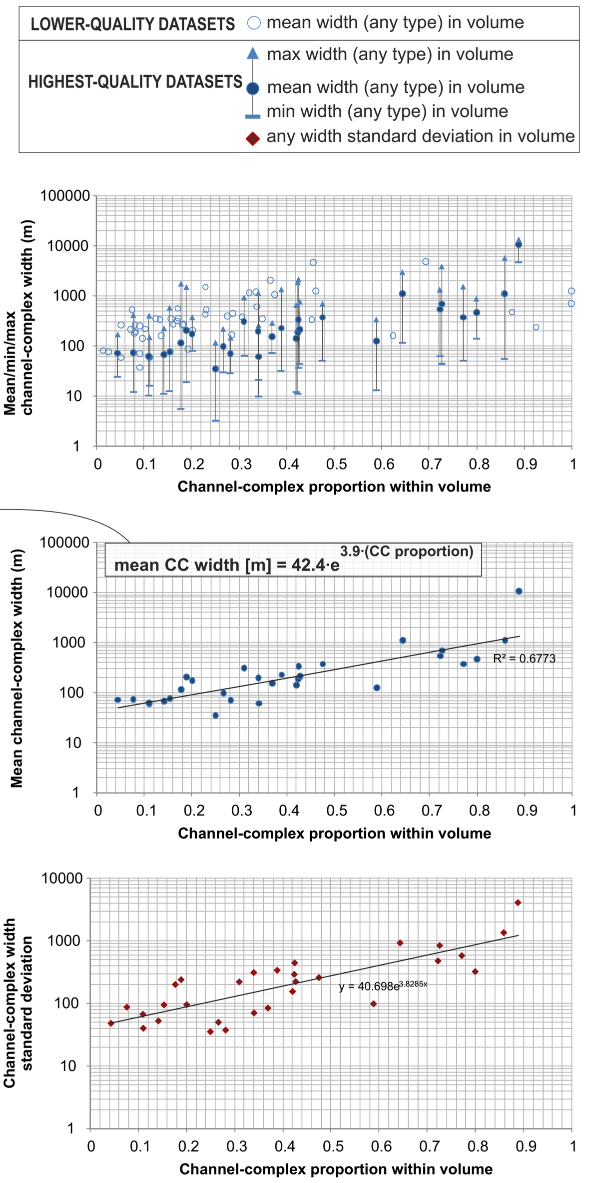
EMPIRICAL RELATIONSHIPS BASED ON ARCHITECTURAL PROPERTIES

PREDICTING CHANNEL-COMPLEX GEOMETRIES FROM BOREHOLE-DERIVED PROPORTIONS

FAKTS can be used to select stratigraphic volumes suitable for investigation at the channel-complex scale, for each volume for which at least two-dimensional information is available. Descriptive statistics can be computed concerning the geometry of channel complexes, and their proportion as based on the product of their thickness and lateral extent. Based on this approach, relationships between channel-complex geometry and proportions can be used as a general constraint to inform well-to-well correlations and stochastic reservoir models.







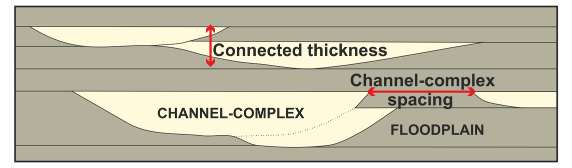
PREDICTING CHANNEL-COMPLEX SPACING AND VERTICAL CONNECTIVITY FROM PROPORTIONS

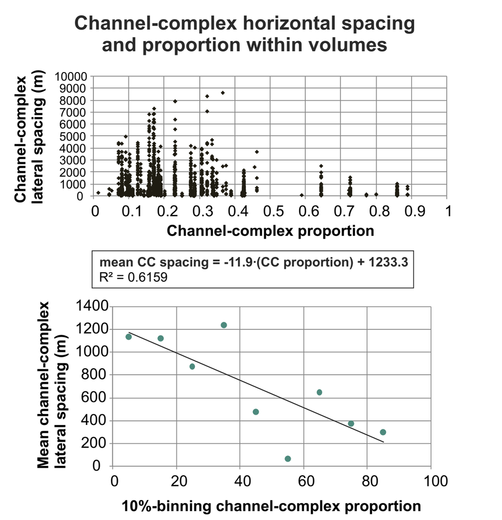
The FAKTS database stores information about genetic-unit spatial relationships, therefore permitting – among others – queries for information concerning channel-complex vertical connectivity and cross-gradient spacing.

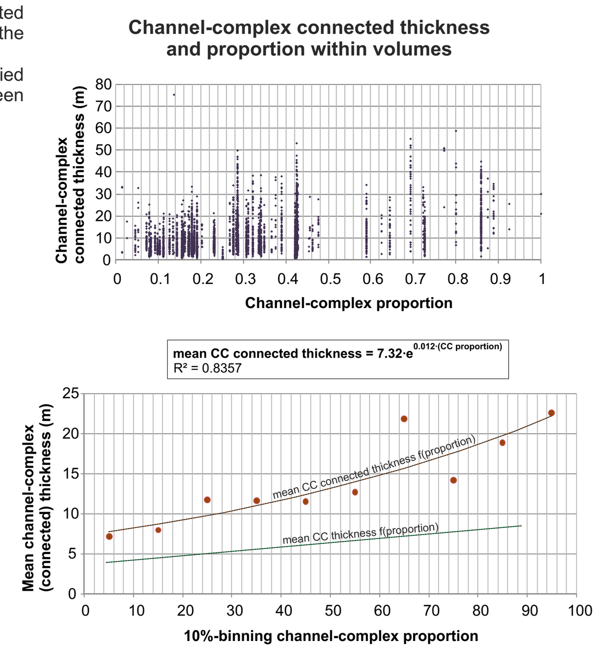
Channel-complex connectivity in the vertical direction is quantified by a value termed *connected thickness* and defined as the sum of the thicknesses of vertically-stacked channel complexes, with the admissible condition of channel complexes being included in more than one stack.

An empirical relationship linking channel-complex connected thickness and proportions has been derived to quantify the effect of channel-body clustering on vertical connectivity.

Channel-complex cross-gradient spacing is instead quantified by the lateral extent of a floodplain element present between two channel complexes.

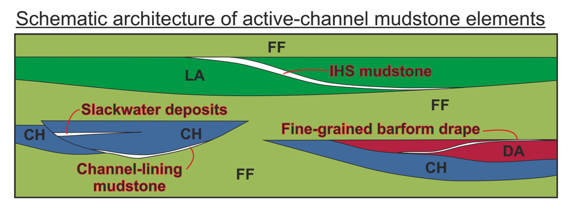


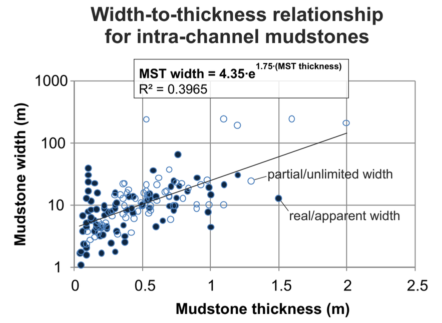


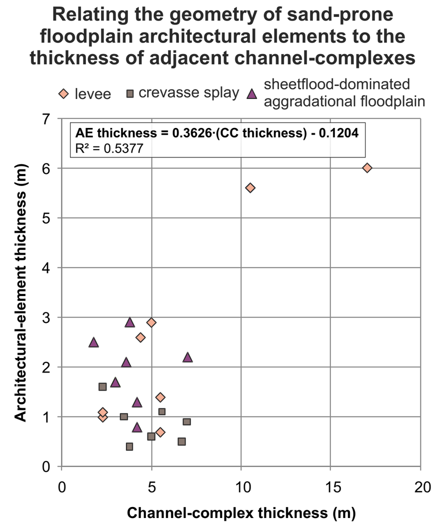


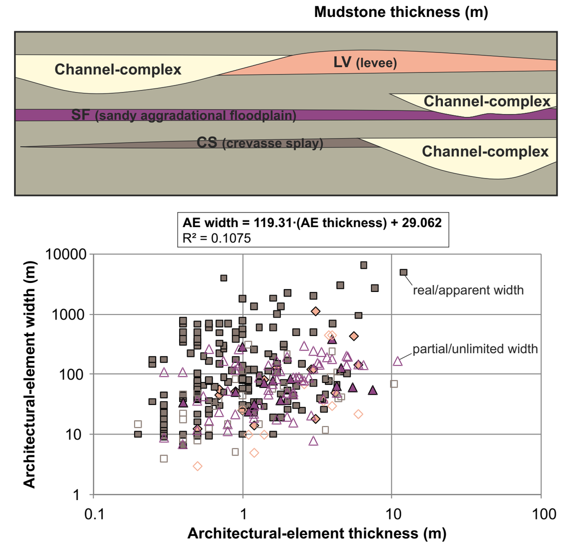
LINKING HIERARCHY, SPATIAL RELATIONSHIPS AND GEOMETRIES: SOME EXAMPLES

The inclusion in the FAKTS database of information about genetic-unit hierarchy and spatial relationships permits improved consideration of lithological heterogeneity at several scales, enabling external geometries to be linked to internal organization and spatial patterns.

