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PS Digital Reproduction of Clastic Sedimentary Architecture by Means of Relational Databases*

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Abstract

As the amount of architectural data collected in sedimentological studies, and typically rendered available in published form, has increased over time, so a fundamental issue has become ever more important: the need to ensure that different datasets collected in different ways by different geologists (e.g. 2D architectural panels, 3D seismic surveys) are stored in a format such that analysis or synthesis of fundamentally different types of data can be made in a sensible and informative manner, without requiring extensive literature search and re-processing. Database systems are here proposed as a means for achieving the convergence of datasets in a common medium. The proposed database approach permits the digital reproduction of sedimentary architecture in tabulated form: hard and soft data referring to depositional products are assigned to standardized genetic units belonging to different scales of observation, which are themselves contained within stratigraphic volumes classified on deposystem parameters (e.g. subsidence rate, physiographic setting). Although the approach has general applicability, two different databases have been independently developed to capture the peculiarities associated with fluvial and deep-marine depositional systems. Through interrogation, the two database systems return output that – being in quantitative form and referring to standardized sedimentary units – is suitable for both synthesis and analysis. Deposystem classification permits data to be filtered on the parameters on which the systems are classified, allowing the exclusive selection of data associated with systems deemed to be analogous to a given subsurface succession in terms of deposystem boundary conditions and environmental setting. Alternatively, the quantification of architectural properties permits users to identify analogy in terms of sedimentary architecture. Outputs from the two databases are here presented in forms suitable for highlighting differences in the way fluvial and deep-water architecture is conceptualized and implemented, and for presenting ways in which analog information can be employed for the characterization and prediction of fluvial and deep-water reservoirs. Specific example applications include the use of database output to (i) generate quantitative facies models with which to guide core interpretation, (ii) to constrain stochastic reservoir models, and (iii) to guide well correlation of fluvial or deep-marine sandstones.

Digital reproduction of clastic sedimentary architecture by means of relational databases

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UNIVERSITY OF LEEDS

ABSTRACT

As the amount of architectural data collected in sedimentological studies, and typically made available in published form, has increased over time, so a fundamental issue has become ever more important: the need to ensure that different datasets collected in different ways by different geologists (e.g. 2D architectural panels, 3D seismic surveys) are stored in a format such that analysis or synthesis of fundamentally different types of data can be made in a sensible and informative manner, without requiring extensive literature search and re-processing.

Database systems are here proposed as a means for achieving the convergence of datasets in a common medium. The proposed database approach permits the digital reproduction of sedimentary architecture in tabulated form: hard and soft data referring to depositional products are assigned to standardized architectural features, which are themselves contained within stratigraphic volumes classified on deposystem parameters (e.g. subsidence rate, physiographic setting). Although the approach has general applicability, two different databases have been developed to capture the peculiarities of fluvial and deep-marine depositional systems.

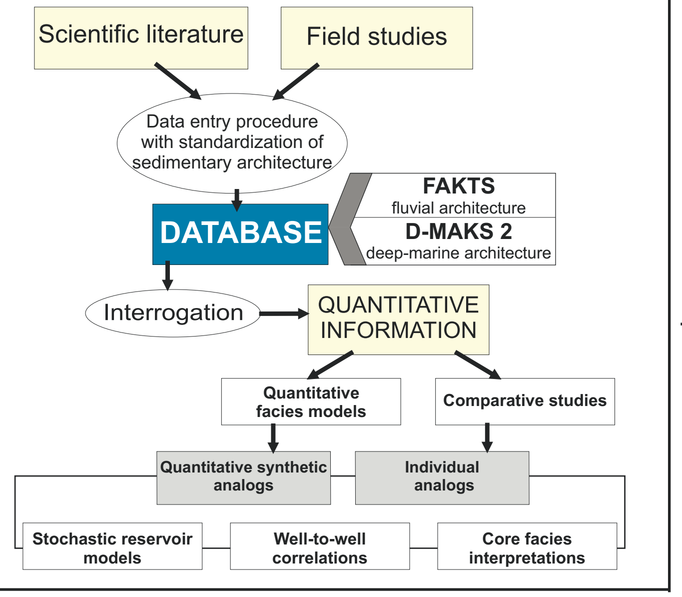
Through interrogation, the two database systems return output that – being in quantitative form and referring to standardized sedimentary units – is suitable for both synthesis and analysis. Deposystem classification permits data to be filtered on the parameters on which the systems are classified, allowing the exclusive selection of data associated with systems deemed to be analogous to a given subsurface succession in terms of deposystem boundary conditions and architectural properties. Otherwise, the quantification of architectural properties permits users to identify analogy in terms of sedimentary architecture.

