A database approach for constraining fluvial geostatistical reservoir models: concepts, workflow and examples

FRG

Luca Colombera, Fabrizio Felletti, Nigel P. Mountney, William D. McCaffrey

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ABSTRACT

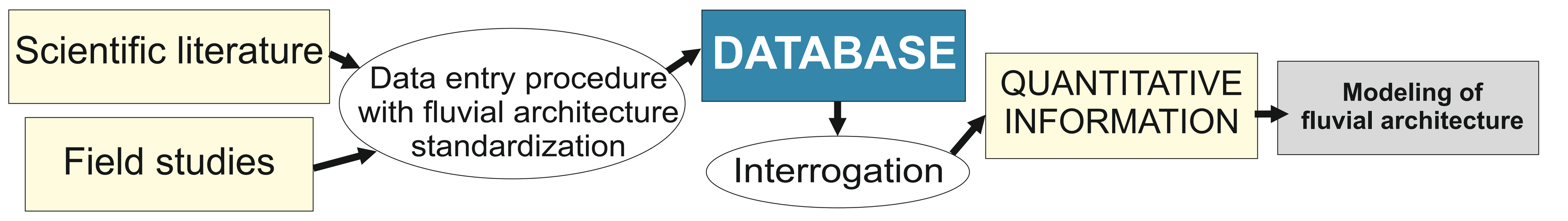
The sedimentary architecture of fluvial depositional systems is characterized by heterogeneities – manifested over a wide range of scales – that control hydrocarbon distribution and fluid-flow behavior; thus, subsurface subseismic-scale sedimentological features are often tentatively predicted by means of geostatistical modeling techniques, often conditioned by hard and soft sedimentological data obtained from outcrop successions or modern rivers considered to be analogous to the reservoir. We propose an alternative database approach as a way to derive such constraints from several classified case studies whose boundary conditions or architectural properties best match with the subsurface system that needs to be modeled.

The relational database characterizes the fluvial architecture of classified case studies from the stratigraphic record and modern rivers at three different scales of observation, corresponding to three types of genetic unit (large-scale depositional elements, architectural elements and facies units) that constitute the building blocks of reservoir models. The database case studies can be filtered on their boundary conditions or architectural properties, generating composite datasets consisting of genetic-unit proportions, dimensions and transition statistics with which to inform and condition fluvial reservoir models.

The potential value of the database in providing constraints to stochastic reservoir models is demonstrated by employing both object-oriented and pixel-oriented techniques to generate unconditional idealized models of fluvial architecture, associated to given system parameters (e.g. river pattern), giving a special focus on the aptness of the hierarchically-nested database output to the integration of different modeling techniques into the same reservoir model, with the scope to improve and/or validate predictions. In addition, simulation realizations depict results as graphical representations of stratigraphic volumes of given synthetic depositional/facies models of fluvial architecture and these could be employed as training images to constrain multi-point statistics-based reservoir models.

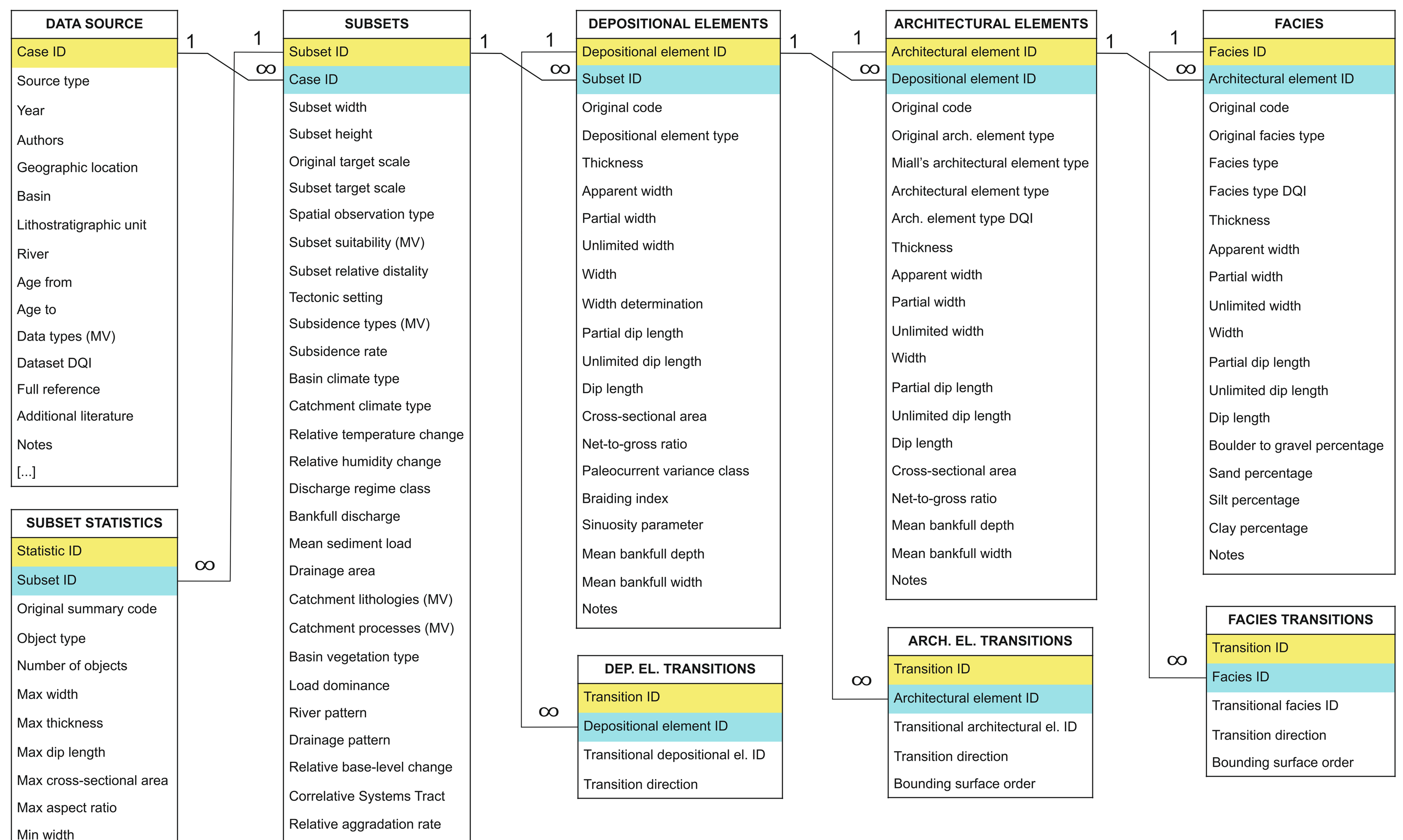
FAKTS DATABASE: overview

Approach



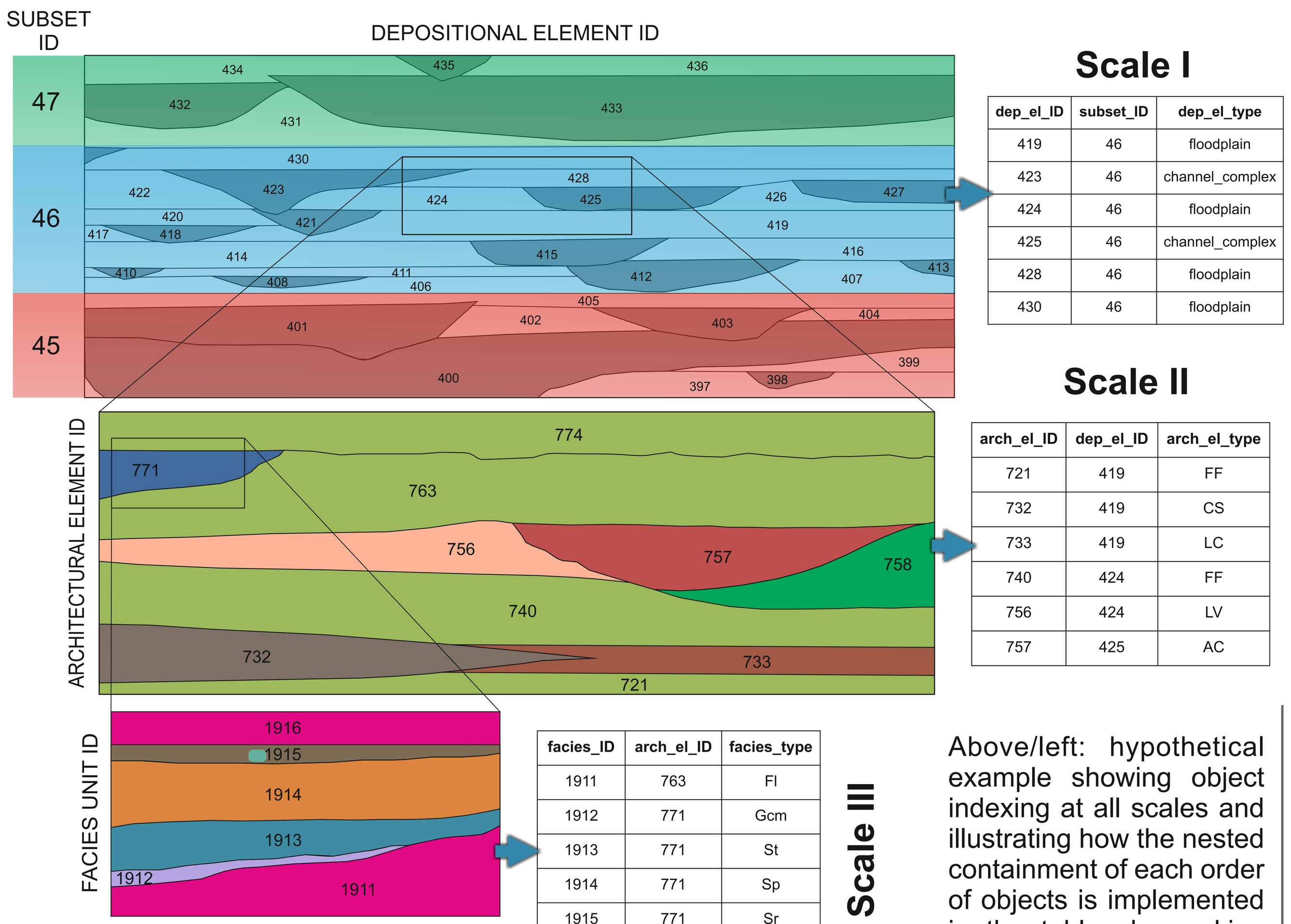
The **Fluvial Architecture Knowledge Transfer System** (FAKTS) is a relational database storing fluvial architecture data populated with literature- and field-derived case studies from modern rivers and ancient successions. The database scheme characterizes fluvial architecture at three different scales 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 tailored on the system being modeled, in order to generate input to object- and pixel-based stochastic simulations of reservoir architecture.

SCOPE Here we aim to demonstrate the all-round applicability of the FAKTS database to a wide range of structure-imitating modeling techniques, as FAKTS enables to determine key input parameters including auto- and cross-indicator variograms, dimensional ratios for neighboring units and transition probabilities/rates, as well as their associated ranges of uncertainty.



FAKTS DATABASE SCHEMA
tables and attributes
modified from Colombera et al. (2012)

Multi-scale genetic-unit nesting



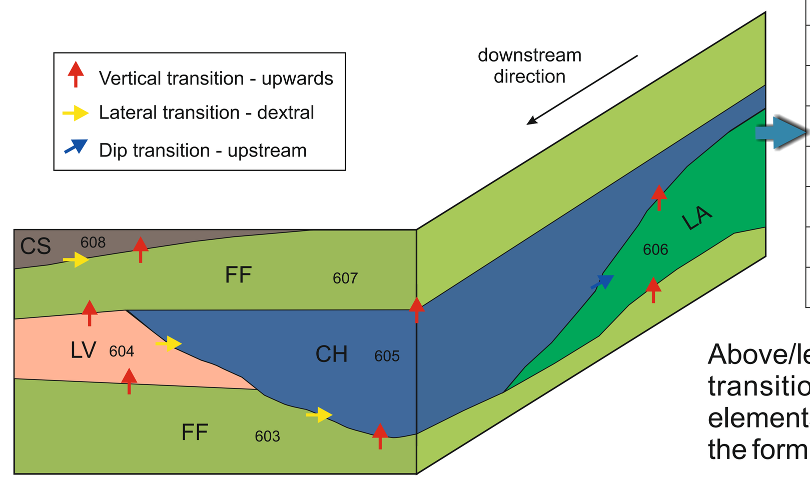
Above/left: hypothetical example showing object indexing at all scales and illustrating how the nested containment of each order of objects is implemented in the tables by making use of the unique indices.

Each case study is subdivided into a series of stratigraphic volumes – called *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).
Every single object is assigned a numeric index that works as its unique identifier; these indices are used to relate the tables (as primary and foreign keys) reproducing the nested containment of each object type within the higher scale parent object (depositional elements within subsets, architectural elements within depositional elements, facies units within architectural elements).

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 density, 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 recorded 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).

Genetic-unit transitions

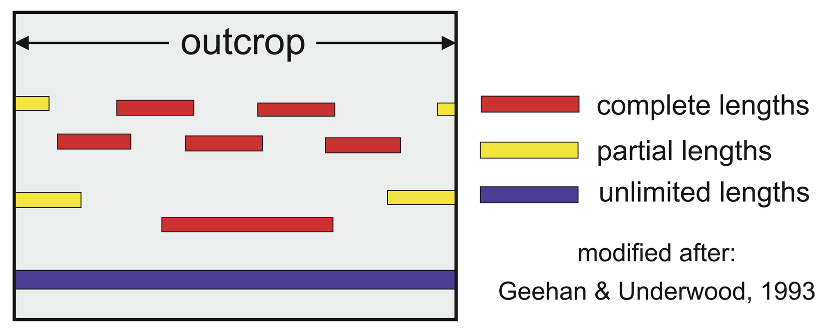


arch_el_ID	trans_el_ID	trans_direction	bound_surf_order
603	604	vertical	4th
603	605	lateral	5th
603	605	vertical	5th
603	606	vertical	5th
604	605	lateral	4th
604	607	vertical	4th
605	606	dip	4th
605	607	vertical	4th
606	605	vertical	4th

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.

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-valley and along-valley directions. The hierarchical order of the bounding surface across which the transition occurs is also specified at the facies and architectural element scales; the bounding surface hierarchy proposed by Miall (1996) has been adopted.

Genetic-unit geometry



modified after: Geehan & Underwood, 1993

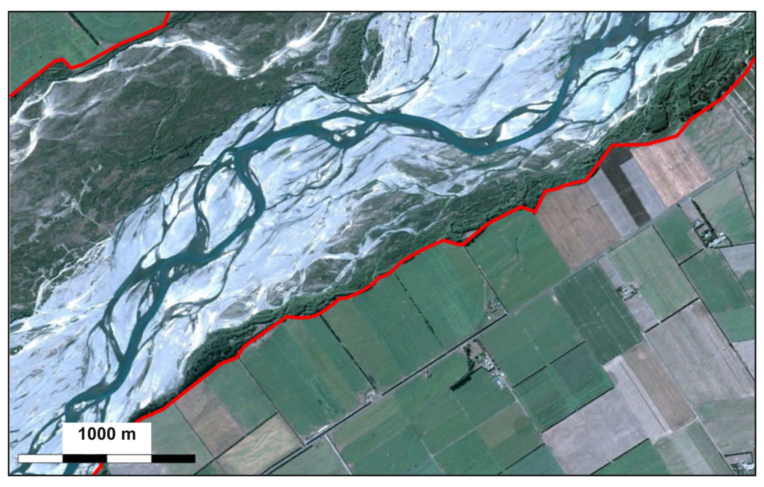
Above: representation of categories of completeness (after Geehan & Underwood 1993) of observed/sampled dimensional parameter. Correlated genetic-unit dimensions are stored as unlimited.