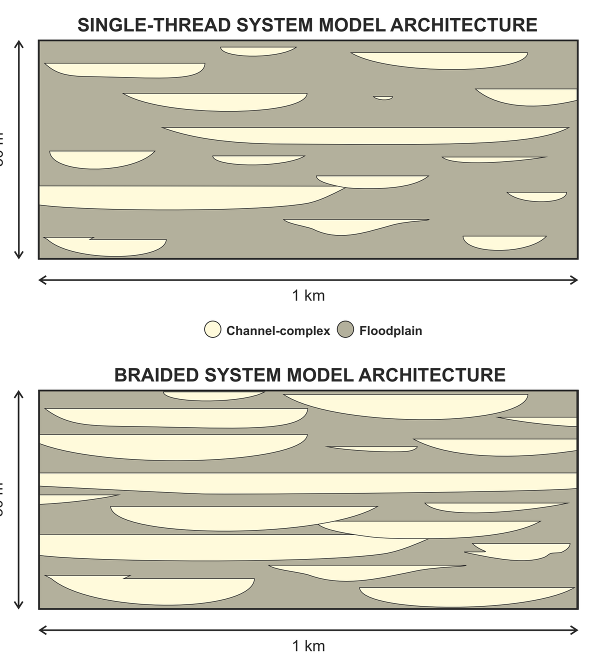


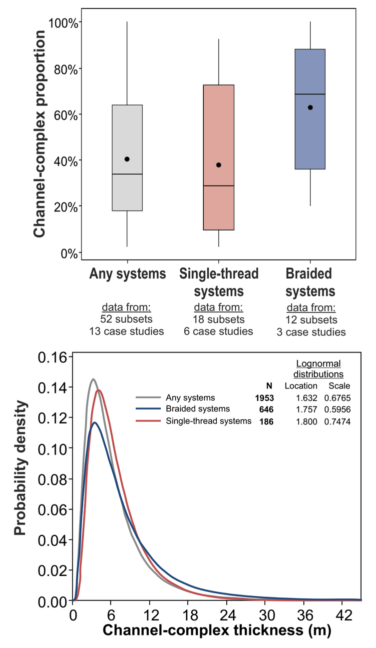




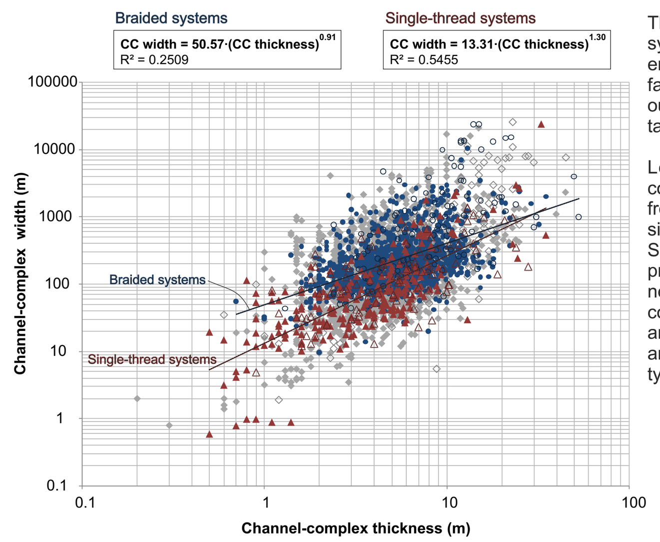


EMPIRICAL RELATIONSHIPS BASED ON SYSTEM INTERPRETATION





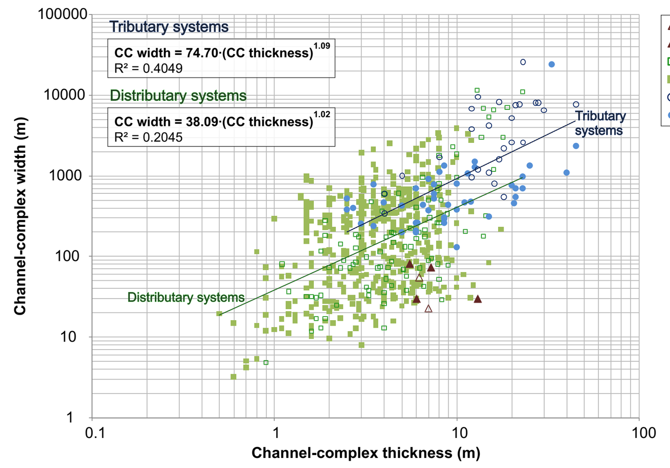
WIDTH-TO-THICKNESS RELATIONSHIPS FOR CHANNEL COMPLEXES CLASSIFIED ON CHANNEL PATTERN



The FAKTS database classifies fluvial systems on observed and interpreted environmental parameters and controlling factors, thereby permitting the derivation of outcrop and modern analog information tailored to the type of subsurface system.

Left: relationships relating channel-complex width to their thickness as derived from systems interpreted as displaying a single-thread or braided channel pattern. Such relationships have very limited predictive value, as explained below, but nevertheless still provide straightforward constraints that can be jointly referred to, and are therefore helpful for expressing architectural variability between system types.

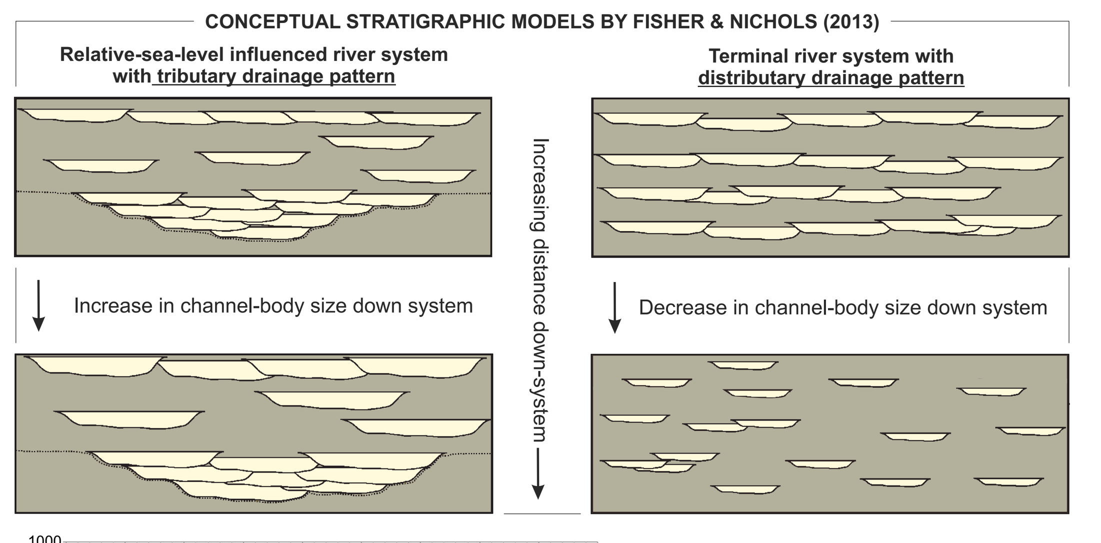
WIDTH-TO-THICKNESS RELATIONSHIPS FOR CHANNEL COMPLEXES CLASSIFIED ON DRAINAGE PATTERN

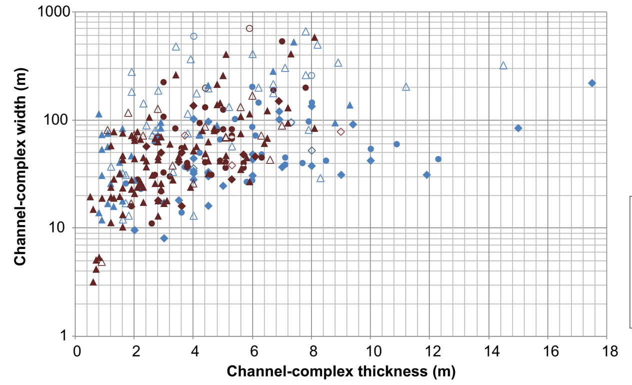


Left: relationships relating channel-complex width to thickness as derived from systems interpreted as recording tributary and distributary drainage patterns respectively.

Channel complexes from tributary systems tend to be wider and display higher values of thickness than their distributary counterparts.

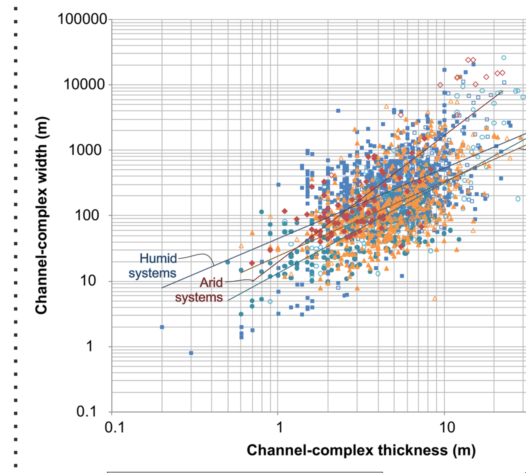
Determination-coefficient values are relatively low, but the observed relationships and their domains may be consistent with common models predicting downstream decrease in formative-channel width and depth for systems with distributary patterns, as opposed to the bankfull width and depth increase expected by tributary inputs.

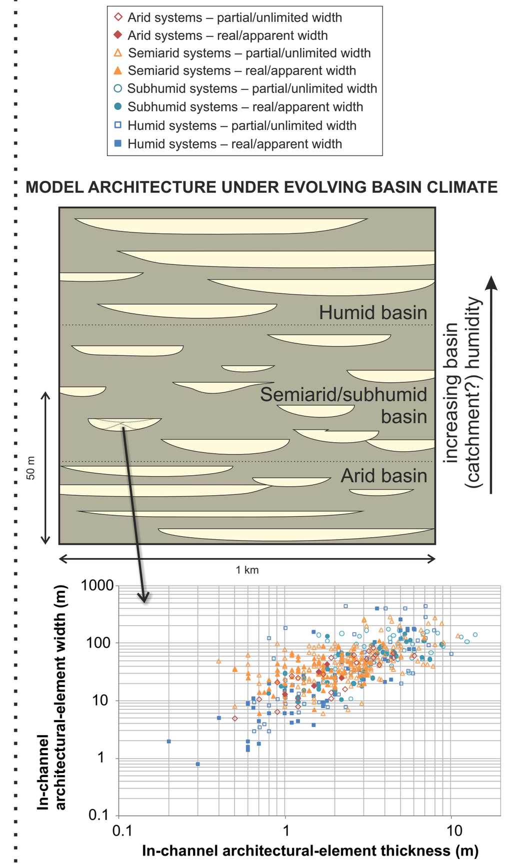




To further test drainage-pattern control on downstream evolution of channel-complex geometry, data from three distributary systems for which observations in streamwise framework are available have been considered: a trend of systematic downstream channel-complex thinning is revealed, whereas only one system is characterized by significant downstream channel-complex narrowing.

WIDTH-TO-THICKNESS RELATIONSHIPS FOR CHANNEL COMPLEXES CLASSIFIED ON BASIN CLIMATE TYPE





Above: relationships relating channel-complex width to thickness as derived from successions that are interpreted as being deposited under different basin climate regimes. These climate types are based on relative humidity only, refer to the locus of deposition, and may or may not refer to conditions averaged through time; the attribution to any given class is based on one or more proxies with variable degrees of reliability.