Output from the two databases is presented with the aims of illustrating the approach highlighting differences in the way fluvial and deep-water architecture is conceptualized and implemented, and of presenting ways in which analog information can be employed for the characterization and prediction of fluvial and deep-water reservoirs. Specific example applications include the use of database output to (i) generate quantitative facies models with which to guide core interpretation, to (ii) constrain stochastic reservoir models, and to (iii) guide well correlation of fluvial or deep-marine successions.

INTRODUCTION

Here we present a relational-database methodology aiming at hosting the steadily growing body of sedimentary architectural data collected in sedimentological studies and made available in published form. In effect, relational databases are here proposed as a means for achieving the convergence of datasets in a common medium, whereby the digital reproduction of sedimentary architecture is obtained by means of tables storing hard and soft data referring to depositional products that are assigned to standardized genetic units, which are themselves contained within stratigraphic volumes classified on deposystem parameters (e.g. subsidence rate, physiographic setting). Although the approach has general applicability, two different databases have been developed to capture the peculiarities of fluvial and deep-marine depositional systems: the Fluvial Architecture Knowledge Transfer System (FAKTS) and the Deep-Marine Architecture Knowledge Store 2 (D-MAKS 2). The necessity to collate different datasets that were originally collected in different ways by different geologists (e.g. 2D architectural panels, 3D seismic surveys) is tackled by dataset standardization: standards are established to ensure unequivocal attribution of each genetic unit to a category in both a hierarchical scheme and a classification scheme. Referring to our in-house standards, all datasets are stored in a format such that analysis or synthesis of fundamentally different types of data can be made in a sensible and informative manner. Through interrogation, the two database systems return output that – being in quantitative form and referring to standardized sedimentary units – is suitable for both synthesis and analysis. Deposystem classification permits data to be filtered on the parameters on which the systems are classified, allowing the exclusive selection of data associated with systems deemed to be analogous to a given subsurface succession in terms of boundary conditions and depositional setting.

SCOPE Here we aim at demonstrating how our relational-database technique for the digitization of clastic sedimentary architecture can be applied to subsurface interpretations and predictions of fluvial and deep-marine reservoirs. The approach is illustrated highlighting differences in the way fluvial and deep-water architectural features are conceptualized and implemented; output analog information is specifically employed for the (i) generation of quantitative facies models that can be used to guide core interpretation, for (ii) constraining stochastic pixel- and object-based reservoir models, and for (iii) guiding well correlation of potential reservoir-quality sandstones.



FAKTS DATABASE OVERVIEW

FLUVIAL 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 of interpretive character (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 units, the geological location, the basin and river or lithostratigraphic unit, and a dataset quality index (DQI), incorporated as a threefold ranking system of perceived dataset quality and reliability based on established criteria. Moreover, subsets are classified according to their suitability for a given query (i.e. type of studied dimensional parameters, proportions, transitions or grain-size data) for a specified scale (target scale). Some example categories on which the stratigraphic volumes are classified are included in the partial list of attributes for the 'subsets' table, on the right.