The dimensional parameters of each genetic unit can be stored as representative 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 palaeoflow are available. Where derived from borehole correlations, widths and lengths are always stored as 'unlimited'.
Future development will involve the inclusion of descriptors of genetic-unit shape, implemented either by linking these objects to 2D/3D vector graphics or by adding table attributes (columns) relating to cross-sectional, planform and/or 3D shape types.

FAKTS GENETIC UNITS: classifications

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.

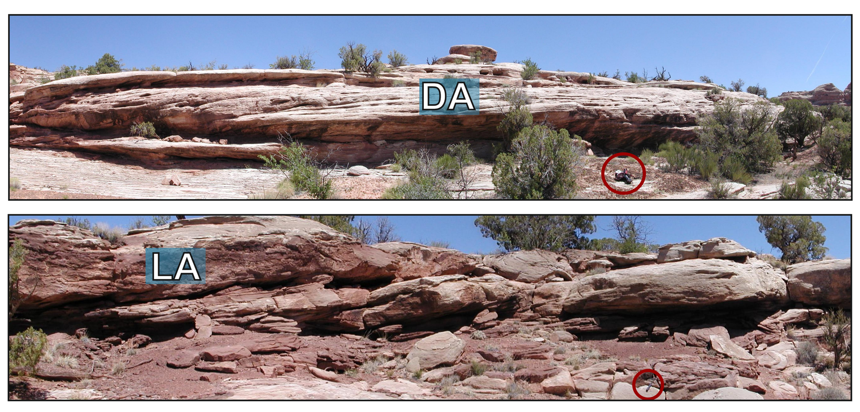


Rakaia River channel-belt (New Zealand.) From Google Earth™.

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.

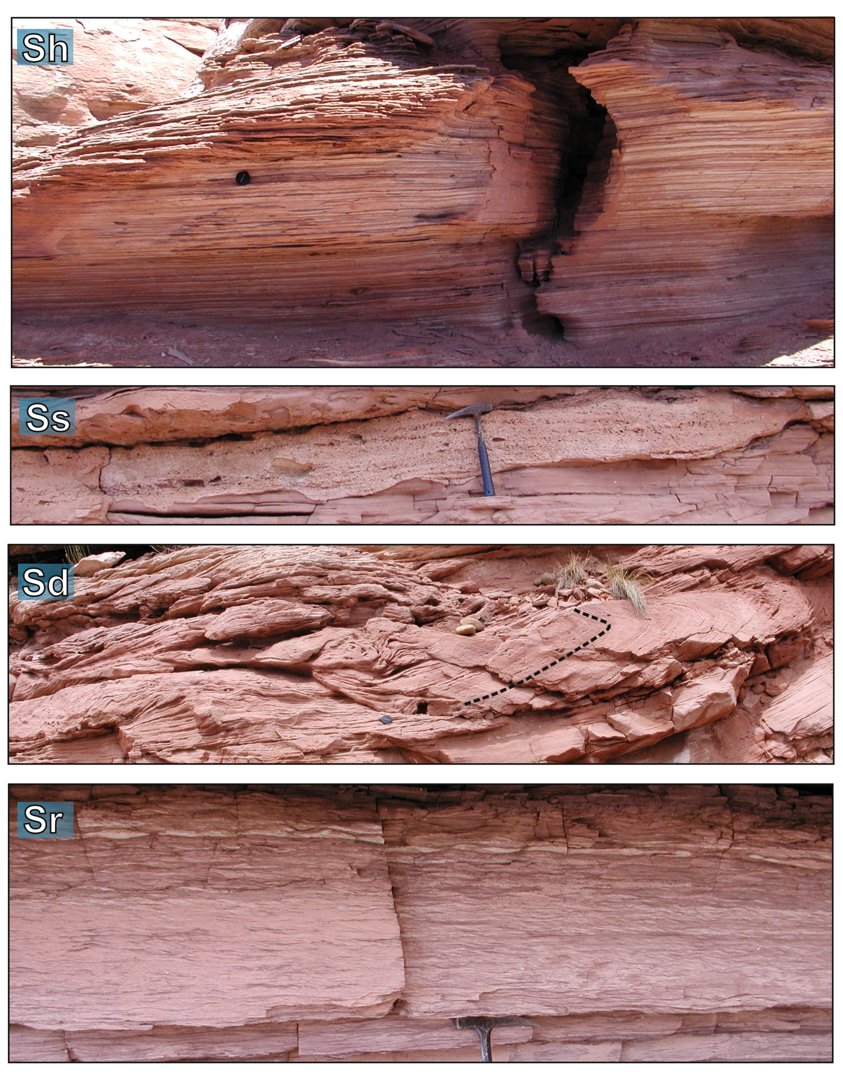


Above: example preserved architectural elements (DA and LA barforms) from the Lower Jurassic Kayenta Formation at Sevenmile Canyon (SE Utah, USA).

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		Ripple cross-laminated sand
Sh		Horizontally-laminated sand
Sl		Low-angle cross-bedded sand
Ss		Scour-fill sand
Sm		Massive or faintly 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 structures is not provided).



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

AREVA bhpbilliton ConocoPhillips nexen Saudi Aramco woodside

FRG

Fluvial Architecture Knowledge Transfer System
FAKTS

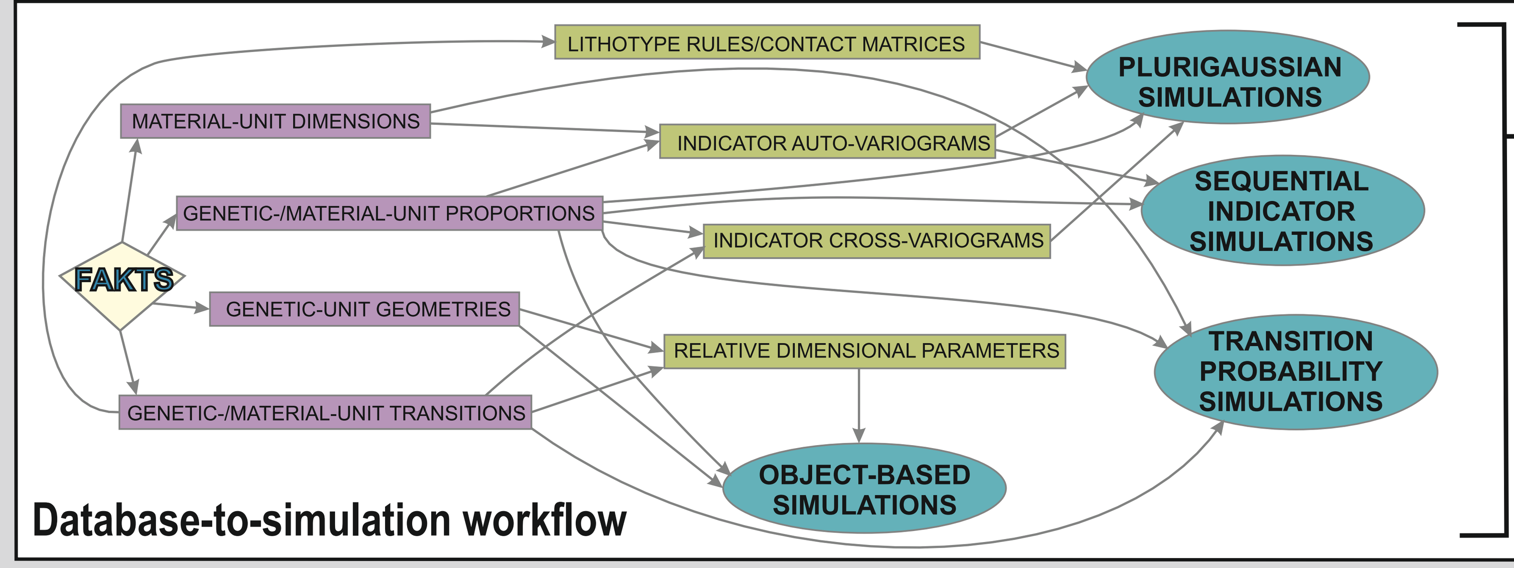
UNIVERSITY OF LEEDS

A database approach for constraining fluvial geostatistical reservoir models: concepts, workflow and examples

Luca Colombera[1], Fabrizio Felletti[2], Nigel P. Mountney[1], William D. McCaffrey[1]

1) School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

2) Dipartimento Scienze della Terra, Università di Milano, Via Mangiagalli 34, 20133, Milano, Italy



Database-to-simulation workflow

summary of the database-to-simulation workflow illustrated in Colombera et al. (accepted)

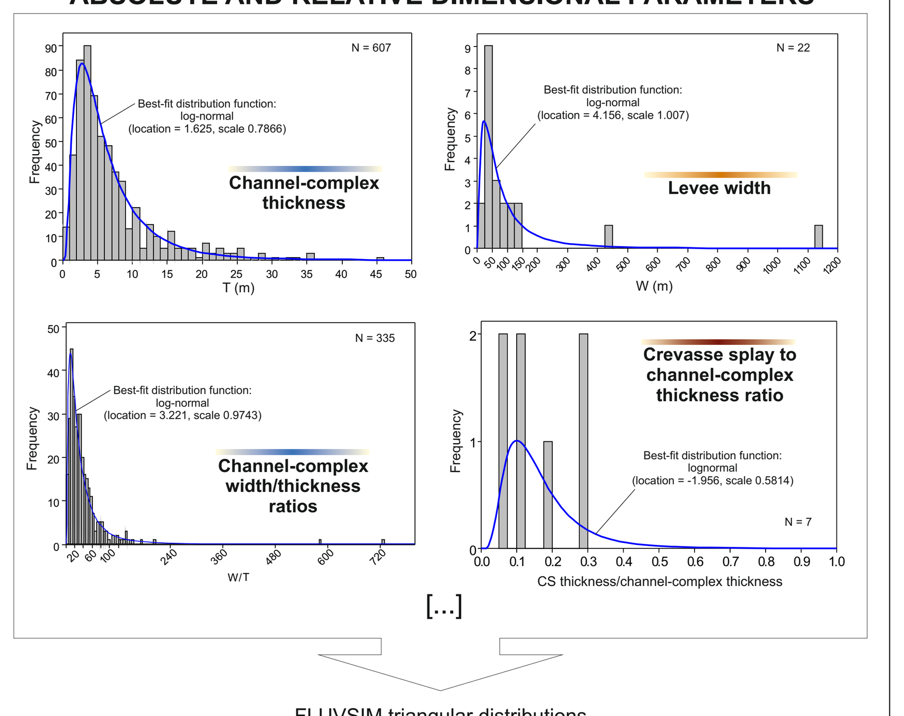
Here we provide an example application to the

MULTI-SCALE SIMULATION OF FLUVIAL ARCHITECTURE

SCALE I+II - object-based simulation

A

DEPOSITIONAL- AND ARCHITECTURAL-ELEMENT ABSOLUTE AND RELATIVE DIMENSIONAL PARAMETERS



FLUVSIM triangular distributions

OBJECTIVE:
to demonstrate how FAKTS output can be used to condition a stochastic object-based simulation of fluvial architecture – consisting of simulated channel-complexes (scale I), levees and crevasse splays (scale II) in a floodplain background – by generating:

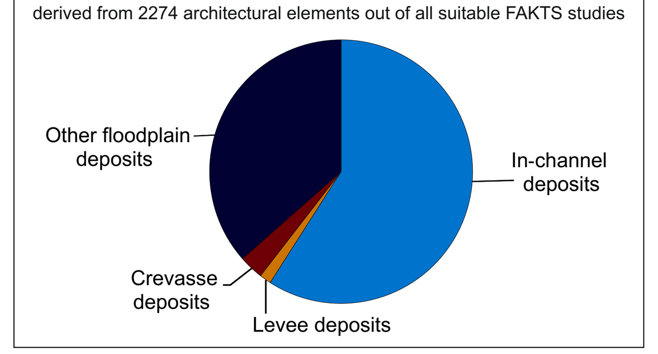
- depositional/architectural element proportions,
- absolute dimensional parameters,
- relative dimensional parameters,

referring to an ideal system including all FAKTS data available (i.e. no filtering on controls or environmental parameters).

SOFTWARE:
Here we use FLUVSIM v. 2.900 (Deutsch & Tran 2002), a public-domain object-based algorithm purposely developed for simulating fluvial architecture by generating stochastic channel centerlines and fitting channel, levee and crevasse splay objects to them.

In-channel, levee and crevasse-splay deposit proportions

derived from 2274 architectural elements out of all suitable FAKTS studies



SCALE II - pixel-based simulation

B

OBJECTIVES:
to demonstrate how FAKTS output can be used to condition stochastic pixel-based simulations of fluvial architecture – consisting in simulated in-channel architectural elements (scale II) within the previously-simulated channel-complexes (scale I) – by providing input parameters that are commonly lacking or poorly defined when working with direct data only, especially for the horizontal directions (well-spacing is usually too large for permitting a curve-fitting approach, and results are often very noisy when the approach is practicable).

These parameters include:

- indicator auto-variograms,
- indicator cross-variograms,
- transition probabilities/rates.

Also, in order to demonstrate how the FAKTS output that quantifies juxtapositional trends existing for genetic/material units (indicator cross-variograms and transition probabilities/rates) is well suited to simulation techniques that permit reproduction of spatial relationships, two alternative sets of simulations have been performed through:

(1) a transition-probability-based algorithm (T-ProGS, Carle & Fogg 1997),

(2) a plurigaussian simulation algorithm (PGSim, Xu et al. 2006),

both of sets of modeling codes being free and public-domain.

All the input parameters to both simulation approaches refer to architectural elements belonging to channel-complex depositional elements associated to an ideal system that includes all FAKTS data available (i.e. no filtering on controls or environmental parameters).

SOFTWARE:
T-ProGS (Carle & Fogg 1997) is a transition-probability/Markov-chain geostatistical simulation method that allows the calculation of three-dimensional Markov-chain models of spatial variability that can be used in sequential indicator simulations (SIS) that are iteratively adjusted – in terms of matching simulated and modeled transition probabilities – by applying a simulated quenching algorithm to generate a geostatistical realization of categorical variables.

PGSim (Xu et al. 2006) is a program for plurigaussian simulations of geological categories: plurigaussian simulations generate two or more Gaussian fields and truncate them at a specified number of thresholds in order to attribute discrete values representing the categories (Le Loc'h and Galli 1997).

T-ProGS input:
N.B. the ensemble of simulation input parameters varies depending on the approach (Carle 1999); we used approach nr. 3 (Carle 1999).

- architectural element proportions (CH set as background),
- architectural element transition probabilities,
- architectural element mean sizes (thickness, width, length).

PGSim input:

- architectural element proportions,
- architectural element Dynamic Contact Matrix,
- discretized architectural element indicator auto- and cross-variograms.