Overall, considering increasing basin humidity, channel-complex width distributions show a trend of channel-complex narrowing through the arid to semiarid/subhumid transition, followed by a trend of channel-complex widening towards more humid climate types.

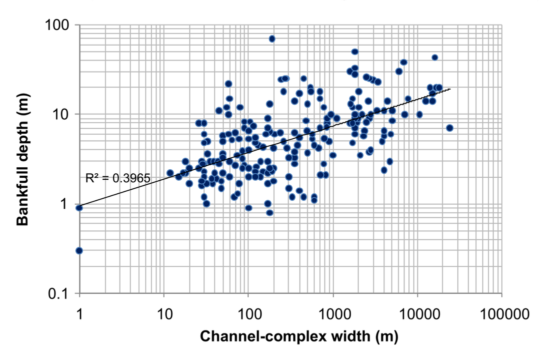
These observations could be indicative of the relative roles played by climate-related variables that may directly control the geometry and evolution of formative channels, thereby influencing channel-complex geometry, such as vegetation-controlled bank stability or water discharge. Nevertheless, comparable relationships do not emerge from the geometry of in-channel architectural elements, which are expected to be more closely related to such controls, but for which less data from fewer systems are available, especially if only fully-preserved storeys are included.

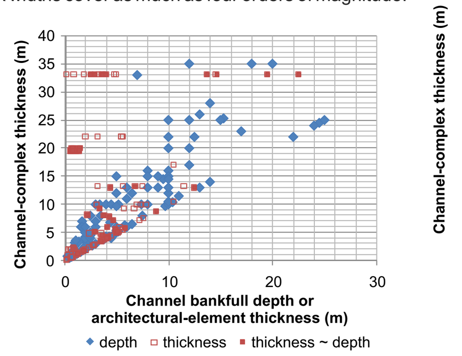
This application suggests the value of the database for investigating the interplay of different factors in controlling fluvial architecture: multivariate analysis involving several dependent (e.g. geometrical parameters, proportions) and independent variables should be applied once sufficient data are available.

BEYOND GEOMETRIC EMPIRICAL RELATIONSHIPS: ANALOG-BASED CORRELABILITY MODELS

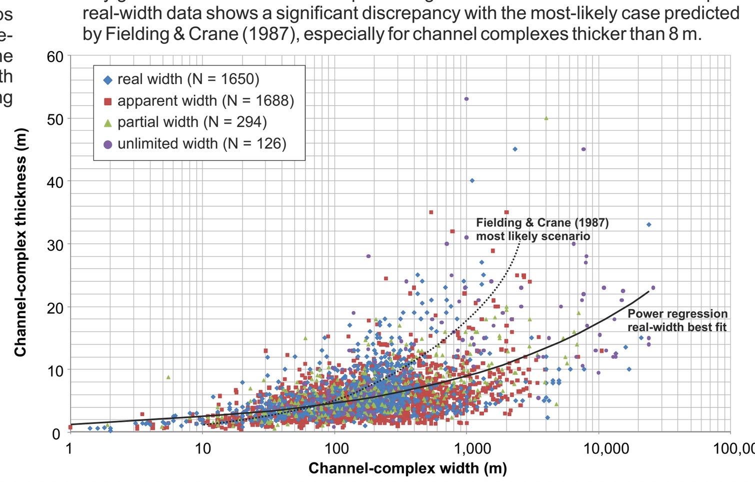
EVALUATION OF TRADITIONAL EMPIRICAL RELATIONSHIPS FOR GUIDING CORRELATION OF FLUVIAL CHANNEL BODIES

Past approaches to the generation of correlation panels of subsurface fluvial architecture made use of empirical relationships to guide the lateral tracing of each individual channel elements, for example, relating channel-body width to the formative-channel bankfull depth. The considerable scatter observed in the architectural data presented here demonstrates the difficulty of reliably inferring channel-body width from the formative-channel bankfull depth, formative-channel bankfull depth from the thickness of a channel sandstone body, or channel-body width directly from its thickness. For example, considering bankfull depths observed in the 7-23 m range, FAKTS channel-complex widths cover as much as four orders of magnitude.





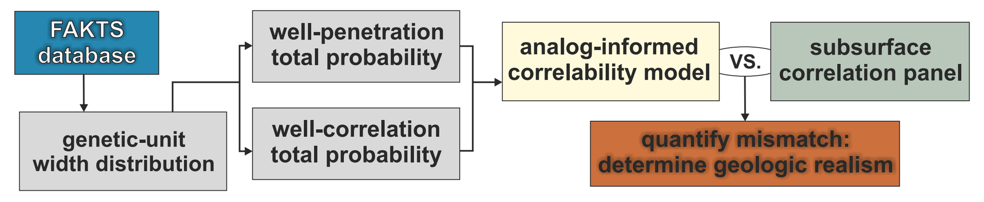
Empirical relationships for predicting the lateral extent of a genetic unit from its thickness are commonly employed. The FAKTS channel-complex width-to-thickness scatterplot displays substantial scatter, even if only real widths are considered, with three to four order of magnitudes in width possibly associated with any given value of thickness: the power-regression best fit of all channel-complex real-width data shows a significant discrepancy with the most-likely case predicted by Fielding & Crane (1987), especially for channel complexes thicker than 8 m.

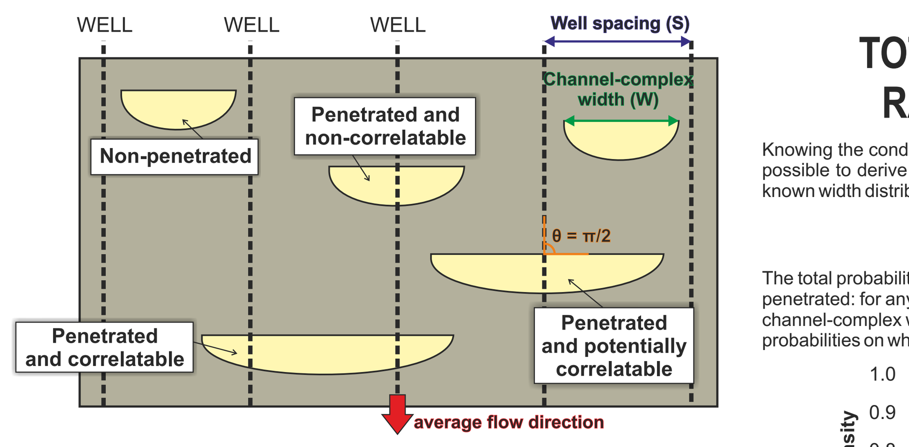


Thus, the application of such empirical relationships for predicting the lateral extent of a genetic unit is severely limited by the actual natural variability in genetic-unit geometry they fail to consider, embodied by the wide scatter in the datasets from which these relationships were derived. Tailoring such relationships (as shown on the left) on classifications that possibly incorporate the minimum intra-type architectural variability and maximum inter-type architectural variability helps improve the predictive value of such expression; yet, the significant data scatter shown in scatterplots demonstrates how, for certain geological bodies (channel complexes), this approach is still only of limited use.

Therefore, a new method to guide and rank subsurface well-to-well correlations has been developed as part of this study that entails the lateral tracing of geological bodies; the method uses probabilistic tools to assess the geological realism of correlations, provided that the well array has constant spacing. Crucially, the approach is not based on expressions applicable to individual bodies; instead, it makes use of outcrop/modern analog-derived distributions of the horizontal extent of geobody types that refer to the entire analog succession.

A NEW PROBABILISTIC APPROACH TO THE CORRELATION OF FLUVIAL CHANNEL BODIES

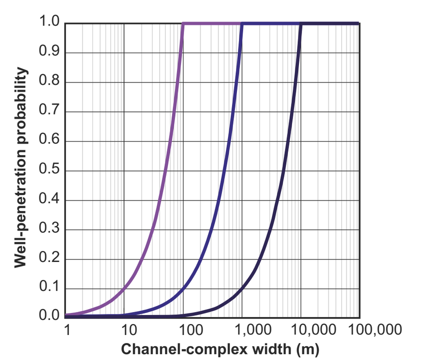




CONDITIONAL PROBABILITY OF CHANNEL-COMPLEX PENETRATION BY WELL ARRAY WITH SPACING = S

On the basis of work by McCammon (1977), the conditional probability of penetration of a channel complex with width W by a well array with spacing S can be expressed as: P(p) = W/S

Orthogonal penetration is assumed.

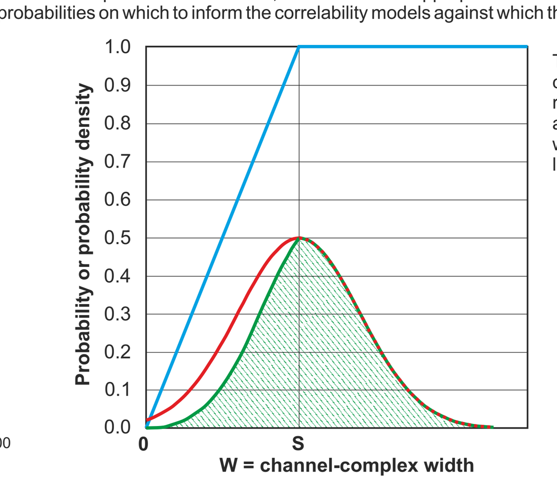


TOTAL PROBABILITY OF PENETRATION OF A RANDOMLY-CHOSEN CHANNEL COMPLEX

Knowing the conditional probability of penetration of a channel complex with width W by a well array with spacing S, it is possible to derive the total probability of penetration of a randomly-selected channel complex drawn from a family with known width distribution, through application of the total probability theorem:

$$P(p) = \int_{W} P\left(\frac{p}{w}\right) P(w)\, dw \longrightarrow P(p) = \int_0^S \left(\frac{W}{S}\right) P(w)\, dw + \int_S^{W_{max}} P(w)\, dw$$

The total probability of penetration corresponds to the proportion of channel complexes from that family that are likely to be penetrated: for any given well-array spacing, this proportion is essentially determined by the probability density function of channel-complex width. Therefore, the choice of an appropriate outcrop analog is fundamental for obtaining values of total probabilities on which to inform the correlability models against which the subsurface correlation panels can be tested.