FAKTS DATABASE SCHEMA

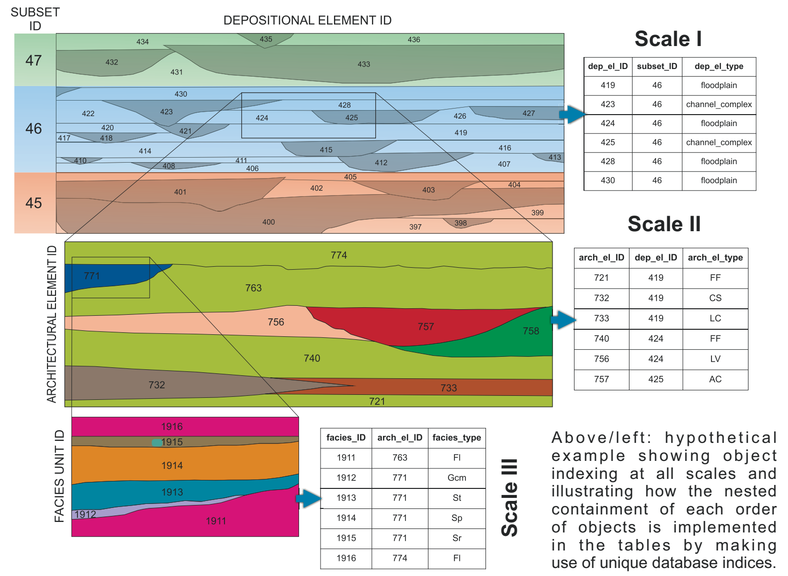
tables and attributes

modified from Colombera et al. (2012a)

FAKTS 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 units, 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).

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).



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.

FAKTS GENETIC-UNIT SPATIAL RELATIONSHIPS

The same numeric indices that are used for representing containment relationships, are also used for object neighboring relationships, represented within tables containing transitions in the vertical, cross-gradient and along-gradient directions. 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.

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	vertical	5th
604	605	lateral	4th
604	607	vertical	4th
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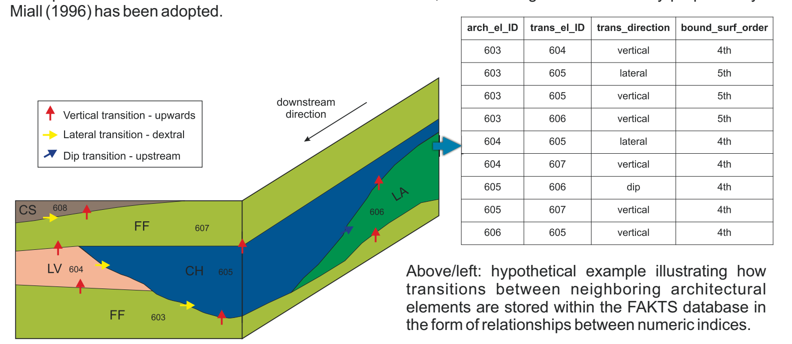
606	605	vertical	4th

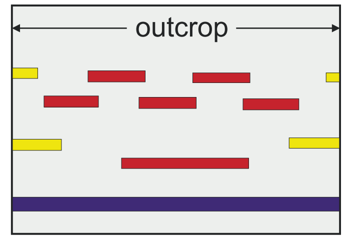


Above/left: hypothetical example of how transitions between neighboring architectural elements are stored in the FAKTS database in the form of relationships between numeric indices.

FAKTS GENETIC-UNIT GEOMETRY

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 database developments may 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 (cf. D-MAKS 2).



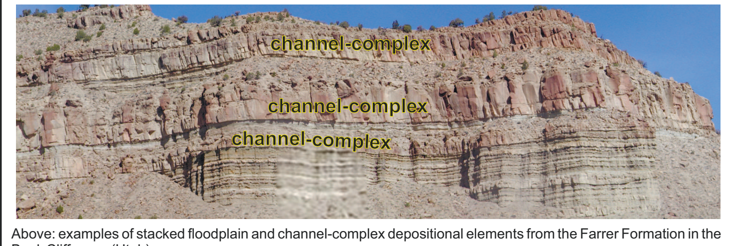
Left: representation of categories of completeness (after Geehan & Underwood 1993) of observed/sampled dimensional parameters. Correlated genetic-unit dimensions are stored as unlimited.

modified after: Geehan & Underwood, 1993

FAKTS GENETIC UNITS

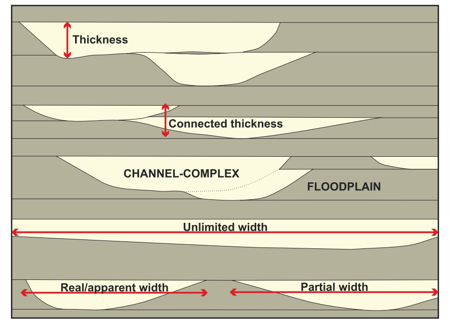
Depositional elements are classified as channel-complex or floodplain elements. Channel-complexes represent channel-bodies defined on the basis of flexible but unambiguous geometrical criteria, and are not related to any particular genetic significance or spatial or temporal scale; they range from the 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.