INTERNAL ORGANIZATION OF SYNTHETIC CHANNEL-COMPLEXES
MARKOV-CHAIN ANALYSIS OF ARCHITECTURAL ELEMENT TRANSITIONS

Independent trials matrix

CROSS-STREAM DIRECTION

	CH	DA	DLA	HO	LA
CH	0	0.354	0.250	0	0.396
DA	0.466	0	0.207	0	0.328
DLA	0.429	0.270	0	0	0.302
HO	0.360	0.227	0.160	0	0.253
LA	0.482	0.304	0.214	0	0

UPSTREAM DIRECTION

	CH	DA	DLA	HO	LA
CH	0	0.367	0.400	0.033	0.200
DA	0.604	0	0.250	0.020	0.125
DLA	0.617	0.234	0	0.021	0.128
HO	0.500	0.190	0.207	0	0.103
LA	0.547	0.208	0.226	0.019	0

Transition probability matrix

CROSS-STREAM DIRECTION

	CH	DA	DLA	HO	LA
CH	0	0.325	0.250	0	0.425
DA	0.571	0	0.286	0	0.143
DLA	0.706	0.235	0	0	0.060
HO	1	0	0	0	0
LA	1	0	0	0	0

UPSTREAM DIRECTION

	CH	DA	DLA	HO	LA
CH	0	0.360	0.440	0	0.200
DA	0.875	0	0.063	0.063	0
DLA	0.900	0	0	0	0.100
HO	0	1	0	0	0
LA	0.857	0.143	0	0	0

Difference matrix

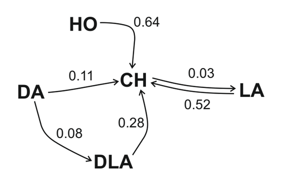
CROSS-STREAM DIRECTION

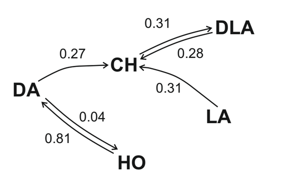
	CH	DA	DLA	HO	LA
CH	0	-0.03	0	0	**0.03**
DA	**0.106**	0	**0.079**	0	-0.18
DLA	**0.277**	-0.03	0	0	-0.24
HO	**0.640**	-0.23	-0.16	0	-0.25
LA	**0.518**	-0.30	-0.21	0	0

UPSTREAM DIRECTION

	CH	DA	DLA	HO	LA
CH	0	-0.01	**0.040**	-0.03	0
DA	**0.271**	0	-0.19	**0.042**	-0.13
DLA	**0.283**	-0.23	0	-0.02	-0.03
HO	-0.50	**0.810**	-0.21	0	-0.10
LA	**0.310**	-0.06	-0.23	-0.02	0

Architectural element transition diagram





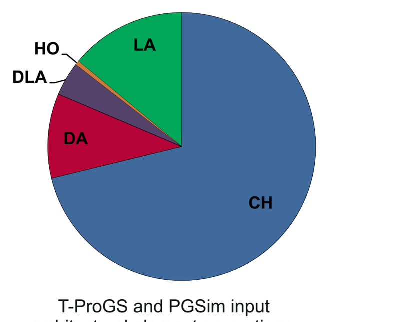
DYNAMIC CONTACT MATRIX
sensu Xu et al. 2006

		CH	DA	DLA	HO	LA
G1	D1	0	1	0	1	0
	D2	1	0	1	0	0
	D3	0	0	0	0	1
G2	D1	0	0	0	1	0
	D2	0	1	0	0	0
	D3	1	0	0	0	0
	D4	0	0	1	0	0

- T-ProGS requires FAKTS transition counts to be converted into either embedded transition frequencies or probabilities (Carle 1999), from which transition-rate matrices for all directions can be derived;

- PGSim makes use of a dynamic contact relationship matrix to specify contact relations among categories (Xu et al., 2006).
Available commercial software for plurigaussian simulations typically permits only a limited number of contact templates to be chosen.

IN-CHANNEL ARCHITECTURAL-ELEMENT PROPORTIONS AND DIMENSIONS

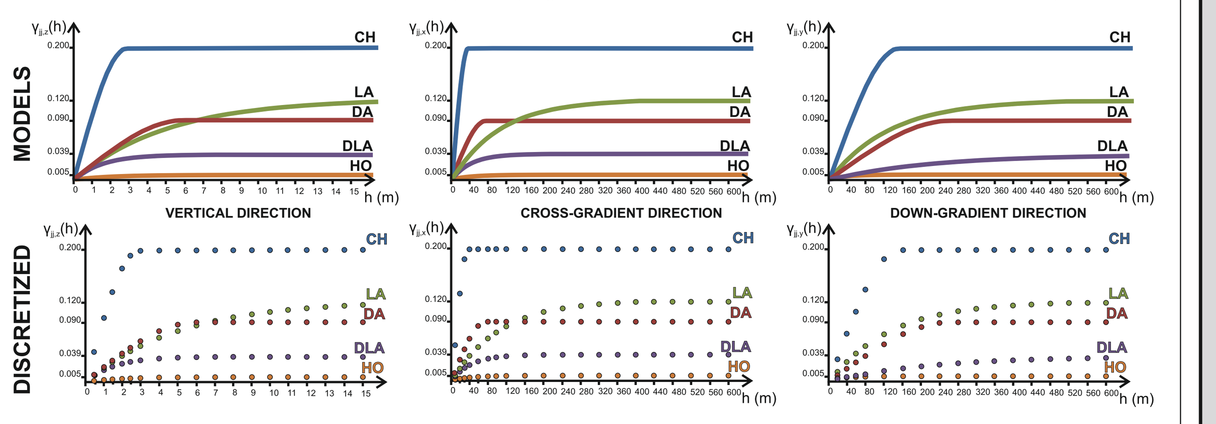


T-ProGS and PGSim input architectural element proportions.

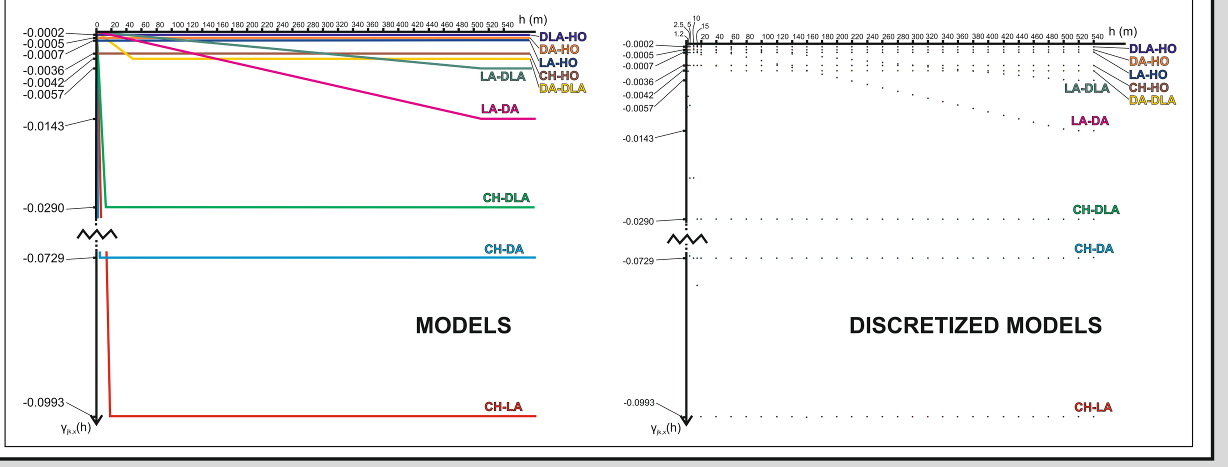
Element type	Mean thickness	Mean width	Mean length	Number of readings
CH	2.4 m	38.6 m	183 m	977/341/145
DA	2.8 m	46.4 m	85 m	118/37/31
DLA	2.3 m	52.6 m	242 m	58/22/11
HO	1.9 m	115 m	14 m	9/1/3
LA	3.7 m	38.4 m	134 m	124/71/36

T-ProGS input mean dimensions: they are variably required depending on the simulation approach (Carle 1999).

ARCHITECTURAL-ELEMENT DATABASE-DERIVED INDICATOR AUTO-VARIOGRAMS



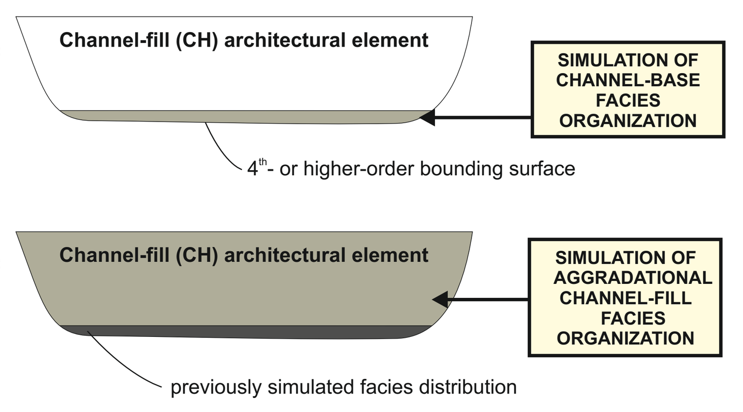
ARCHITECTURAL-ELEMENT DATABASE-DERIVED HORIZONTAL INDICATOR CROSS-VARIOGRAMS



SCALE III - pixel-based simulation

C

INFORMING SEQUENTIAL INDICATOR SIMULATIONS ON BOUNDING-SURFACE ORDER DATA



STEPS REQUIRED:

- determination of marginal probabilities of facies-type material units overlying channel-base

- determination of indicator variograms of facies-type material units overlying channel-base

STEPS REQUIRED:

case A - constraining on simulated channel-base:

- determination of marginal probabilities of facies-type material units occurring within channel-fills

- determination of indicator variograms of facies-type material units occurring within channel-fills

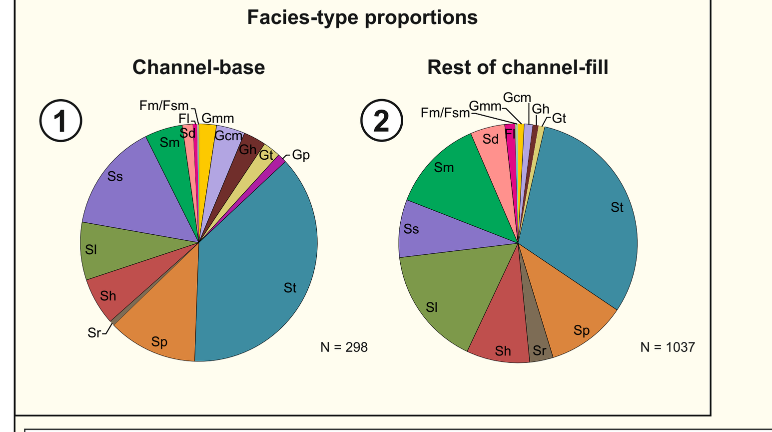
case B - no constraint on simulated channel-base:

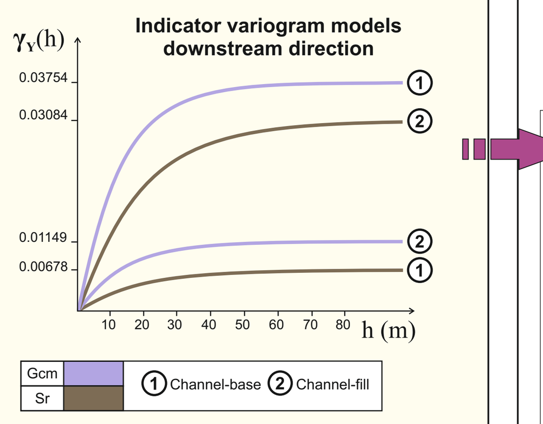
- determination of marginal probabilities of facies-type material units occurring within channel-fills and overlying 2nd- or 3rd-order bounding surfaces

- determination of indicator variograms of facies-type material units occurring within channel-fills and overlying 2nd- or 3rd-order bounding surfaces

Facies-type based material unit proportions and indicator variograms

Facies-type proportions





INDICATOR VARIOGRAM PARAMETERS

FACIES TYPE	(1) Channel-base MODEL	Channel-base RANGE (m) X	Channel-base RANGE (m) Y	Channel-base SILL	Channel-fill (case A) MODEL	Channel-fill (case A) RANGE (m) X	Channel-fill (case A) RANGE (m) Y	Channel-fill (case A) RANGE (m) Z	Channel-fill (case A) SILL	(2) Channel-fill (case B) MODEL	Channel-fill (case B) RANGE (m) X	Channel-fill (case B) RANGE (m) Y	Channel-fill (case B) RANGE (m) Z	Channel-fill (case B) SILL
Gmm	Exponential	7.9	19.3	0.023429	Exponential	8.0	19.7	2.5	0.005392	Exponential	8.0	19.6	2.5	0.008232
Gcm	Exponential	21.2	36.7	0.037542	Exponential	21.8	39.8	1.1	0.011058	Exponential	21.8	39.8	1.1	0.011486
Gh	Spherical	12.1	26.6	0.029659	Spherical	11.7	25.7	1.1	0.060202	Spherical	12.4	27.3	1.2	0.007742
Gt	Spherical	13.2	80.5	0.023429	Spherical	13.1	79.9	1.5	0.030934	Spherical	13.4	81.8	1.5	0.008232
Gp	Exponential	88.4	80.0	0.012547	Exponential	87.5	79.1	2.2	0.022366	-	-	-	-	-
St	Exponential	27.1	26.3	0.234447	Exponential	28.0	27.1	2.9	0.228912	Exponential	30.0	29.1	3.1	0.213242
Sp	Exponential	15.6	45.3	0.107155	Exponential	15.8	45.8	2.7	0.100836	Exponential	15.9	46.0	2.8	0.096500
Sr	Exponential	54.3	57.2	0.006779	Exponential	53.7	56.6	1.4	0.018934	Exponential	53.0	55.8	1.4	0.030844
Sh	Exponential	142.1	34.0	0.060327	Exponential	137.1	32.8	2.9	0.087953	Exponential	138.8	33.3	3.0	0.078395
Sm	Exponential	71.4	42.2	0.048843	Exponential	70.0	41.5	3.7	0.066149	Exponential	65.8	39.1	3.5	0.110104
Sl	Exponential	43.9	22.3	0.072626	Exponential	43.6	22.2	3.3	0.078600	Exponential	40.0	20.4	3.0	0.134889
Sd	Spherical	7.3	9.8	0.014379	Spherical	7.1	9.6	3.3	0.035525	Spherical	7.0	9.5	3.2	0.044775
Ss	Exponential	19.7	27.3	0.126121	Exponential	21.5	29.8	1.9	0.066650	Exponential	21.3	29.6	1.9	0.072220
Fl	Spherical	24.8	23.2	0.005849	Spherical	24.7	23.1	1.7	0.010370	Spherical	24.6	23.0	1.7	0.013670
Fm/Fsm	Spherical	34.2	23.9	0.002114	Spherical	34.2	23.9	0.8	0.002493	Spherical	34.1	23.9	0.8	0.003969

OBJECTIVES:
to demonstrate the possbile application of FAKTS for derivation of quantitative architectural information linked to bounding-surface order. Such soft data may find application in facies modeling workflows. This is done by conditioning a stochastic pixel-based sequential indicator simulation (SIS) of the internal facies organization of a CH (aggradational channel-fill) architectural element (scale II), performed by firstly placing the dominant 14 types of facies units (scale III) at a channel-base interface and subsequently simulating the distribution of facies units within the channel-body using the previously-simulated facies types for hard-data conditioning.
Once again, all input parameters refer to an ideal system including all FAKTS data available (i.e. no filtering on controls or environmental parameters), and they include:

- channel-base facies-unit type proportions,
- channel-base facies-unit type indicator auto-variograms,

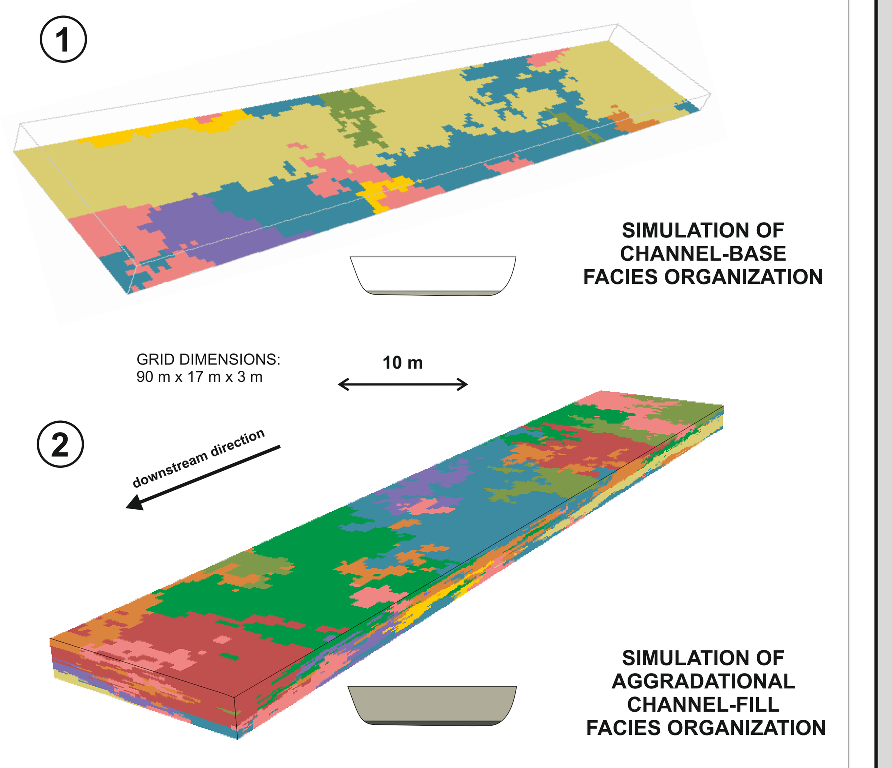
for the channel-base simulations, and:

- channel-body facies-unit type proportions,
- channel-body facies-unit type indicator auto-variograms.

for the channel-body simulations.

SOFTWARE:
SISIM (Deutsch & Journel 1998) is a GSLIB program that incorporates a SIS simulation algorithm, which builds a categorical image within a 3D grid by simulating individual voxels by drawing from the local probability distributions of indicator categories, and updating probability distributions to account for categories that have already been simulated at neighboring voxels.

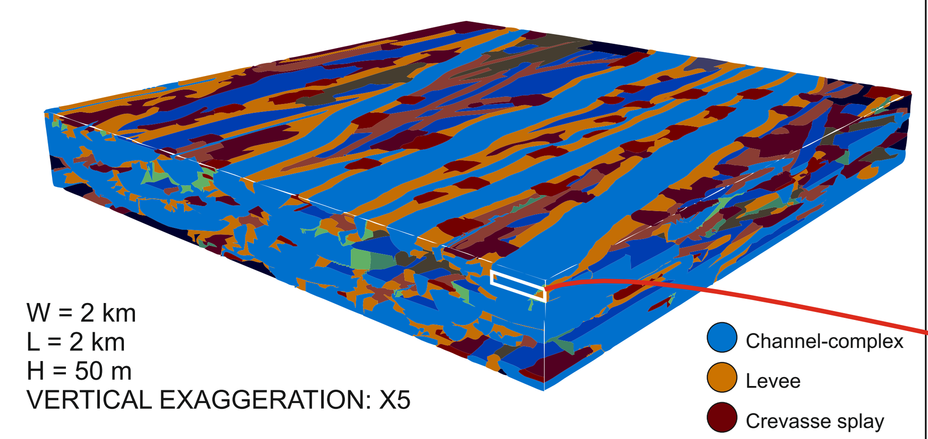
SISIM example simulation of a channel-fill facies organization



Refer to pie-charts on the left for color coding

DATABASE-INFORMED MULTI-SCALE STRUCTURE-IMITATING SIMULATION OF FLUVIAL ARCHITECTURE - SUMMARY

FLUVSIM (Deutsch & Tran 2002) SIMULATION



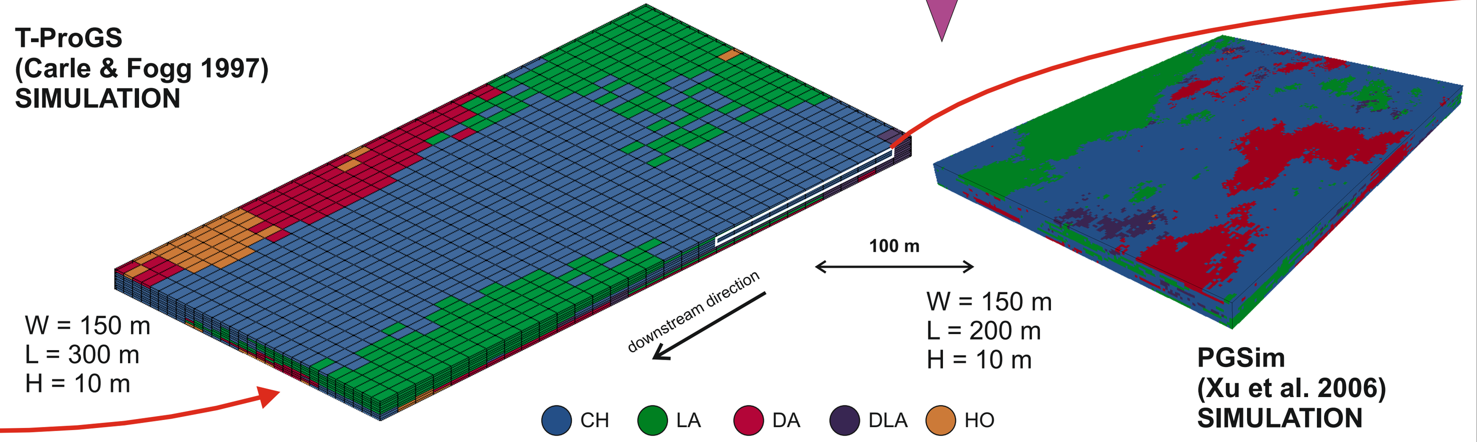
A

Depositional element + architectural element scales

—

Object-based simulation of channel-complex - levee - crevasse splay distribution

T-ProGS (Carle & Fogg 1997) SIMULATION



PGSim (Xu et al. 2006) SIMULATION

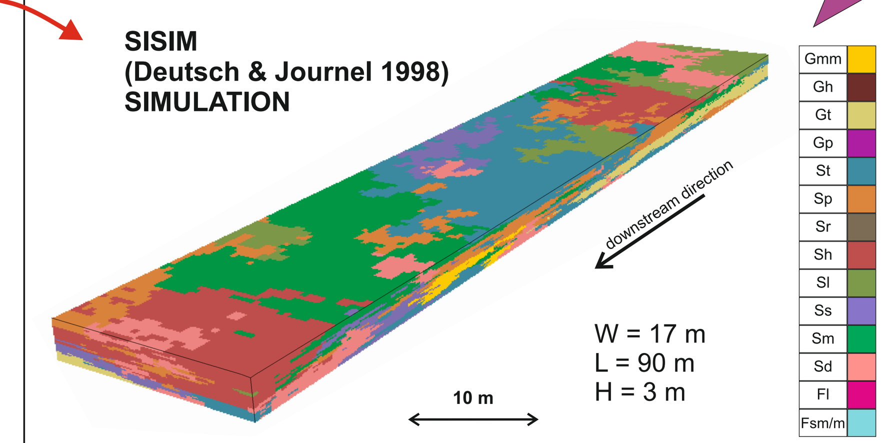
B

Architectural element scale

—

Pixel-based simulations of in-channel architectural-element distribution within channel-complexes

SISIM (Deutsch & Journel 1998) SIMULATION



C

Facies unit scale

—

Pixel-based simulation of facies type distribution within CH (channel-fill) architectural elements

DISCUSSION

Some important implications regarding the database approach to fluvial reservoir modeling presented here:

- the FAKTS database – not being limited to the storage of dimensional data as is the case for many other analog architectural databases, but instead permitting a full characterization of sedimentary architecture that encompasses also genetic- and material-unit volumetric proportions and spatial relationships – allows for the **derivation of simulation input parameters that are often arbitrarily chosen rather than obtained: it is possible to derive relative dimensional parameters, transition probability matrices and indicator auto- and cross-variograms**, all of which are the result of the synthesis of data drawn from multiple-classified case studies;

- the database permits the **filtering of data on a multitude of attributes describing internal parameters and external controls** of both modern and ancient fluvial systems, ensuring that the knowledge-base that is most relevant to the subsurface case study that needs to be modeled can be selectively chosen;

- the database permits **filtering architectural data on other associated architectural features** (e.g. containment within larger-scale genetic units, bounding-surface order data), thereby providing an additional constraint to data selection for generating simulation input parameter;

- the FAKTS-derived parameters refer to a variety of genetic or material units belonging to three spatial scales nested in a hierarchical framework, thereby **permitting the choice of input parameters referring to the scale that best suits the model case and enabling a multi-scale approach**.

CiPEG
Fluvial Research Group
School of Earth and Environment
University of Leeds
Leeds LS2 9JT UK
http://frg.leeds.ac.uk

Contacts:
Luca Colombera
email: eelc@leeds.ac.uk
mobile: +44 (0)7554096074

AREVA bhpbilliton ConocoPhillips nexen Saudi Aramco Shell woodside

A database approach for constraining fluvial geostatistical reservoir models: concepts, workflow and examples

Luca Colombera, Fabrizio Felletti, Nigel P. Mountney, William D. McCaffrey

UNIVERSITY OF LEEDS

STATIC-CONNECTIVITY ANALYSIS OF *FAKTS*-INFORMED SIMULATIONS

FAKTS
database for the digitization of fluvial sedimentary architecture

- possibility to derive input parameters suited to many different simulation techniques for the structure-imitating modeling of fluvial architecture
- possibility to investigate the **impact of the adopted simulation technique** on the static connectivity of the output reservoir model
- possibility to derive input parameters to facies modeling programs referring to a variety of genetic and material units, belonging to different hierarchically-nested spatial scales
- possibility to study the **influence of several scales of sedimentary heterogeneity** on reservoir static connectivity through sequential inclusion in the simulated realizations
- possibility to filter the knowledge-base on system boundary conditions, sorting architectural data – extracted from several case studies – on environmental parameters and external controls in order to derive synthetic quantitative depositional models, which can be simulated with geostatistical techniques
- possibility to analyze the static connectivity of simulated realizations with the purpose of **deriving general models of static connectivity and of variability associated with types of fluvial depositional systems** (e.g. meandering systems, braided systems)

STATIC CONNECTIVITY TERMINOLOGY

S = phase whose connectivity is being investigated
u = point of the investigated volume
h = lag distance along the direction for which the connectivity is being investigated

CONNECTIVITY FUNCTION (Allard et al. 1993):

probability that two points belonging to *S* separated by a lag *h* are connected, i.e. belonging to the same cluster.

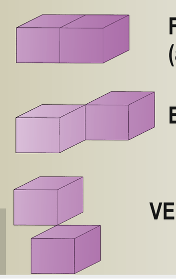
$$\tau(h)=(u\Leftrightarrow u+h|u,u+h\in S)$$

ESTIMATED CONNECTIVITY FUNCTION:

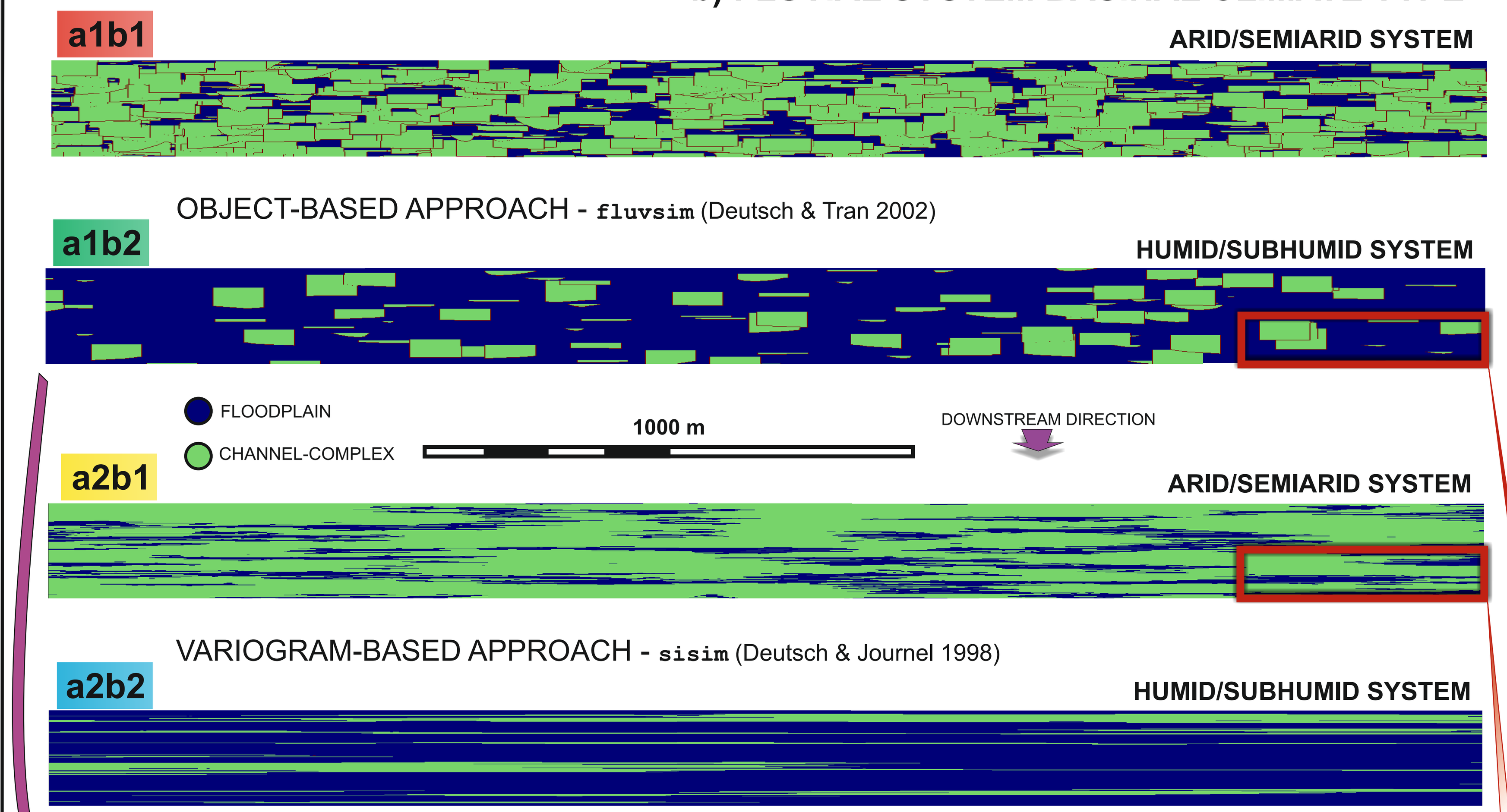
– here computed by using CONNEC3D (Pardo-Igúzguiza & Dowd 2003) –

ratio between the number of cells separated by a lag *h* that belong to phase *S* and are connected and the number of cells separated by a lag *h* that belong to phase *S* and that may or may not be connected.