The ideal example on the left shows how the channel-complex width distribution affects the resulting total probability of penetration by a well-array with spacing S; if, for instance, the width pdf was translated to the right so that W was always larger than S, the total probability would be 1.0.

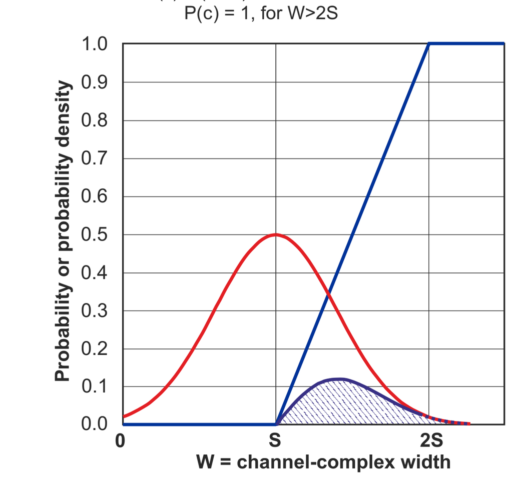
IDEAL EXAMPLE:
– normal distribution of channel-complex widths
– S-spaced well array
conditional probability of penetration of W-wide channel-complex by S-spaced well array
channel-complex width probability density function
total probability of penetration of a random channel-complex in a population following pdf by S-spaced well array

TOTAL PROBABILITY OF CORRELATION OF A RANDOMLY-CHOSEN CHANNEL COMPLEX

CONDITIONAL PROBABILITY OF CHANNEL-COMPLEX CORRELATION BY WELL ARRAY WITH SPACING = S

On the basis of work by McCammon (1977), the conditional probability of correlation of a channel complex with width W between two wells with spacing S can be expressed as:

P(c) = 0, for W<S;
P(c) = (W-S)/S, for S≤W≤2S
P(c) = 1, for W>2S



Knowing the conditional probability of correlation of a channel complex with width W between two S-spaced wells, it is possible to derive the total probability of correlation of a randomly-selected channel complex drawn from a family with known width distribution, through application of the total probability theorem:

$$P(c) = \int_0^S 0 \cdot P(w)dw + \int_S^{2S} \left(\frac{w-S}{S}\right) P(w)dw + \int_{2S}^{W_{max}} P(w)\, dw$$

The ideal example on the left shows how the channel-complex width distribution affects the resulting total probability of correlation between two wells with spacing S; if, for instance, the width pdf was translated to the right so that W was always larger than 2S, the total probability would be 1.0, i.e. 100% of channel complexes could be correlatable.

IDEAL EXAMPLE:
– normal distribution of channel-complex widths
– S-spaced well array
conditional probability of correlation of W-wide channel-complex between two S-spaced wells
channel-complex width probability density function
total probability of correlation of a random channel-complex in a population following pdf between two S-spaced wells

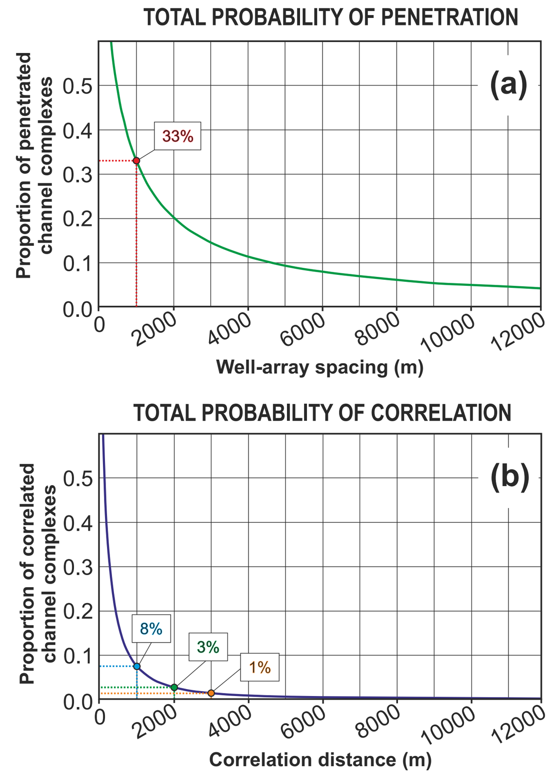
CORRELABILITY MODELS FOR COMPARISON WITH SUBSURFACE INTERPRETATIONS

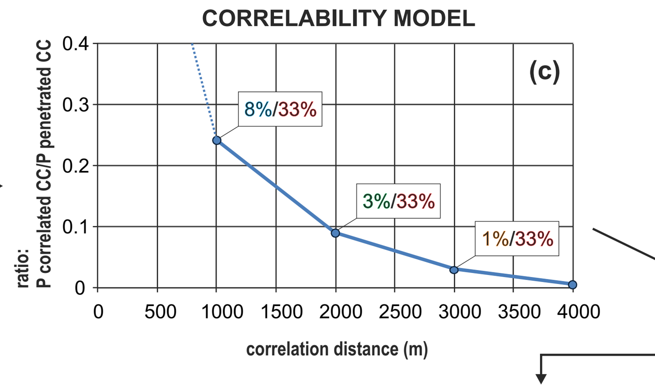
To obtain relationships describing the total probability of (a) channel-complex penetration by a well array as a function of well spacing S, and (b) correlation between two S-spaced wells as a function of well spacing S, the following are required: (1) inclusion in the total-probability expressions of a realistic probability density function describing the likely width distribution of the channel complexes, as derived from suitable analogs, and (2) operation of the definite integral. Most FAKTS systems and synthetic facies models display channel-complex width distributions that are best described by lognormal models (with location μ and scale σ). The total probability expressions that need to be integrated can therefore be written as:

$$P(p) = \int_0^S \left(\frac{W}{S}\right)\left(\frac{1}{w\sigma\sqrt{2\pi}}\right)e^{-\frac{(\ln w-\mu)^2}{2\sigma^2}}dw + \int_S^{W_{max}} \left(\frac{1}{w\sigma\sqrt{2\pi}}\right)e^{-\frac{(\ln w-\mu)^2}{2\sigma^2}}dw$$

$$P(c) = \int_S^{2S} \left(\frac{W-S}{S}\right)\left(\frac{1}{w\sigma\sqrt{2\pi}}\right)e^{-\frac{(\ln w-\mu)^2}{2\sigma^2}}dw + \int_{2S}^{W_{max}} \left(\frac{1}{w\sigma\sqrt{2\pi}}\right)e^{-\frac{(\ln w-\mu)^2}{2\sigma^2}}dw$$

Thus, once knowledge of total probability of penetration and correlation is obtained for a suitable field analog or database-informed synthetic analog, it is possible to employ total-probability curves to draw values of total probability for each multiple of the well-spacing (in the example on the right: figures *a* and *b*) and operate the ratio between the total probability of correlation and the total probability of penetration (in the example on the right, figure *c*). So, these values quantify the proportion of penetrated channel complexes that are also correlatable, and will represent the model of correlability against which to test subsurface interpretations based on well-to-well correlation across a uniformly-spaced well array. If these values are plotted as a function of inter-well distance (in the example on the right, figure *c*), then the actual process of comparison between the model of correlability and the subsurface interpretation can be carried out graphically, allowing for recognition of the degree of approximation of the interpretation to the model and whether the interpretation is too conservative or excessively confident (in the example on the right: figures *d* and *e*).

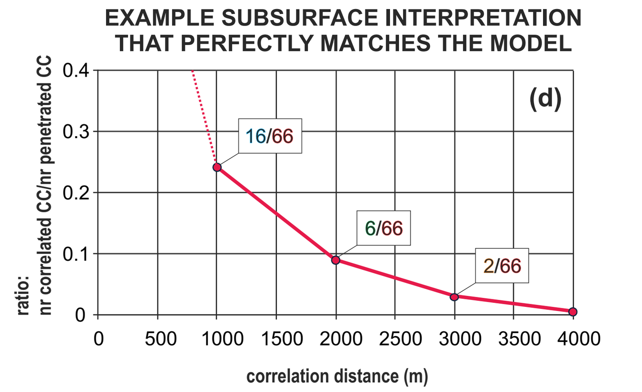


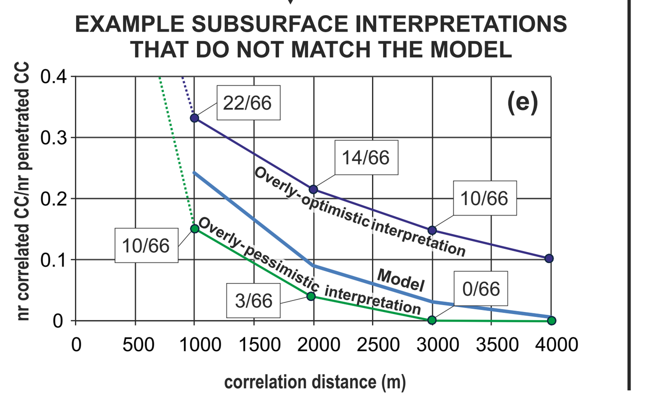


IDEAL EXAMPLE:
– well spacing = 1000 m
– penetrated channel complexes = 66

In this fictitious example, a correlability model based on a lognormal channel-complex width pdf that incorporates all FAKTS channel complexes is used to assess and rank the quality of alternative well-to-well correlation panels, for given well spacing (1000 m) and number of penetrated channel complexes (66).