Above: examples of stacked floodplain and channel-complex depositional elements from the Farrer Formation in the Book Cliffs area (Utah).

DEPOSITIONAL ELEMENTS



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.

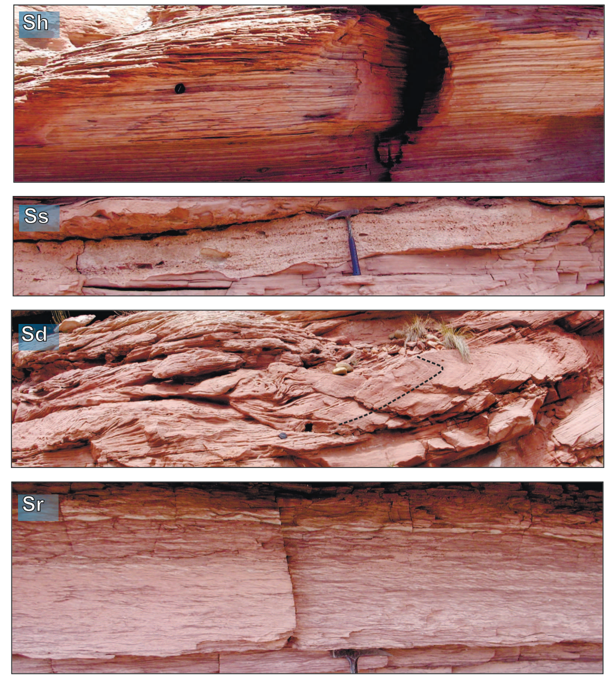
FAKTS is designed for storing architectural element types classified according to both Miall's (1996) classification and also to a classification derived by modifying some of Miall's classes in order to make them more consistent in terms of their geomorphological expression, so that working with datasets 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 sandstone facies units from the Lower Jurassic Kayenta Formation in SE Utah.