$$\tau_e(h)=\#N(u\Leftrightarrow u+h|u,u+h\in S)/\#N(u,u+h\in S)$$

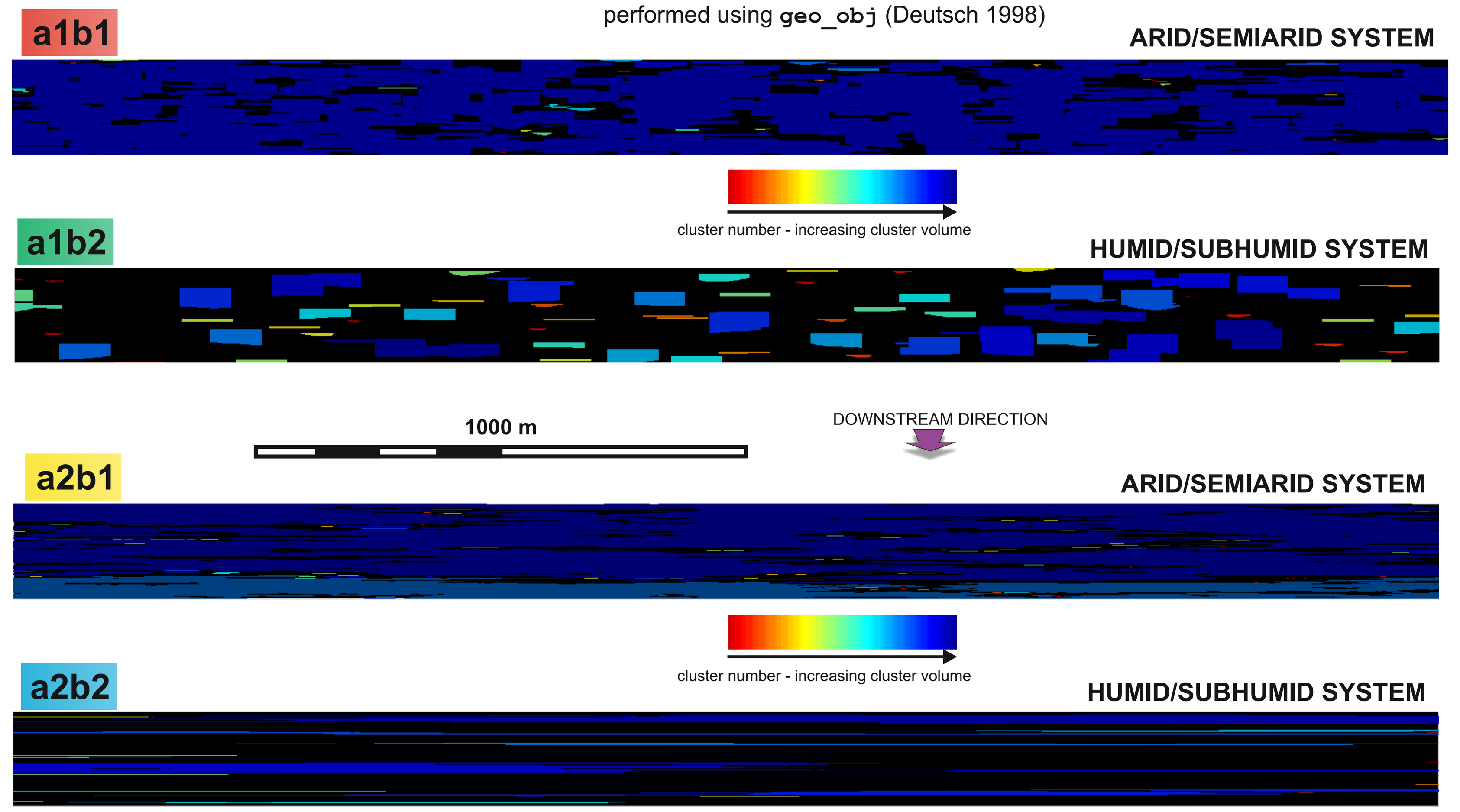


ASSESSMENT OF THE SENSITIVITY OF CHANNEL-DEPOSIT CONNECTIVITY TO:
a) SIMULATION APPROACH
b) FLUVIAL SYSTEM BASINAL CLIMATE TYPE



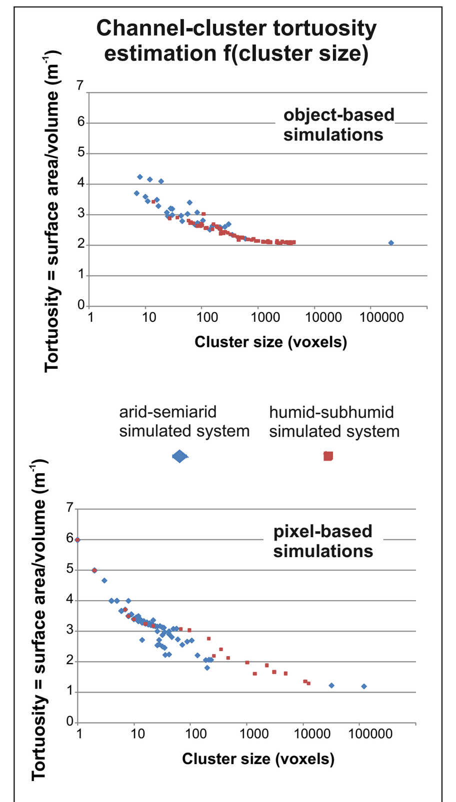
CLUSTER IDENTIFICATION

performed using `geo_obj` (Deutsch 1998)



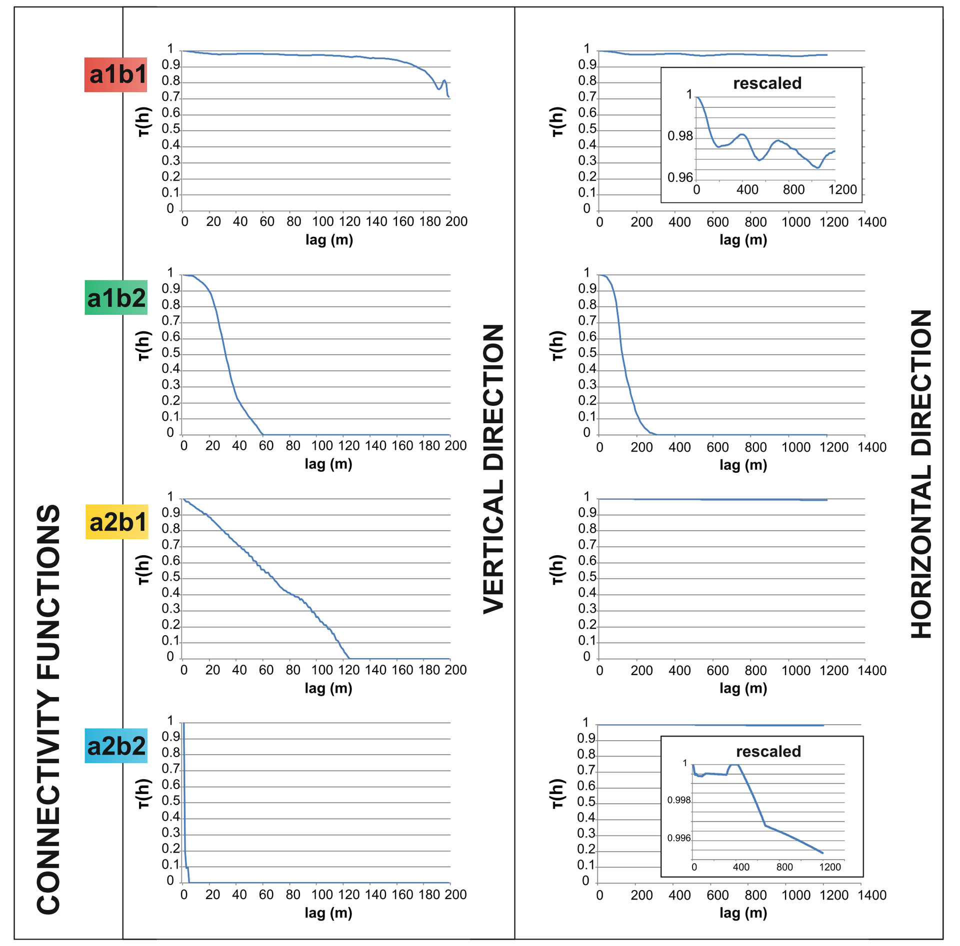
CLUSTER TORTUOSITY ESTIMATION

Deutsch (1998) proposes the ratio of surface area to volume as a measure of cluster tortuosity, as, for a fixed volume, the greater the surface area the more tortuous the object.



CONNECTIVITY ANALYSIS

performed using `CONNEC3D` (Pardo-Igúzguiza & Dowd 2003)

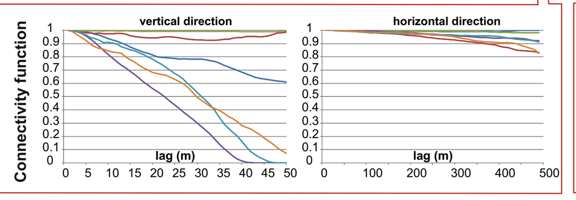


The stratigraphy simulated by the object-based FLUVSIM (Deutsch & Tran 2002) algorithm for the ideal humid/subhumid system is unrealistic, as the input width/thickness aspect ratios are not honored: this is evident when comparing the width/thickness ratios of the channelized objects with the aspect ratios of the channelized indicator in the pixel-based simulation of the same system. This flaw – sensibly affecting the estimated connectivities – seems to be related to poor performance of the object-based program when working in two dimensions.

The same database-informed humid/subhumid system has then been simulated on a 3D grid, returning a more realistic stratigraphy, with much higher channel-object aspect ratio. This time we run several simulations of the same model and we include database-conditioned levee and crevasse splay objects for the purpose of assessing their influence on reservoir phase connectivity, assuming that their deposits are reservoir quality.

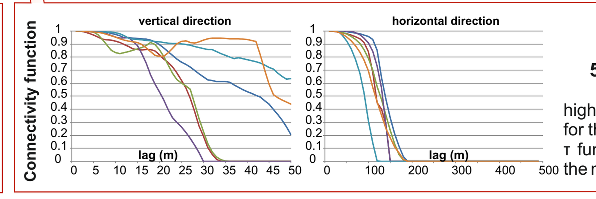
Connectivity metrics for six different 500x100 m² simulations

high variability in τ(h), especially for the vertical direction (τ ranging from 0 to 1 at 50 m lag).



Connectivity metrics for six different 500x100 m² simulations

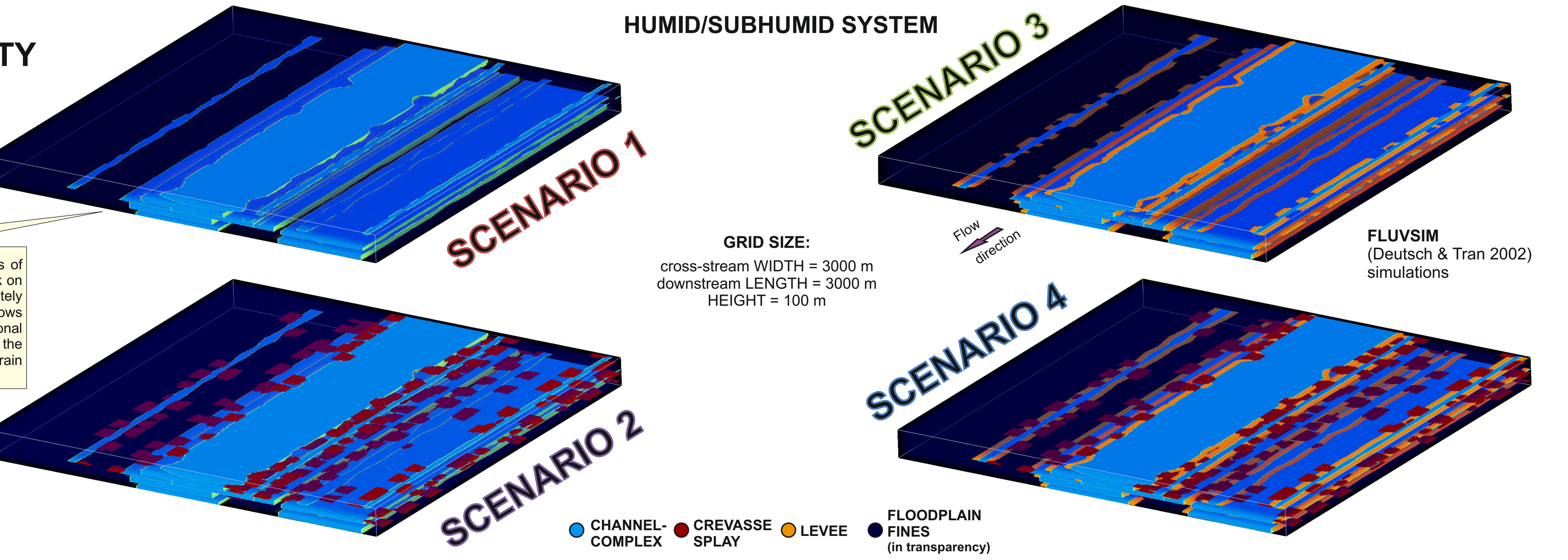
high variability in τ(h), especially for the vertical direction; horizontal τ functions must be discarded as the models are flawed.