COMPARISON WITH SUBSURFACE INTERPRETATIONS





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Quantitative empirical relationships for the prediction of subsurface fluvial sedimentary architecture

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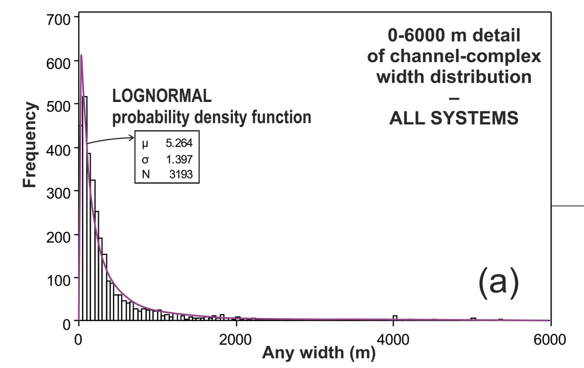
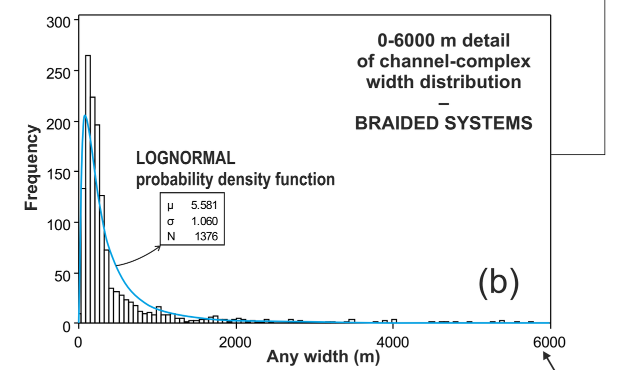
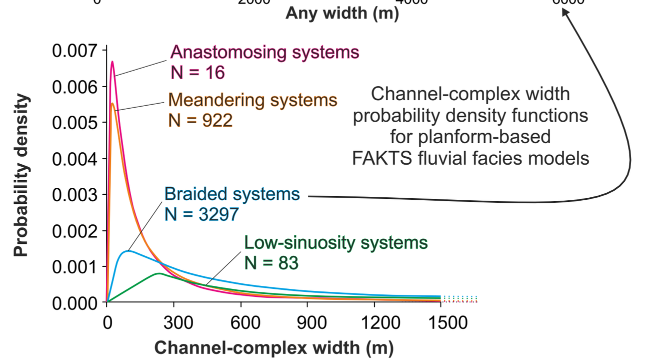
UNIVERSITY OF LEEDS

FAKTS-DERIVED CORRELABILITY FOR FLUVIAL-SYSTEM TYPES

TOTAL-PROBABILITY CURVES BASED ON CHANNEL-COMPLEX WIDTH FROM ALL FAKTS SYSTEMS AND BRAIDED SYSTEMS ONLY

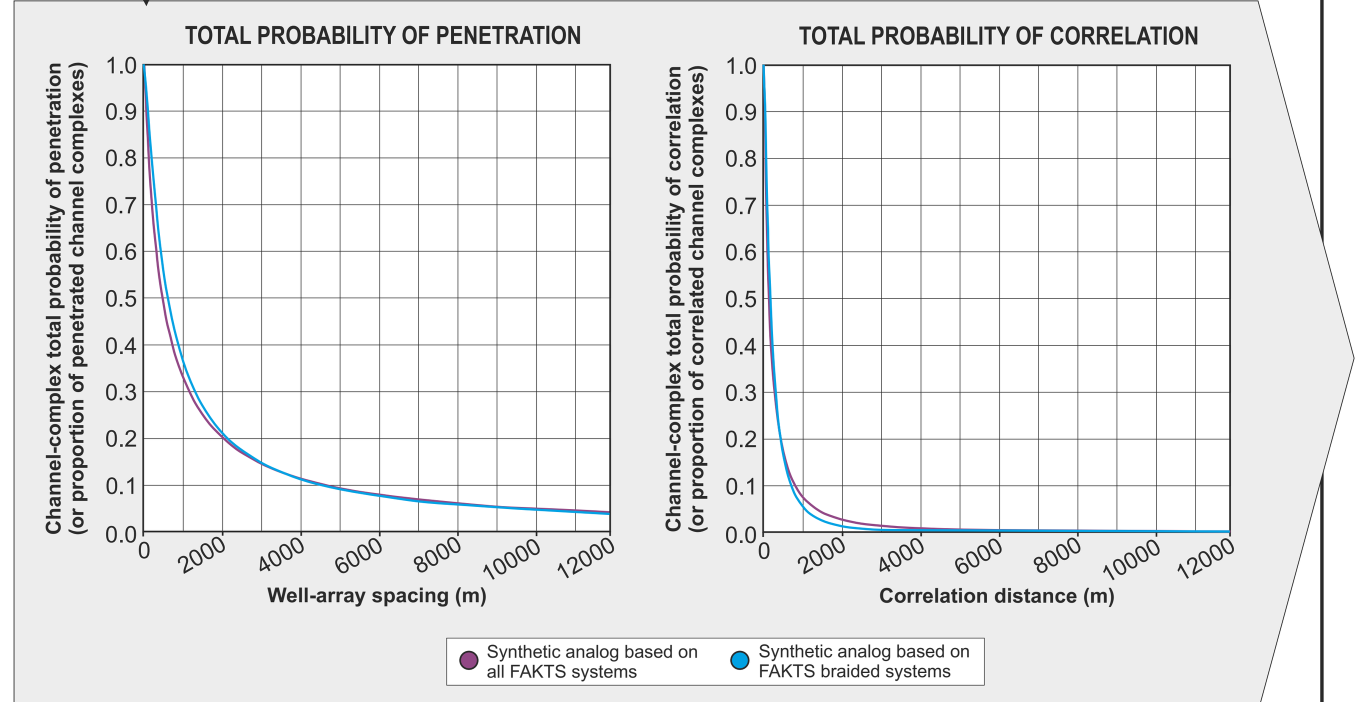




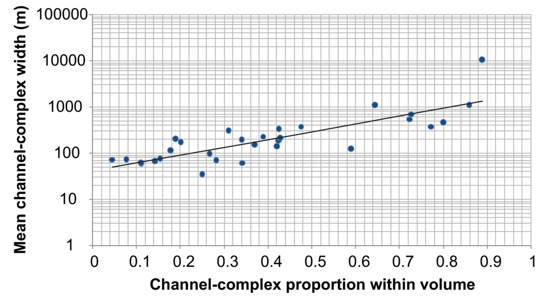


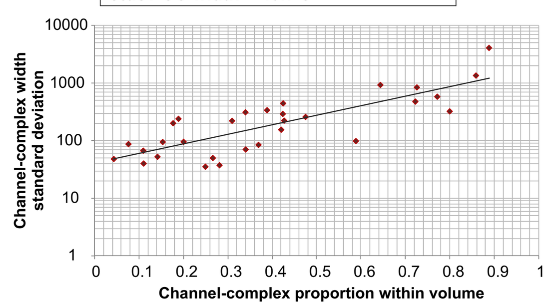
The FAKTS database permits derivation of width distributions for a variety of genetic-unit types (e.g. channel complexes, coal swamps), drawn from several ancient and/or modern systems that can be considered as suitable analogs to subsurface successions. Channel-complex width distributions can therefore be used to generate correlability models with which to inform well-to-well correlations of subsurface stratigraphy. System analogy needs to be established on any of several system parameters, such as channel-pattern planform types. Next, the FAKTS database is filtered accordingly, so that bespoke probability density functions of genetic-unit lateral extent can be obtained. The probability density functions are included in the total-probability expressions to derive curves describing total-probability of genetic-unit penetration and correlation as a function of inter-well distance. These curves have general applicability: total-probability values can be drawn from them to tailor the correlability model on the well spacing.

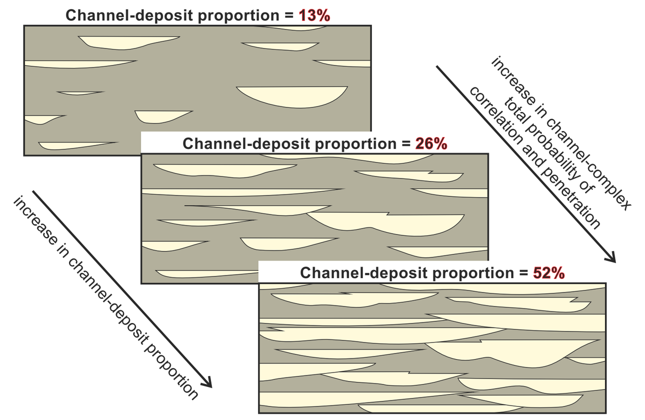
In the example below, total-probability curves were derived for channel complexes belonging to a generic fluvial system model – by including all FAKTS channel-complex widths – and to an ideal braided system model – by including only FAKTS data from systems interpreted as braided. These curves have been applied to test three published alternative interpretations of the same well array (on the right).



TOTAL-PROBABILITY CURVES BASED ON EMPIRICAL RELATIONSHIPS LINKING CHANNEL-COMPLEX WIDTH STATISTICS AND PROPORTION







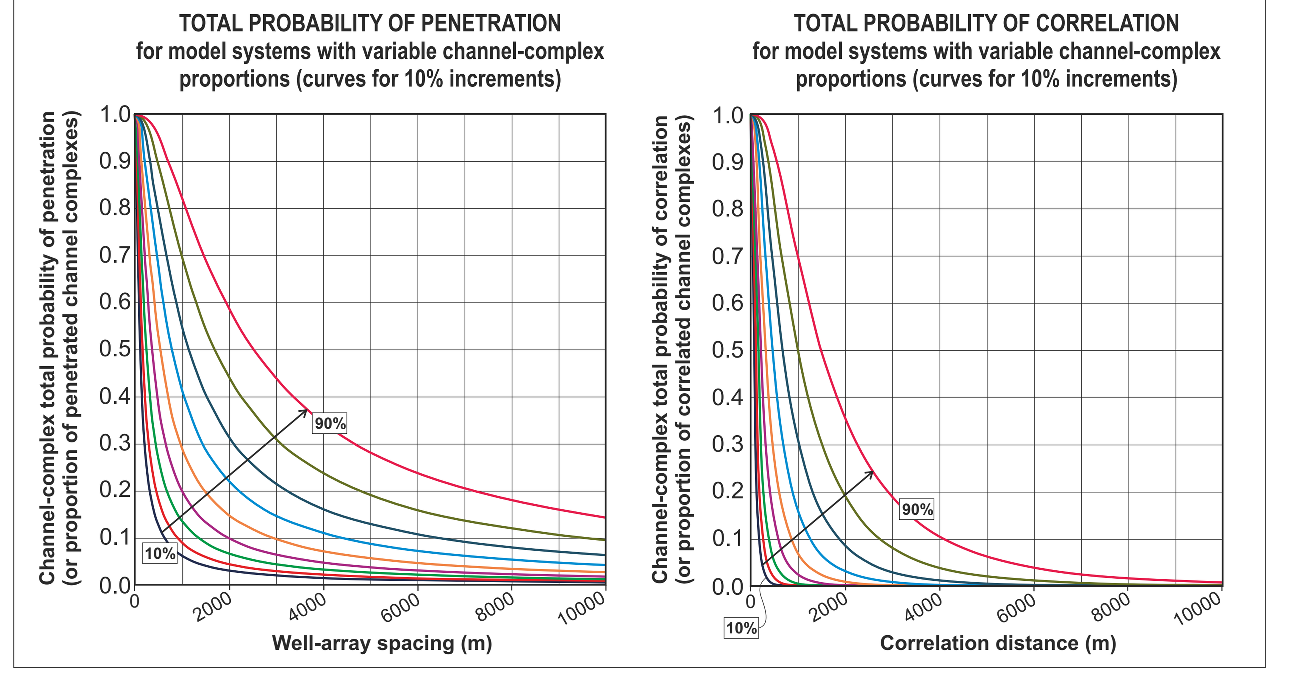
Total-probability-based models of channel-complex correlability such as the ones presented for braided systems (see above) can be customized on any fluvial environmental type (e.g. fluvial coastal plain, meandering system in subhumid basin; cf. Colombera et al., 2013), provided that a channel-complex width distribution is available.

Such models can be constructed on architectural properties that are distinctively associated with a given distribution of channel-complex width; it is thus useful to be able to generate models categorized on properties that can directly be derived from interpreted well data, such as the relative proportion of channel and floodplain deposits.

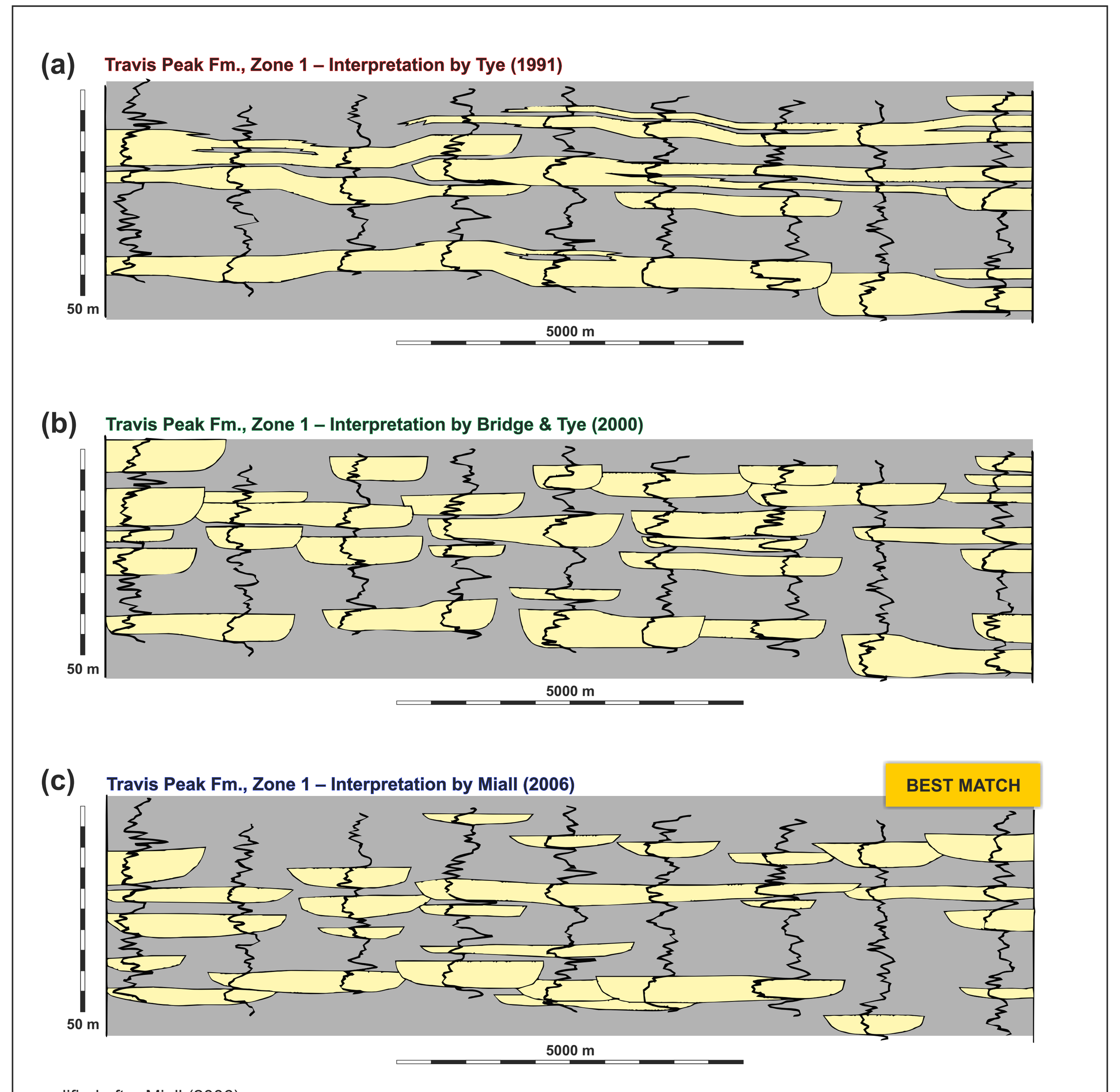
Therefore, assuming a log-normal distribution as appropriate for describing channel-complex width distribution for any proportion, empirical relationships have been employed that relate channel-complex mean width and width standard deviation to express location and scale parameters of the log-normal pdf as a function of proportions. Curves of total probability of channel-complex penetration and correlation by a well array in stratigraphic volumes with channel-deposit proportions variable between 10% and 90% were then derived (see below). The application of the resulting correlability model only requires well-derived channel-deposit proportion.

$$\mu = 2\ln(42.4e^{3.9P}) - \left(\frac{\ln((42.4e^{3.9P})^2 + (40.7e^{3.8P})^2)}{2}\right) \quad \text{Location}$$

$$\sigma = \sqrt{\ln((42.4e^{3.9P})^2 + (40.7e^{3.8P})^2) - 2\ln(42.4e^{3.9P})} \quad \text{Scale}$$



TRAVIS PEAK FM. CASE STUDY: RANKING THE GEOLOGIC REALISM OF 3 CORRELATION PANELS

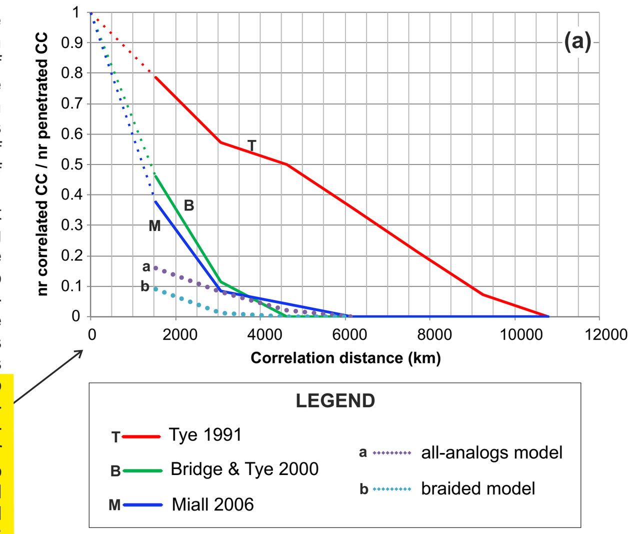


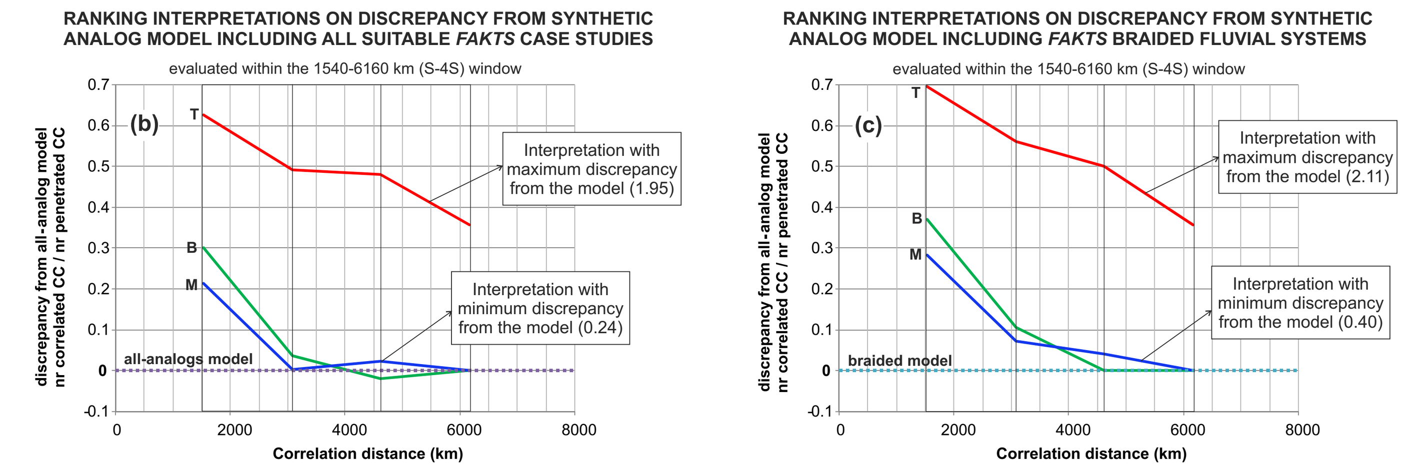
modified after Miall (2006)

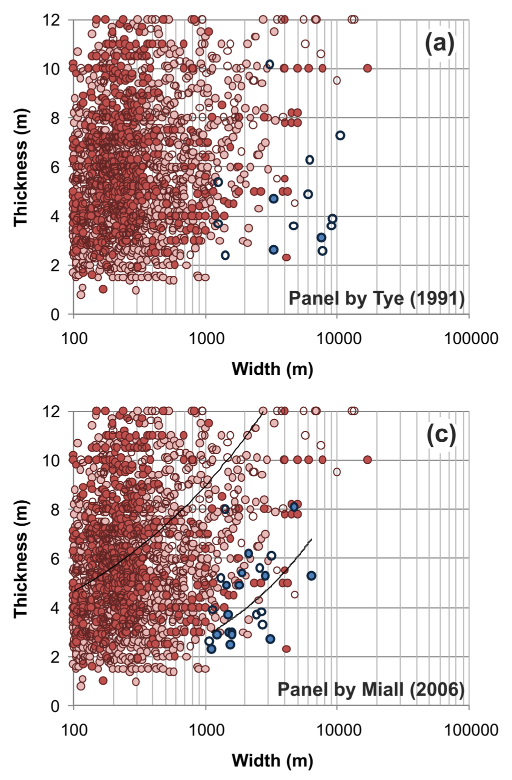
To illustrate the application of the probabilistic method for informing correlation-based deterministic models of subsurface fluvial sedimentary architecture, the technique is here applied to rank the architectural likelihood of three alternative interpretations proposed by Tye (1991), Bridge & Tye (2000) and Miall (2006) for the same well array, through a stratigraphic interval of the Lower Cretaceous Travis Peak Formation, Texas. The correlation panels are represented on the left. This dataset was chosen because it is a good published example of different models of fluvial subsurface architecture based on different assumptions; however, it is not the most suitable dataset for the method as the channel/floodplain interpretation of the logs differs slightly for the different panels and it is therefore necessary to assume that the wells were equally spaced (spacing = 1.54 km), even tough in reality the actual spacing varies between 0.8 and 2.2 km. These limitations are ignored in the following discussion, as our only purpose is to illustrate the method.