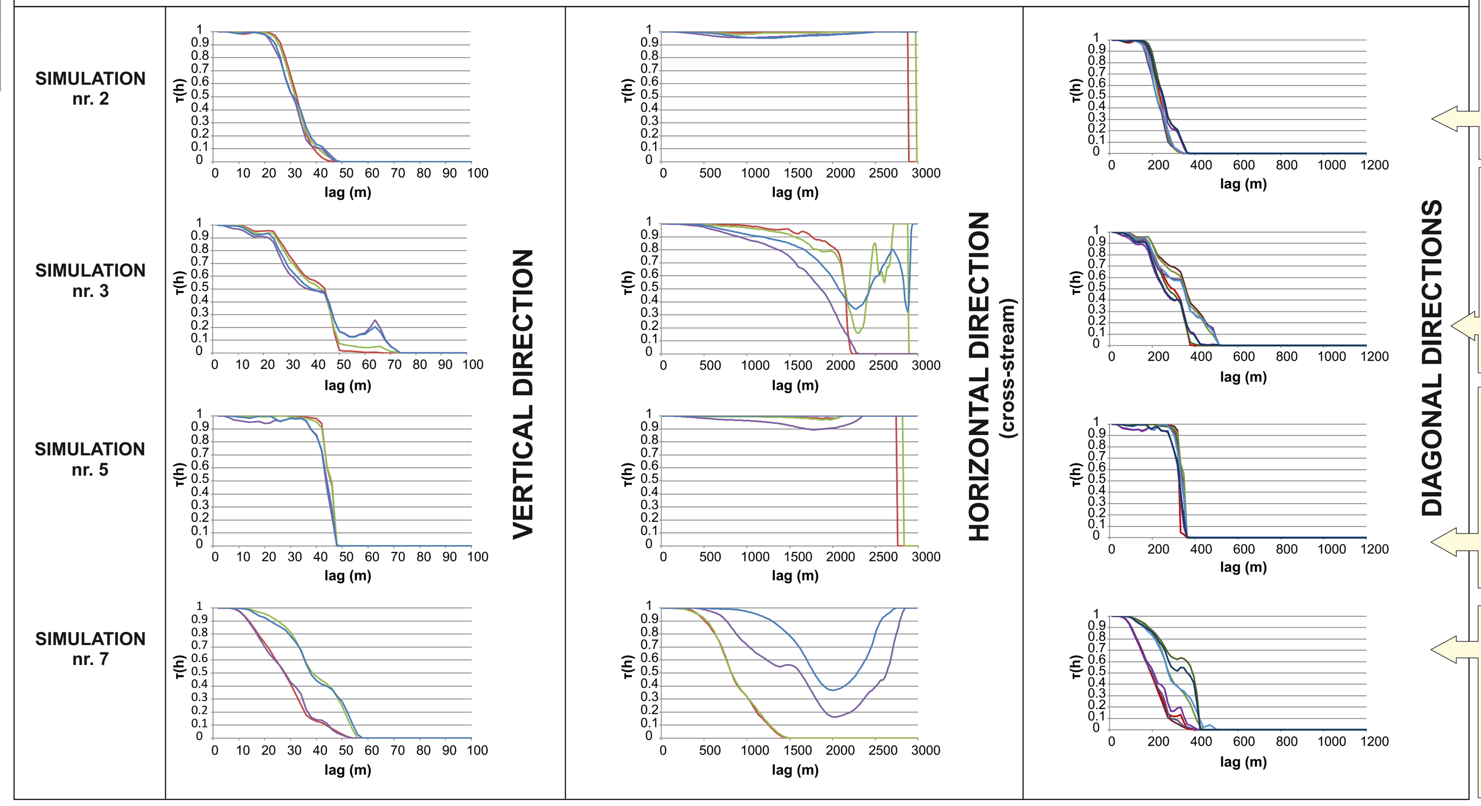
ASSESSMENT OF THE SENSITIVITY OF STATIC CONNECTIVITY TO LEVEE AND CREVASSE SPLAY INCLUSION AS RESERVOIR-QUALITY DEPOSITS

As FAKTS channel-complexes represent channel-clusters defined on the basis of geometrical rules, FLUVSIM (Deutsch & Tran 2002) channels – which can stack on each other themselves generating channel-complexes – would more appropriately embody 5th and/or 6th order (*sensu* Miall, 1996) channel-belts. Since FAKTS allows storing information on the order of the lower bounding surface of depositional elements, it is possible to filter the database in order to obtain parameters relating to the geometry of 5th-order surface bounded channel-clusters with which to better constrain the object-based simulation.

RESERVOIR-QUALITY DEPOSITS	
SCENARIO 1	Channel-complexes
SCENARIO 2	Channel-complexes, crevasse splays
SCENARIO 3	Channel-complexes, levees
SCENARIO 4	Channel-complexes, crevasse splays, levees



CONNECTIVITY FUNCTIONS for all scenarios in a selection of four simulations



Vertical connectivity function substantially unchanged by levee and/or crevasse splay inclusion as reservoir phase; **full horizontal** connectivity reached at 3000 m lag for scenarios 2 and 4, thanks to crevasse splay connections.

Vertical connectivity function slightly increased by crevasse splay connections; **full horizontal** connectivity reached at 3000 m lag for scenario 4, thanks to crevasse splay + levees connections: levees or crevasse splays alone do not guarantee full horizontal connectivity.

Vertical connectivity function substantially unchanged by levee and/or crevasse splay inclusion as reservoir phase; **full horizontal** connectivity reached at 3000 m lag for scenarios 2 and 4, thanks to crevasse splay + channel connections.

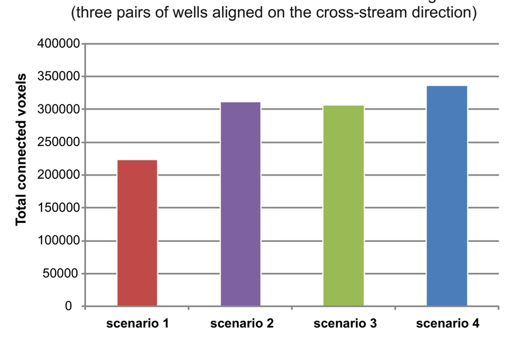
Vertical and diagonal connectivity functions increased by levee connections; **full horizontal** connectivity reached at 3000 m lag for scenarios 2 and 4, thanks to crevasse splay connections; levee inclusion does not affect horizontal connectivity.

WELL-TO-WELL CONNECTIVITY RANKING

performed using `rank2loc` (Deutsch 1998)

Well-to-well connectivity ranking of the four scenarios – horizontal direction

based on one simulation and three different well configurations (three pairs of wells aligned on the cross-stream direction)



WELL-TO-WELL CONNECTIVITY

Probability that two locations are connected by the reservoir quality phase; estimated by the cumulative number of connected voxels between an arbitrary number of pairs of wells (Deutsch 1998), e.g. injector + producer.

APPLICATION OF DATABASE-INFORMED MULTI-SCALE SIMULATION OF FLUVIAL ARCHITECTURE FOR THE QUANTITATIVE ASSESSMENT OF THE INFLUENCE OF FACIES-SCALE HETEROGENEITIES ON RESERVOIR-QUALITY LITHOSOME CONNECTIVITY

Architectural-element spatial relations are based on Markov-chain-informed lithotype rules, constrained by FAKTS-derived transition statistics.

Facies-unit proportions and indicator variograms have been tailored to characterize the simulated architectural element type each facies unit belongs to.
Realistic facies-unit spatial relationships are not reproduced by the SIS simulation technique.

STEP 1: object-based simulation of channel-complex distribution - floodplain in transparency

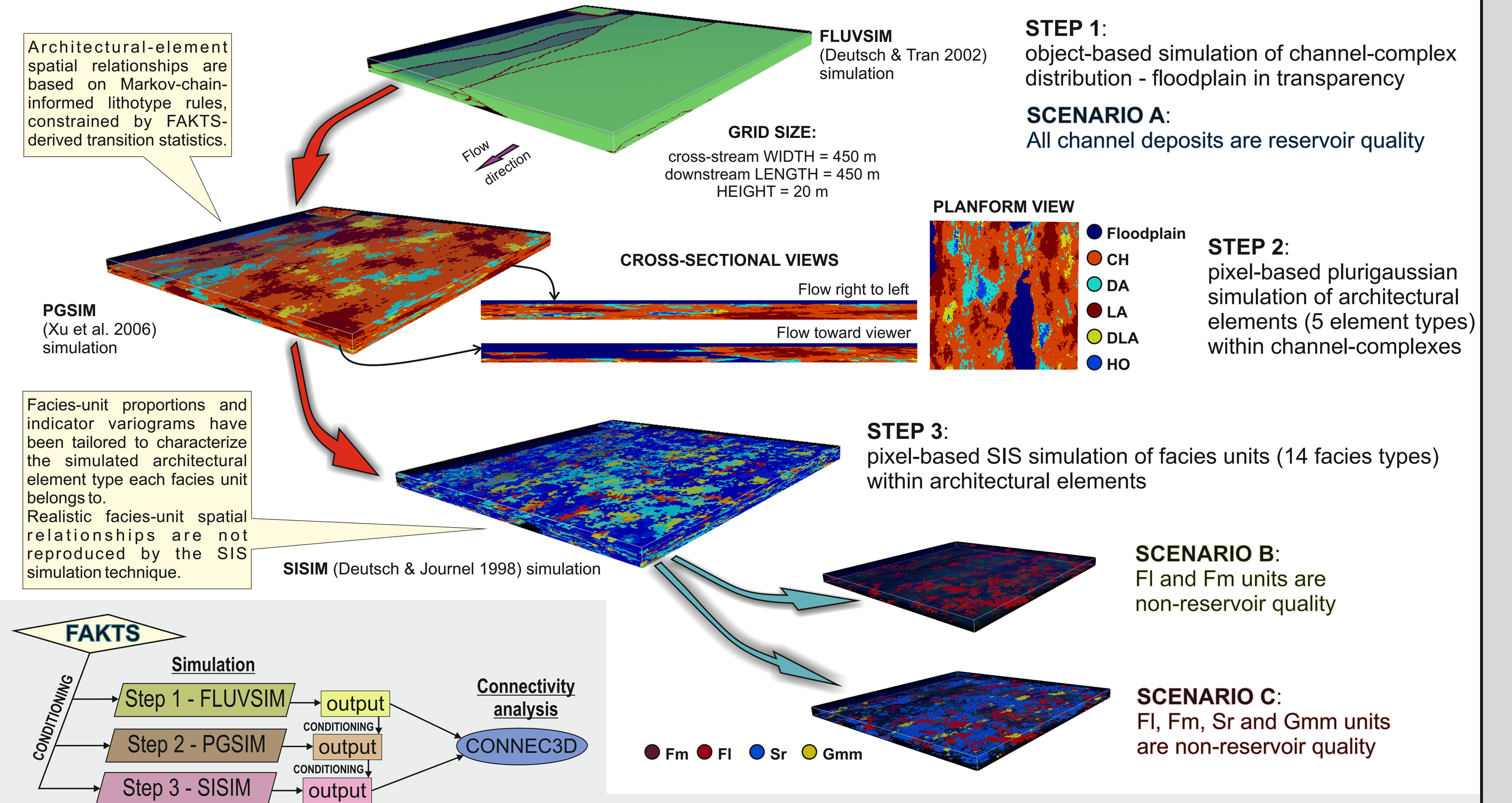
SCENARIO A: All channel deposits are reservoir quality

STEP 2: pixel-based plurigaussian simulation of architectural elements (5 element types) within channel-complexes

STEP 3: pixel-based SIS simulation of facies units (14 facies types) within architectural elements

SCENARIO B: Fl and Fm units are non-reservoir quality

SCENARIO C: Fl, Fm, Sr and Gmm units are non-reservoir quality

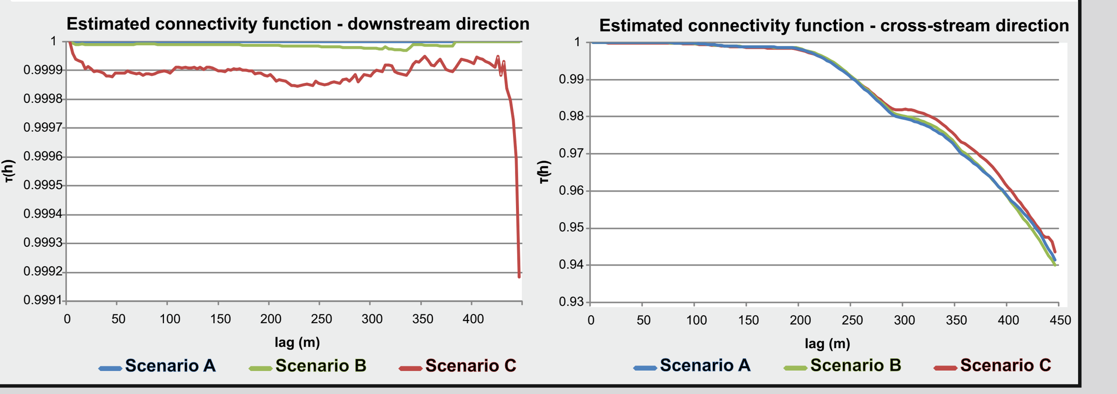


Main results:

- estimated connectivity function for downstream direction is less than unity only if in-channel facies-scale heterogeneities are included in the model; lowest value at 450 m-lag for Scenario C;
- on the contrary, connectivity function for cross-stream direction not greatly affected by facies-scale heterogeneity inclusion.

Possible developments:

- inclusion of non-reservoir architectural elements (e.g. abandoned channels);
- tailoring models on system parameters and controls;
- simulating the distribution of channel-belts rather than geometrically-defined complexes;
- constraining architectural-element and facies-unit spatial relationships to transition statistics (simulating through T-PROGS, Carle & Fogg 1997).



CONCLUSIONS

Here we have demonstrated how FAKTS can be used to:

- derive a variety of reservoir-modeling constraints serving different simulation techniques, some of which cannot be derived from standard databases of sedimentary architecture or are difficult to infer from direct data, especially for the horizontal directions (i.e. relative dimensional parameters, indicator auto- and cross-variograms, transition probabilities);
- refer reservoir-modeling constraints to different types of genetic- and material-units nested in a hierarchical framework, making them **suitable for employment in multi-scale simulation workflows in which a variety of reservoir and non-reservoir categories can be flexibly defined**;
- filter architectural output on the basis of concurrent architectural features and/or system boundary conditions so that (i) simulation input parameters **can be tailored to the subsurface case study that needs to be modeled** and (ii) simulation techniques can be **used to generate ideal geostatistical models of classified fluvial-architecture styles**.

We have also shown how **these database capabilities have important implications for performing static connectivity analysis** aimed at:

- investigating the impact of the simulation technique on the static connectivity of the simulated system;
- studying the influence that the inclusion of different scales of heterogeneity in the models has on its static connectivity;
- deriving general models of static connectivity and of their variability associated with various types of fluvial depositional systems (e.g. meandering vs. braided systems).

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CiPEG
Fluvial Research Group
School of Earth and Environment
University of Leeds
Leeds LS2 9JT UK
http://frg.leeds.ac.uk

Contacts:
Luca Colombera
email: eelc@leeds.ac.uk
mobile: +44 (0)7554096074

AREVA bhpbilliton ConocoPhillips nexen Saudi Aramco Shell woodside

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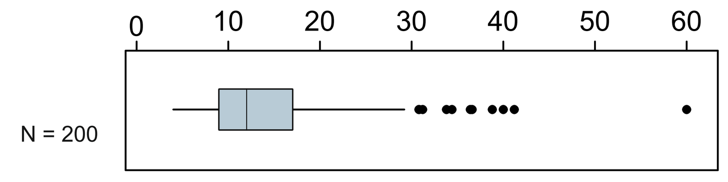
UNIVERSITY OF LEEDS

BASIC FAKTS OUTPUT

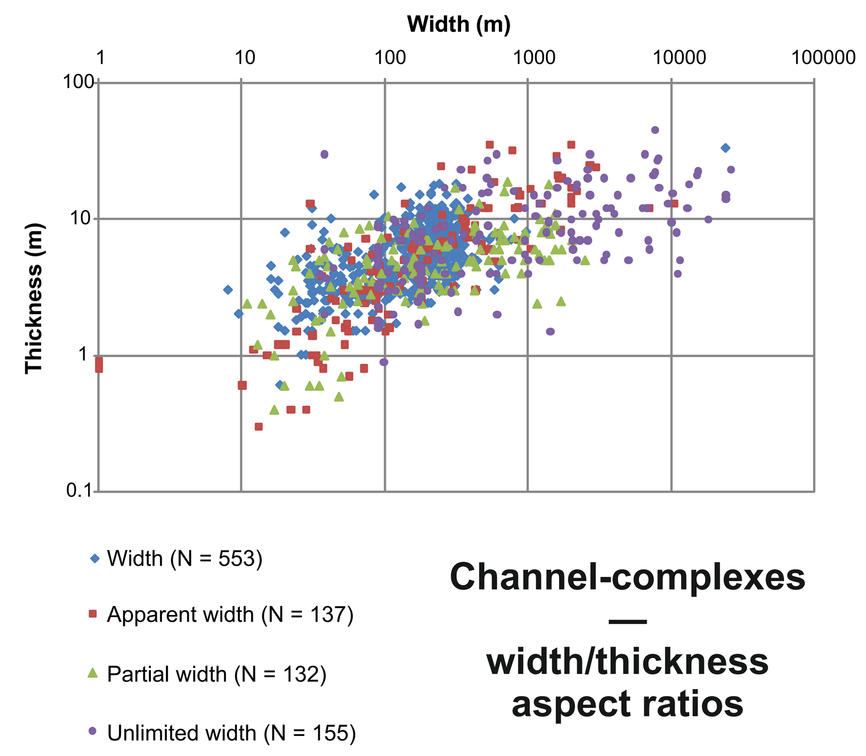
FAKTS can be interrogated through SQL queries in order to generate quantitative information on fluvial architecture; this information can be exported to spreadsheets, analysed and represented in a variety of forms.