The scope is to rank the interpretations by determining which of these panels represents the most realistic subsurface fluvial architecture by comparison with an ideal channel-complex width distribution obtained by (1) all FAKTS analogs or (2) a synthetic analog based on many systems matching the dataset in terms of interpreted planform type (i.e. braided river). Thus, the curves describing the total probability of penetration and correlation obtained for the two types of synthetic analogs (panel on the left) were used to derive the total probability of penetration for S = 1540 m and total probability of correlation for S and multiples of S were derived. A penetrability model based on total probabilities could thus be plotted as the ratio between total probability of correlation and total probability of penetration for S and its multiples.

The definition of subsurface units must match with the definition of outcrop-analog units. So, the channel bodies depicted in the panels were identified geometrically to match with the FAKTS definition of channel-complex, to ensure that results are comparable with penetrability models based on width probability density functions derived from the database. Then, the ratio between the number of correlated channel-complexes and the number of channel-complexes in each panel was computed for multiples of S. Resulting ratios relating to the subsurface interpretations were plotted together with the total-probability-based penetrability models based on FAKTS analogues for graphical comparison against correlation distance (figure *a*). It is evident how, as compared to either of the other models, the interpretation by Tye (1991) consisted of lateral correlations that were significantly too optimistic. To facilitate comparison and quantification of the discrepancy between the subsurface interpretations and each of the two correlability models (i.e. all analogs vs. braided systems), the difference between the ratio of correlated and penetrated channel complexes for the interpretation and for the model were also plotted, independently for the two models (figures *b* and *c*). The total discrepancy can then be measured as the sum of the absolute values of the discrepancy at each correlation distance to rank the realism of the interpretations. The interpretation panels by Bridge & Tye (2000) and Miall (2006) show comparable results: they both appear to be overly optimistic with well correlations, especially over a single well spacing (i.e. between adjacent wells), and have similar values of discrepancy; the interpretation panel by Miall (2006) has the lowest total discrepancy value and ranks highest when compared with both correlability models.







LEGEND
- channel-complex real width (all FAKTS analogs)
- channel-complex apparent width (all FAKTS analogs)
- channel-complex partial/unlimited width (all FAKTS analogs)
- channel-complex width (subsurface interpretation)
- channel-complex partial width (subsurface interpretation)

Above: comparison between the geometry of channel complexes represented in the three Travis Peak Fm. panels by Tye (1991; figure *a*), Bridge & Tye (2000; figure *b*), and Miall (2006; figure *c*) and the geometry of channel complexes included in the FAKTS database, in the form of width-to-thickness scatterplots. The widths in the graphs consider the positions of lateral channel-body pinch-out as represented in the panels. These graphs do not provide information about the likely geometry of penetrated channel complexes; also, the fact that thickness values associated with well data are obtained from one-dimensional sampling strongly limits the significance of the comparison, as FAKTS channel-complex thickness refer to maximum thickness instead, and the thickness of these bodies can be highly variable laterally. Nevertheless, these plots can be useful for first-order assessment of interpretations that are certainly unrealistic (figure *a*) and for improving the realism of the panels by a-posteriori adjusting the likely position of pinch-out of channel bodies within two wells.

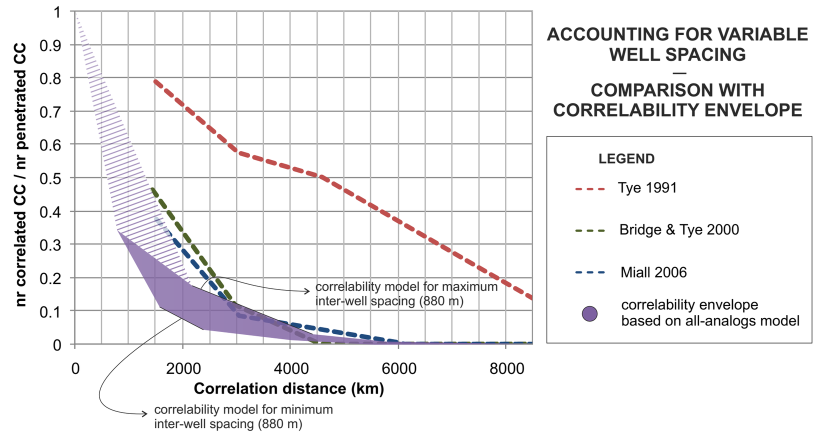
Well configurations characterized by constant inter-well distance are common, making this approach of direct use for such situations.

Whenever the condition of constant well spacing is not applicable, if there exist adjacent stratigraphic portions within which inter-well distance is roughly constant, the quality-check method presented here could be applied separately for different segments.

Instead, if the well spacing is variably distributed, correlability models could be obtained for the maximum and minimum values of well spacing, in order to identify a confidence interval – rather than a single correlability curve – with which subsurface interpretations could be compared, for example in terms of discrepancy between the underlying area and the curve given by the ratio between correlated and penetrated units plotted for the average spacing.

This last approach has been employed – as represented here on the right – to carry out a comparison between (a) the curves given by the ratio between correlated and penetrated units for the three Travis Peak Fm. panels, plotted for the average spacing of the Travis Peak Fm. dataset, and (b) the correlability envelope given by the ratios between total probabilities of correlation and penetration for the model including all the FAKTS analogs, computed for minimum (800 m) and maximum (2200 m) well spacing encountered in the Travis Peak Fm. dataset.

Again, even qualitative graphic comparison could be sufficient for discriminating the degree of realism of different interpretations.

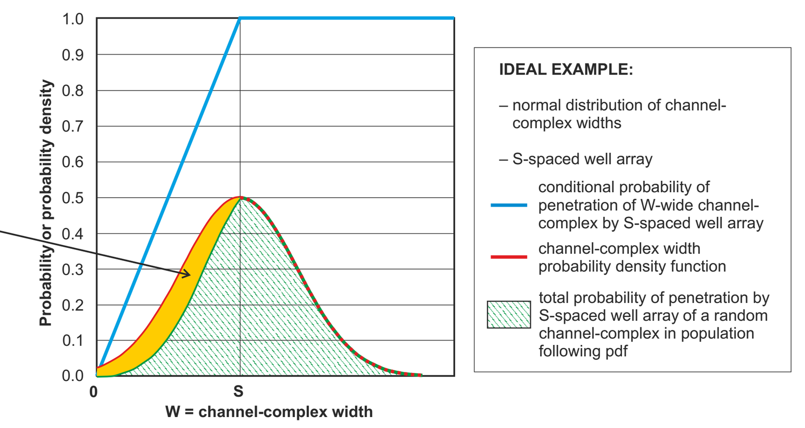


If this analog-oriented probabilistic approach is followed to guide interpretations, additional features that can be informed in subsurface reconstructions based on well correlations are:

- the percentage (as fractional number) of channel-complexes that are not yet penetrated by the array, which coincides with '1 - total probability of penetration',

- and the expected width distribution of those channel complexes, given by the difference between the analog channel-complex width probability density function and the curve obtained as the product between the same probability density function and the conditional probability of penetration.

From this information volumetric proportions of non-penetrated channel complexes can then be estimated relating widths to likely thickness, for example by following usual empirical relationships.



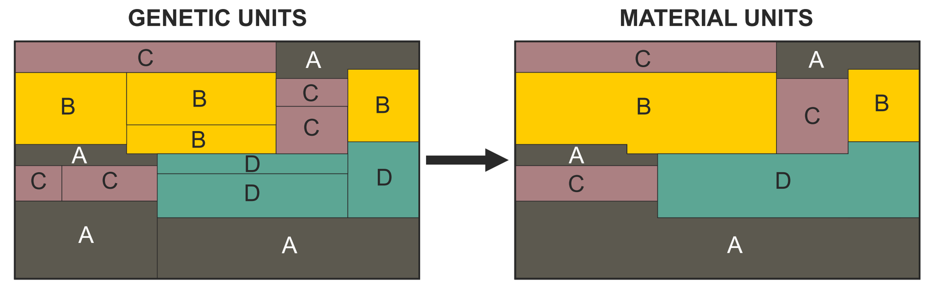
EMPIRICAL RELATIONSHIPS AND PIXEL-BASED RESERVOIR MODELS

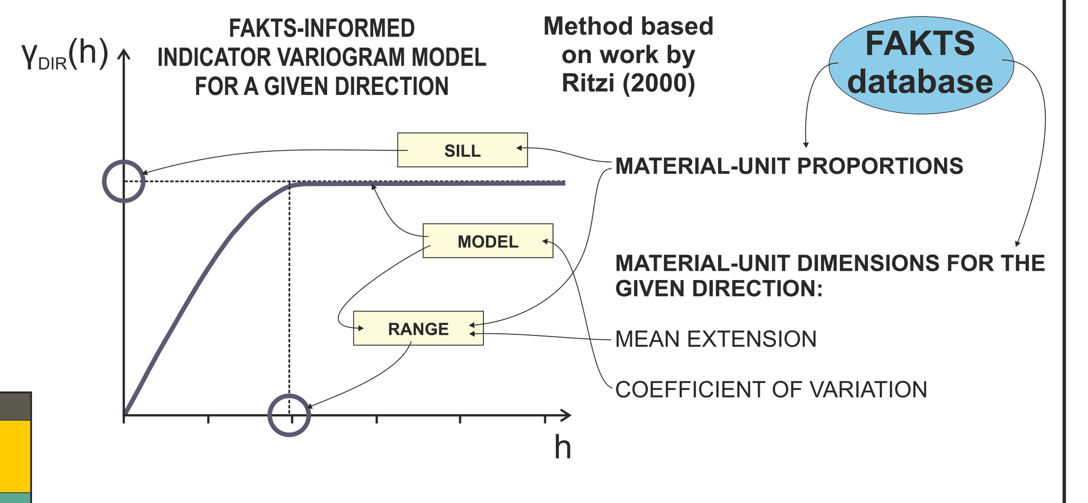
MATERIAL UNITS AND INDICATOR VARIOGRAMS

FAKTS material units are defined (Colombera et al. 2012b) as contiguous volumes of sediment characterized by having the same value of a given categorical or discretized continuous variable, or of any combination of two or more of them. An individual material unit corresponds with all the physically adjacent FAKTS genetic units having the required attribute values. Practically, this enables derivation of virtually any type of user defined reservoir and non-reservoir categories and their relative reservoir-modeling constraints.

One important implication is that the geometry of material units defined on genetic-unit types are different from the geometry of genetic units of that type, invariably resulting in larger size distributions, which will importantly control indicator variogram ranges.

For every direction of FAKTS' space, descriptive statistics (mean and coefficient of variation) of the size of material units (thickness, strike-width and dip-length) can be used in conjunction with their proportions to derive the ranges of material-unit indicator auto-variograms, whereas their sills can be calculated from material-unit marginal probabilities (i.e. proportions) and the variogram model inferred from the coefficient of variation of the dimensional parameters, as formulated by Ritzi (2000).



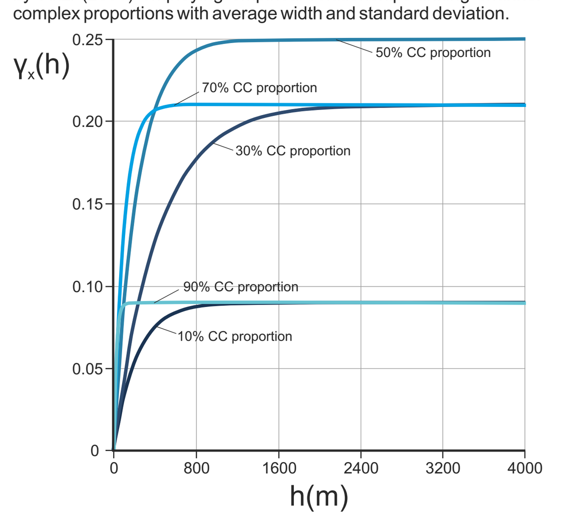


FAKTS permits informing indicator variogram models referring to any type of material unit, and so to any user-defined reservoir and nor-reservoir modeling categories, whenever the scarcity of direct data impedes the typical curve-fitting procedure: for hydrocarbon reservoirs this is routinely the case in the horizontal directions as the majority of boreholes are vertically oriented and too widely spaced to provide usable horizontal indicator variograms.

EXAMPLE PIXEL-ORIENTED MODELS OF FLUVIAL ARCHITECTURE BASED ON EMPIRICAL RELATIONSHIPS

Channel-complex indicator variograms (horizontal cross-stream direction)

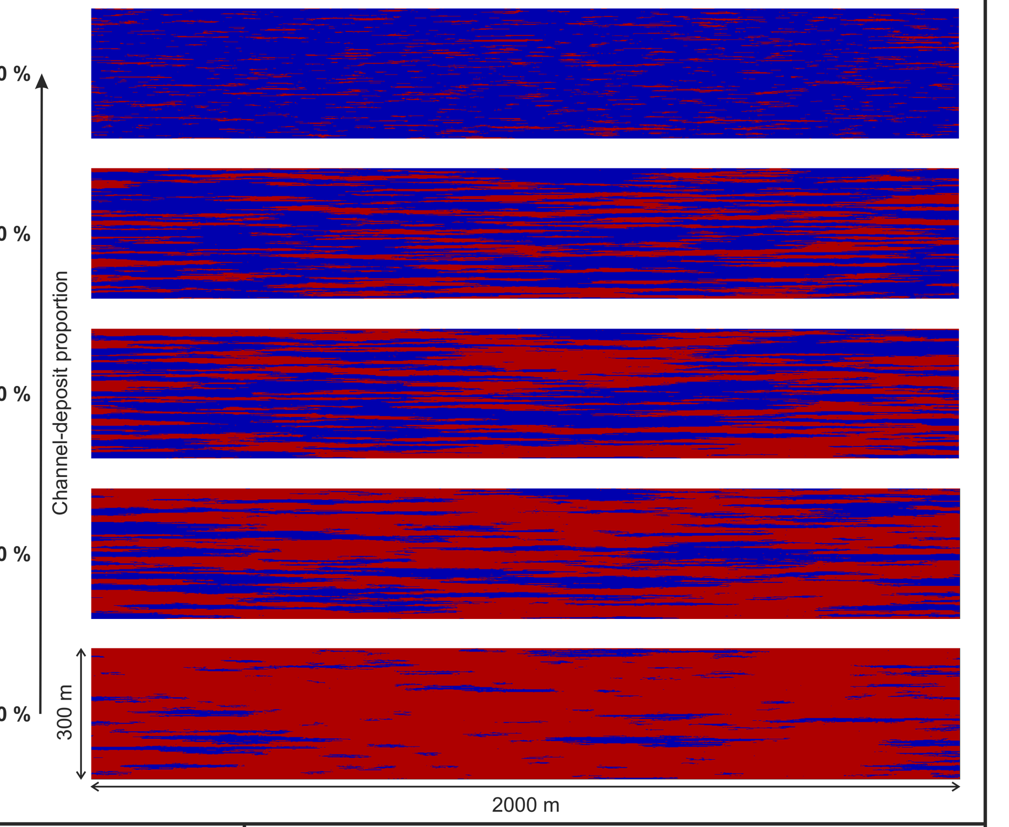
Approach based on values of sill and range obtained after equations by Ritzi (2000) employing empirical relationships linking channel-complex proportions with average width and standard deviation.



CC prop	Sill	avg(W)	std(W)	cv(W)	Model	Phi	Range
0.1	0.09	62.624	59.693796	0.95321	Exponential	3	169.085
0.2	0.16	92.4944	87.551579	0.94656	Exponential	3	221.987
0.3	0.21	136.612	128.40998	0.93996	Exponential	3	286.886
0.4	0.24	201.774	188.33609	0.9334	Exponential	3	363.193
0.5	0.25	298.016	276.22841	0.92689	Exponential	3	447.025
0.6	0.24	440.164	405.13814	0.92042	Exponential	3	528.197
0.7	0.21	650.114	594.20721	0.914	Exponential	3	585.103
0.8	0.16	960.206	871.51066	0.90763	Exponential	3	576.124
0.9	0.09	1418.21	1278.2255	0.9013	Exponential	3	425.462

Empirical relationships linking depositional-element width descriptive statistics (mean, standard deviation, coefficient of variation) with proportions have been employed to derive range, sill and model for indicator variograms for the horizontal cross-stream direction, for both channel-complex (as represented on the left) and floodplain depositional elements. These horizontal indicator variogram models could be employed in real-world situations by coupling them with indicator variograms for the vertical direction, which could be readily derived through the common curve-fitting approach applied to well data.

Here, this approach has been used to simulate the sedimentary architecture of ideal fluvial systems with variable proportion of channel deposits with a SIS algorithm (`sisim`; Deutsch & Journel 1998). The same work undertaken to obtain horizontal variograms has been performed for the vertical direction for material units built from channel complexes, by employing relationships linking channel-complex connected thickness with proportion, and the same vertical range value has been applied to floodplain depositional elements for sake of simplicity. Results are presented in the form of simulated (2 km wide x 0.3 km high) cross sections for 20% channel-proportion increments (to the right).



CONCLUDING REMARKS

The FAKTS database stores data that quantifies the sedimentary architecture of several ancient and modern fluvial depositional systems that may be considered as analogs to subsurface fluvial hydrocarbon-bearing successions. Therefore, the system has application to the guidance of deterministic reservoir models by providing analog information that can be variably employed.

Here we have shown how database information can be used for:

- **identification of large-scale architectural styles** based on the geometry of channel complexes, which typically act as flow units; the recognition of architectural styles has implications concerning the appropriateness of analog choice and allows for placing a constraint on channel-body geometry;

- derivation of **empirical relationships describing the association of different architectural properties** (genetic-unit geometries, proportions and spatial relationships); such relationships provide quantitative constraints that can be applied whenever partial architectural information is available (e.g. use of relations to derive analog genetic-unit width descriptive statistics if genetic-unit proportion is known from borehole data), and can be referred to as general predictive models (e.g. linking genetic-unit lateral spacing as a function of their proportion);

- derivation of **empirical relationships between system controls or parameters and architectural properties**, which can be referred to whenever analogy in terms of boundary conditions governing the subsurface depositional system can be established; as different system types show distinctive architectural signatures, tailoring relations to match with the interpretation of subsurface systems provides tighter constraints;

- derivation of probability density functions of genetic-unit lateral extent with which to **generate correlability models** based on total probabilities of genetic-unit penetration by a well array with given well spacing and of correlation between two wells with given spacing; these models can be **employed to inform well-to-well correlations or to test the realism of a correlation panel** against one or more field analogs.

Significantly, correlability models permit the likelihood of the subsurface interpretation to be assessed by comparison with dimensional parameters obtained by outcrop analogs not just by considering the most likely width of individual units, but by ensuring geological realism for the whole succession: the approach is integrative to traditional methods based on the use of empirical relationships for predicting the lateral extent of individual units.

Empirical relationships describing descriptive statistics of genetic-unit dimensional parameters as a function of unit proportions can also be employed in the **generation of database-informed indicator-variogram models for horizontal directions**.

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