Genetic-unit dimensions



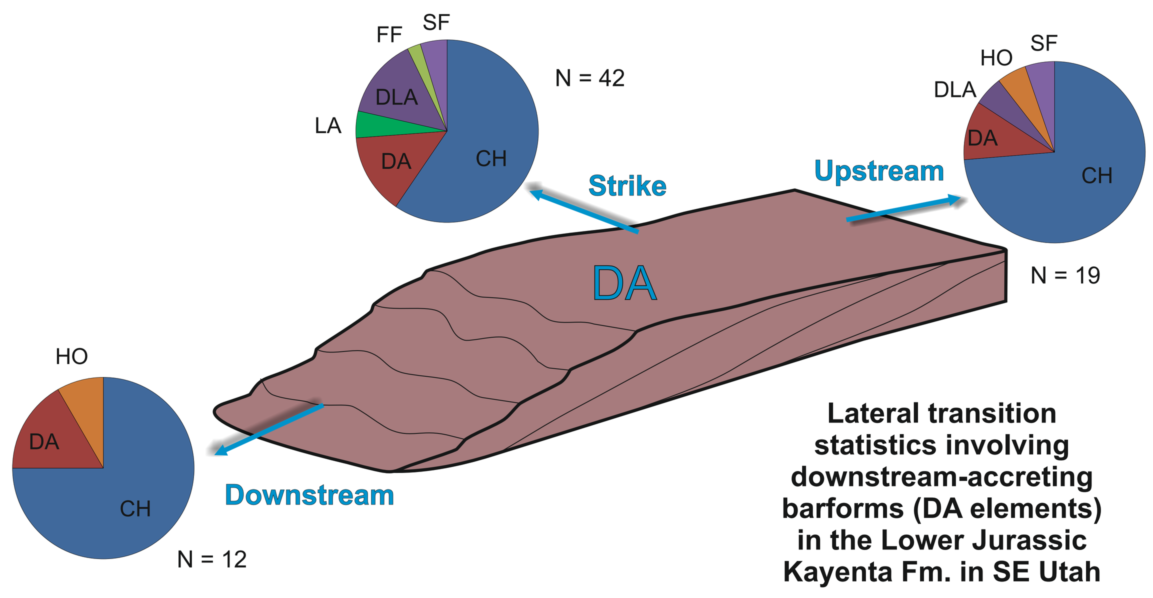
CH channel-fills — width/thickness aspect ratio distribution

FAKTS allows probability density functions of given dimensions to be derived or syntheses of aspect ratios for any genetic unit or genetic-unit type to be computed, choosing whether to include or not underestimated (partial and unlimited) and overestimated (apparent) dimensions.



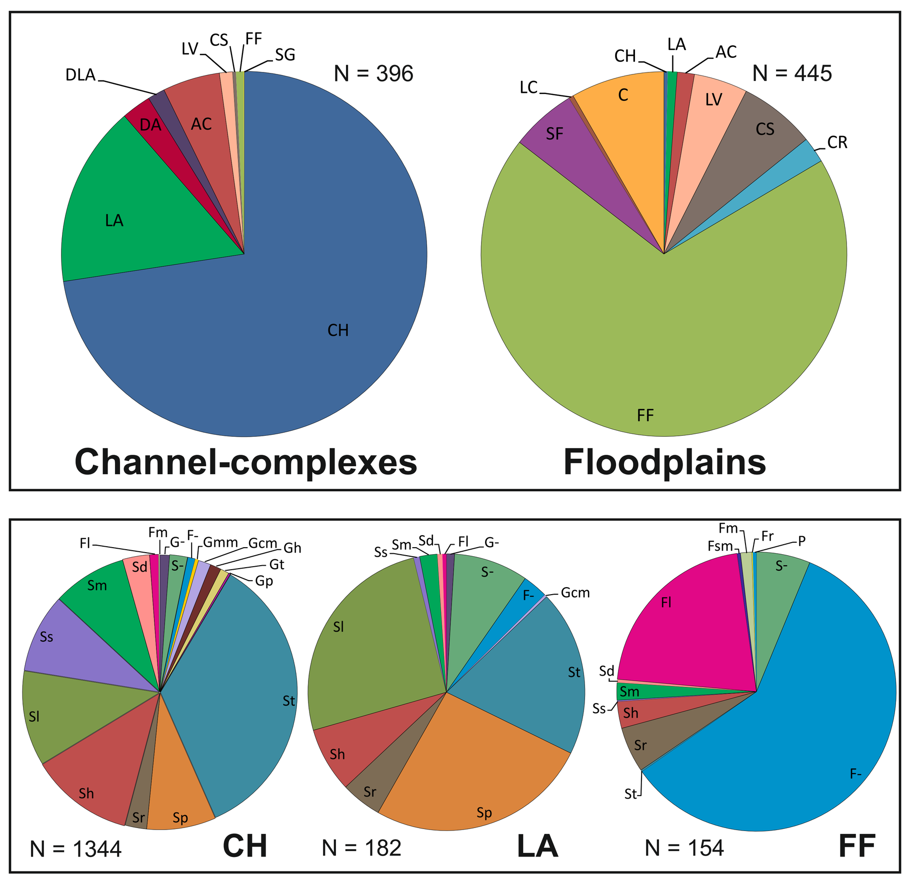
Channel-complexes — width/thickness aspect ratios

Genetic-unit transition statistics

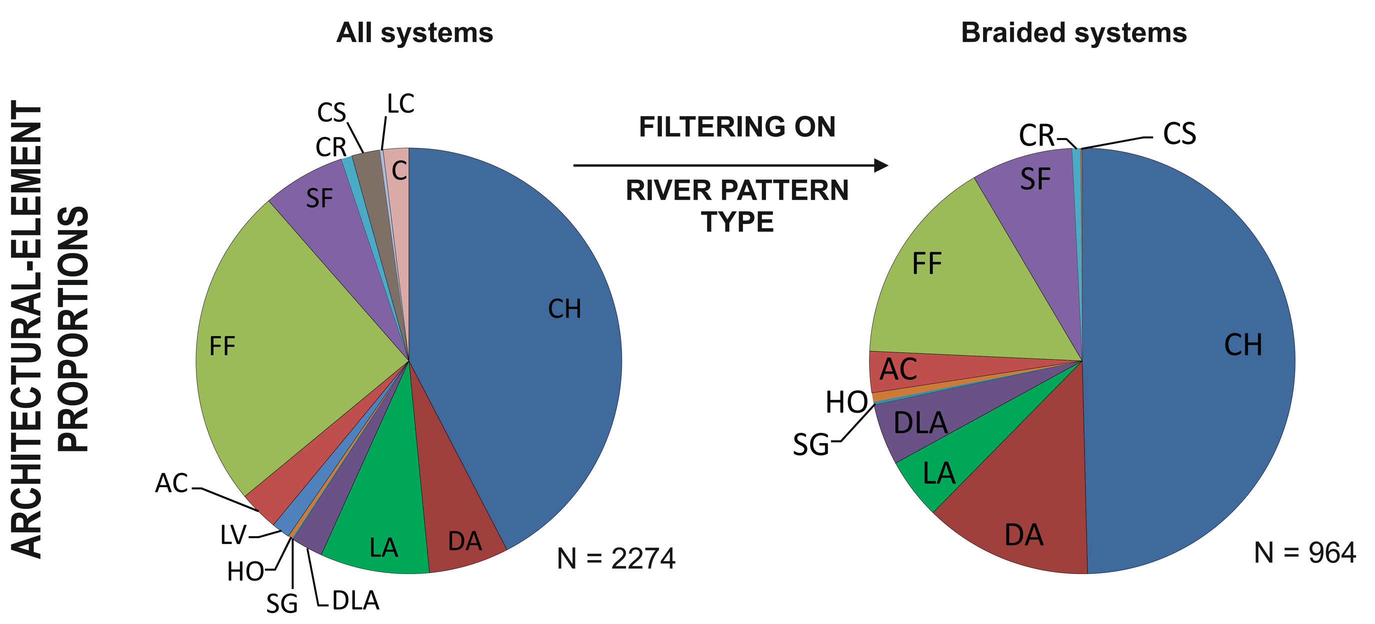


FAKTS can be queried to derive data on occurrences of transitions between genetic units, in order to obtain a quantitative description of spatial depositional trends. To further characterize genetic units internally, transition statistics can be filtered so that only transitions observed within the type of element investigated and across given bounding-surface orders are taken into account. Through a special query, 2D- and 3D-dataset transitions can be filtered with random selections in order to force the sampling to be one dimensional.

Genetic-unit proportions

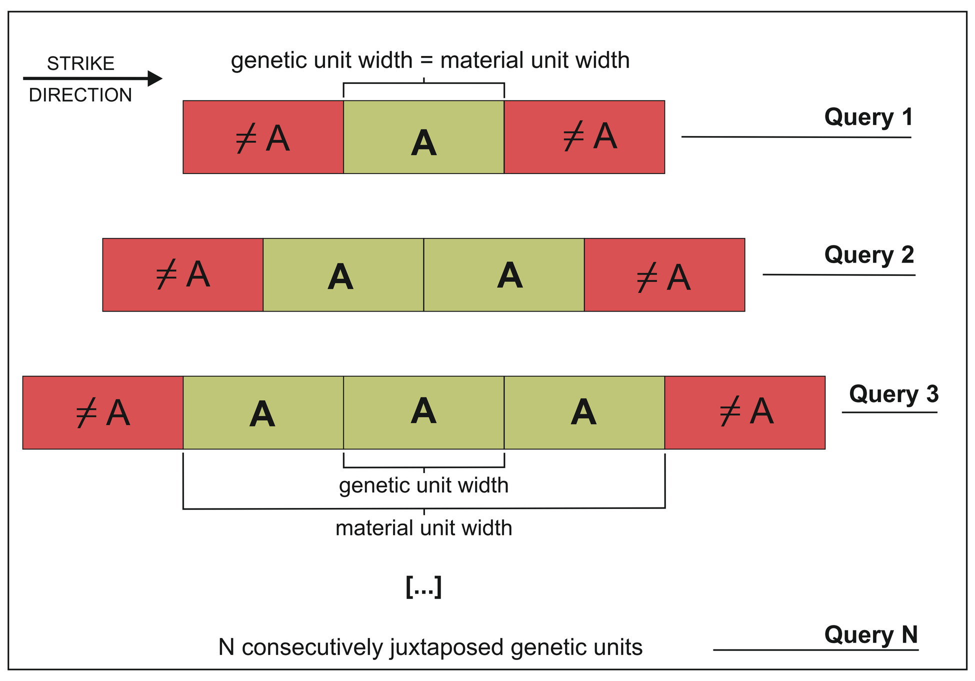


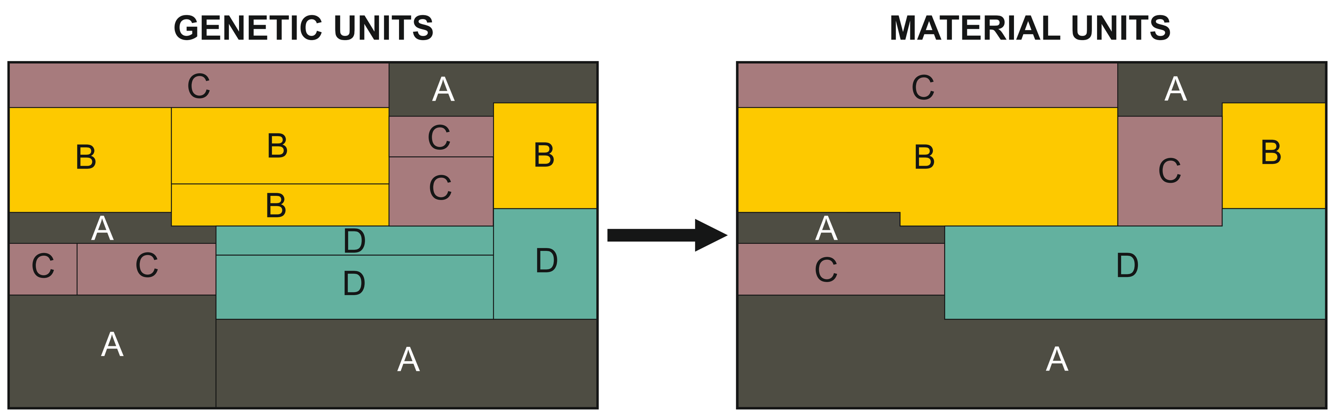
The internal organization of genetic packages can be characterized in terms of the objects belonging to lower-order scales.
Information on their composition is given by the relative volumetric proportions of their building blocks. For example, the internal composition of channel-complexes or floodplains in terms of architectural elements, and of architectural elements in terms of facies units (as shown in the pie-charts) can be derived by estimating volumetric proportions by object occurrences only, or by combining occurrences and dimensions in a variety of ways; variably defined net:gross ratios can then be easily computed for each object.

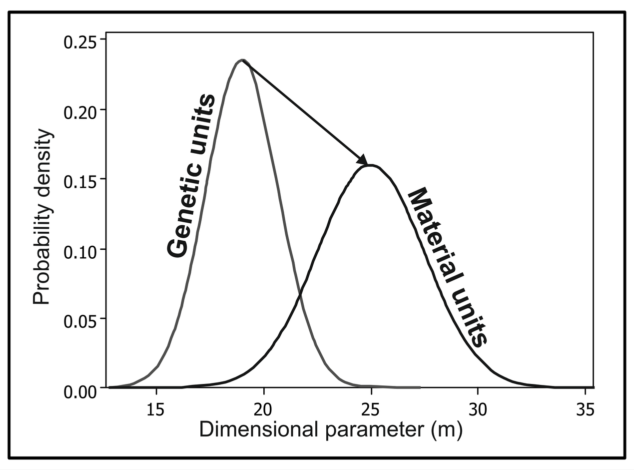


Material-unit properties

We define FAKTS material units 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. For example we may wish to define a material unit on the basis of a given lithofacies type, or on the basis of a threshold percentage content in clay and silt, or on the combination of the two criteria. An individual material unit would then correspond with all the physically adjacent FAKTS genetic units having the required attribute values. Practically, this means that we can derive 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. As material units are not directly stored within the FAKTS database, they are generated by querying N-times for properly-classified vertically and laterally juxtaposed genetic units, as sketched in the figure on the left.



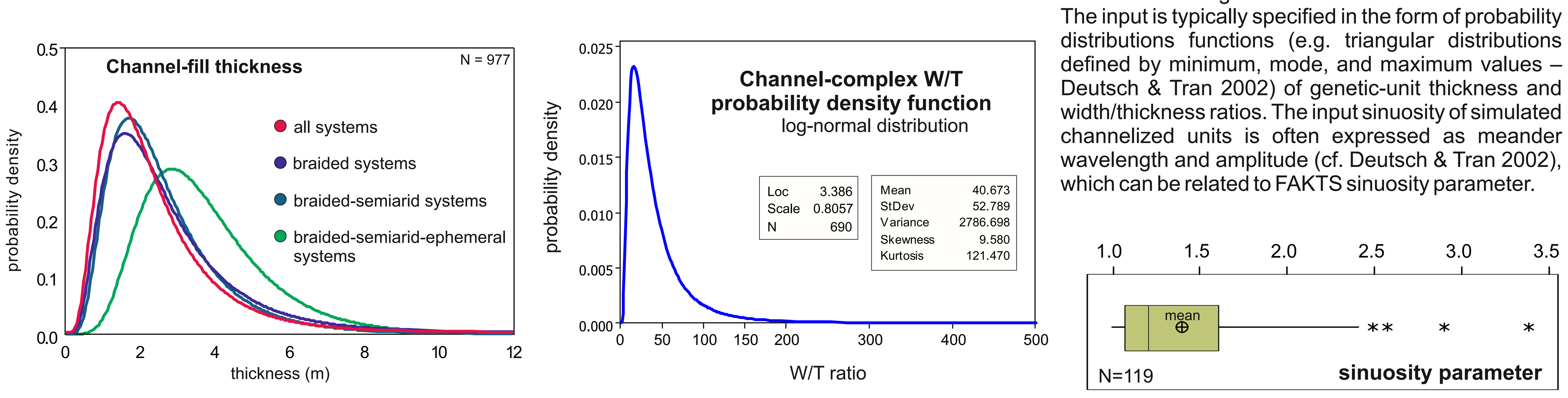




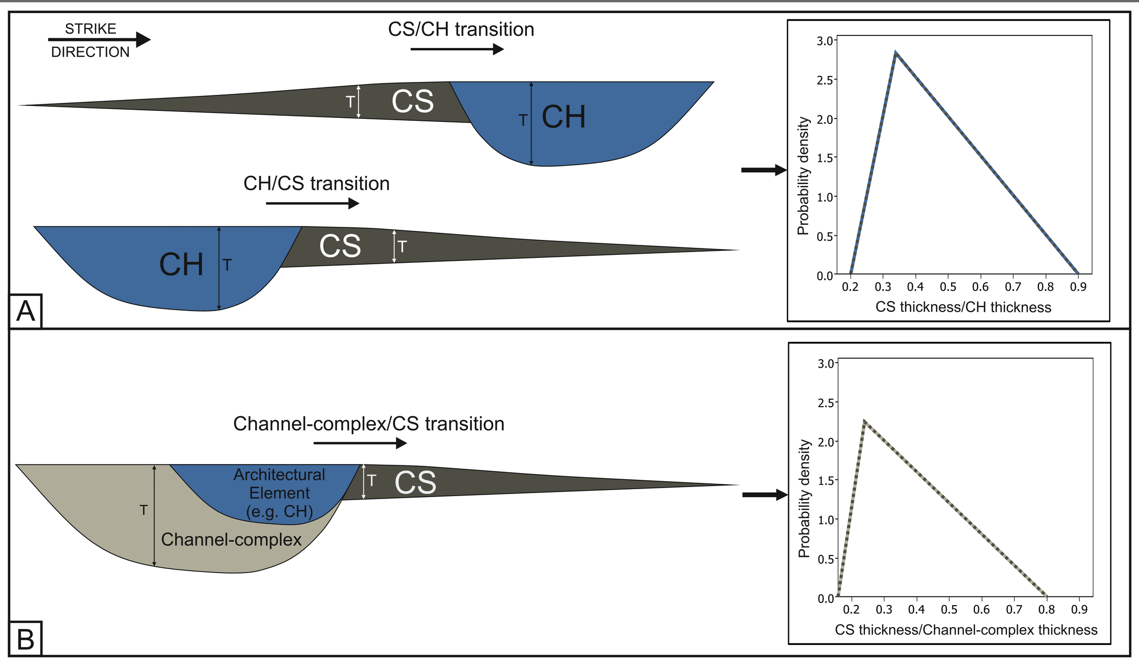
DATABASE-DERIVED RESERVOIR MODELING CONSTRAINTS

While some FAKTS output can be directly used as input to software for the structure-imitating simulation of fluvial sedimentary architecture, some key input parameters – like size ratios, transition rates and indicator auto-variograms or cross-variograms – require additional data processing, as outlined here (and discussed in greater detail in Colombera et al., accepted).

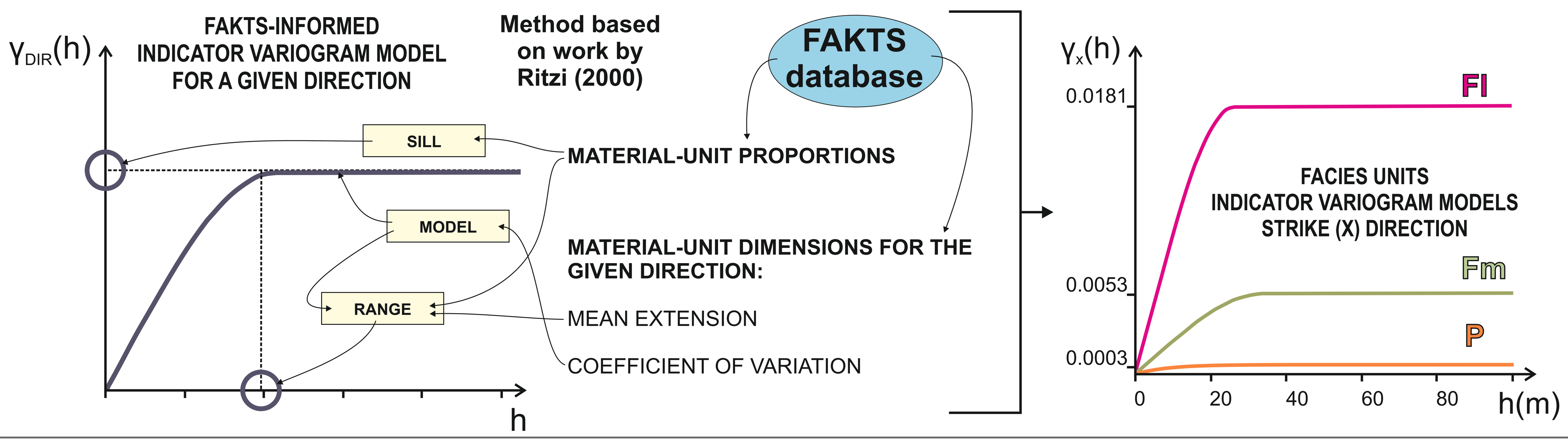
Absolute and relative dimensions and geometry parameters



Dimensional parameters of fluvial genetic units are commonly required by object-based algorithms for structure-imitating simulations of fluvial architecture. The input is typically specified in the form of probability distributions functions (e.g. triangular distributions defined by minimum, mode, and maximum values – Deutsch & Tran 2002) of genetic-unit thickness and width/thickness ratios. The input required for simulated channelized units is often expressed as meander wavelength and amplitude (cf. Deutsch & Tran 2002), which can be related to FAKTS sinuosity parameter.



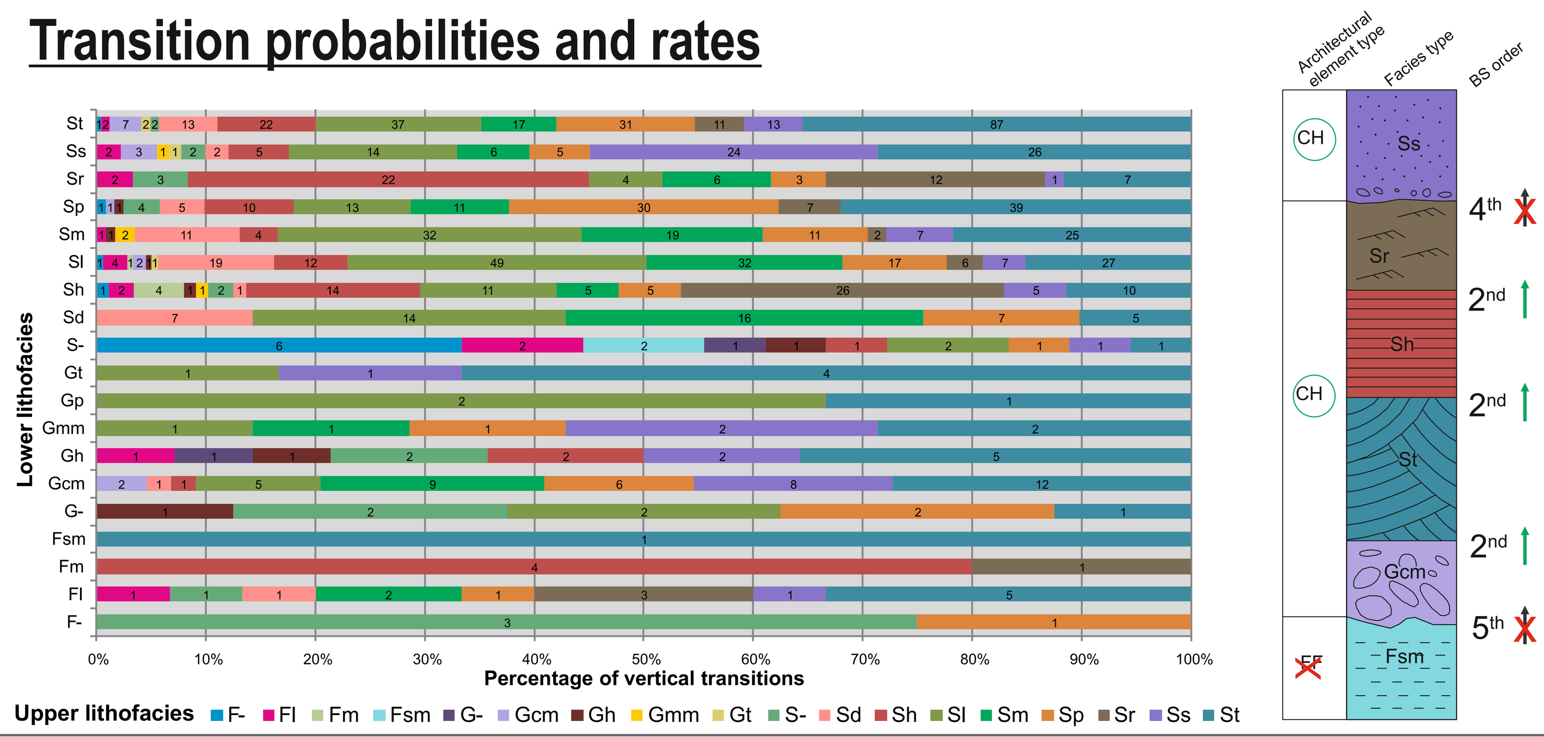
Object-based methods routinely require relative dimensional parameters (e.g. channel-fill thickness/levee thickness ratio; cf. Deutsch & Tran 2002) as input: FAKTS allows the derivation of size ratios referring to juxtaposed genetic units belonging to the same scale (case A in figure on the left) or to different scales (case B), as genetic unit sizes, juxtaposition (in form of transitions) and scale-nesting are all digitized.



Indicator auto-variograms

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).
This means that FAKTS permits informing indicator variogram models referring to any type of material unit (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.

Transition probabilities and rates



The example on the left shows vertical transition-count statistics filtered so that only facies-unit transitions observed within a given type of genetic unit (CH architectural element) and across given bounding surface orders (2[nd] and 3[rd]) are taken into account. Transition probability matrices can thereby be derived from such transitions-count matrices.
Transition rates between units j and k along direction x ($r_{jk,x}$) can be estimated from mean sizes and embedded transition frequencies or probabilities (Carle 1997; 1999) as:

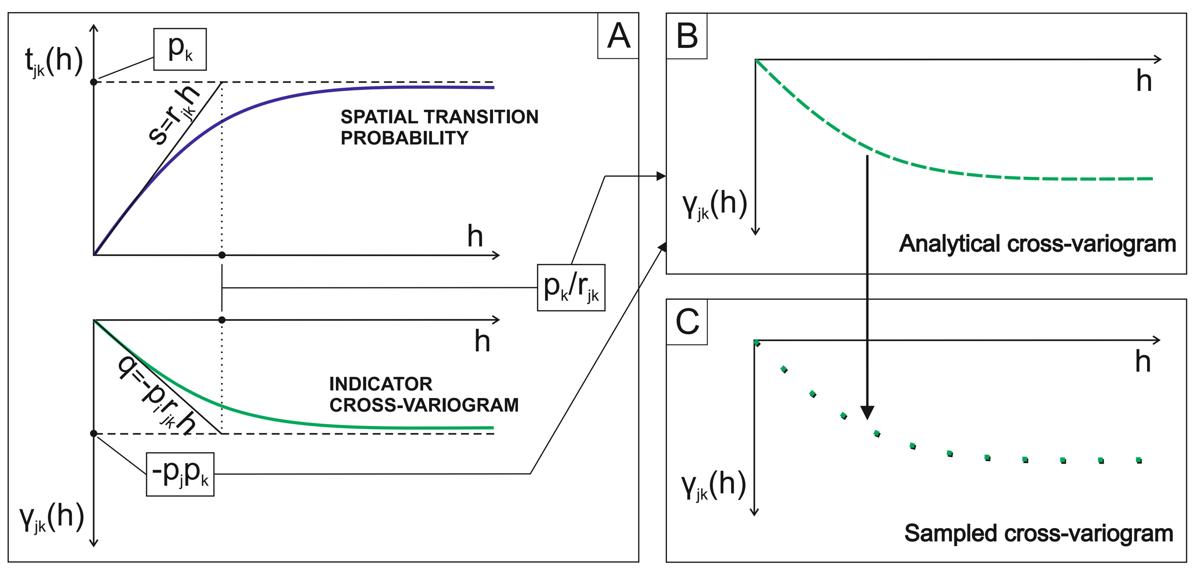
$$r_{jk,x} = f_{jk,x} / f_{j,x} L_{j,x}$$

$$r_{jk,x} = p_{jk,x} / L_{j,x}$$

Transition rates between materia units along a given direction are required to obtain database-derived indicator cross-variogram models for the same material units along that direction, as explained on the right.

Indicator cross-variograms

The sills of indicator cross-variogram models referring to a pair of material units for a given direction can be computed from unit proportions, as they approach $-p_j p_k$ (Carle & Fogg 1996), whereas cross-variogram ranges are approximated by the lag values at the intersection between the sill of the cross-variogram for the same units and the tangent (q, computed from unit proportions and transition rates) to the same cross-variogram at lag zero (Colombera et al., accepted).



On the left: Relationship between the continuous-lag transition probability of two material units and the corresponding indicator cross-variogram. A database derived cross-variogram mode is obtained from proportions and transition rates.l