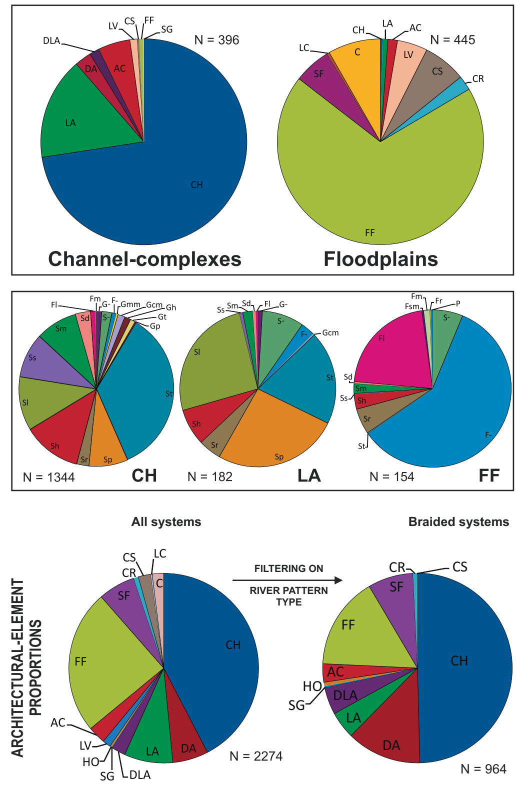
BASIC FAKTS OUTPUT

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 PROPORTIONS

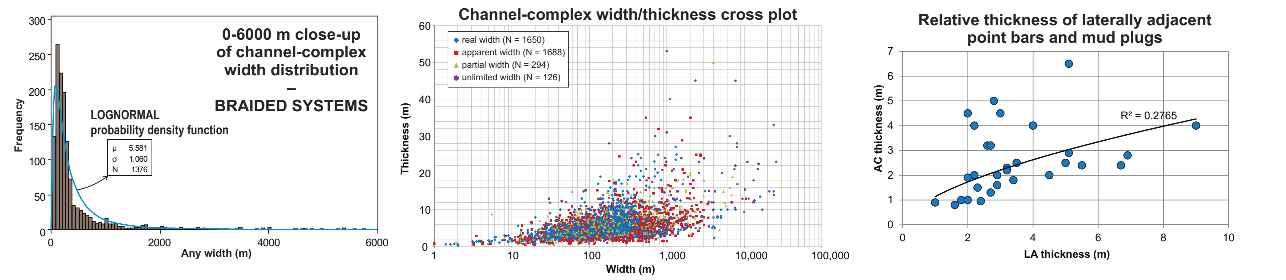
The internal organization of genetic packages can be characterized in terms of the objects belonging to lower-order scales.

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 genetic-unit type.



GENETIC-UNIT DIMENSIONS

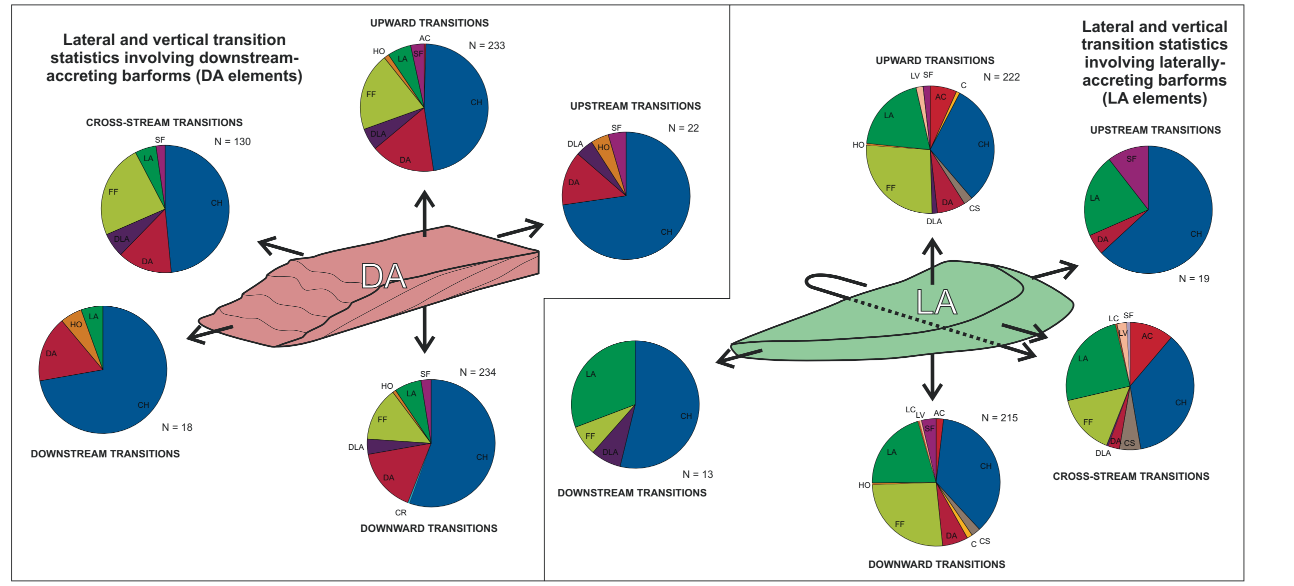
FAKTS permits the derivation of dimensional parameters of genetic-unit types; from this output it is possible to readily derive descriptive statistics or probability density functions of given geometrical parameters or cross-plots of aspect ratios (e.g. width/thickness, width/length), choosing whether to include or not underestimated (partial and unlimited) and overestimated (apparent) dimensions. It is also possible to obtain output for relative dimensional parameters of adjacent genetic units (e.g. channel-fill thickness/levee thickness ratio), belonging to the same hierarchical scale or to different scales, as genetic unit sizes, juxtaposition (in form of transitions) and scale-nesting are all digitized.



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 depositional or architectural element investigated and across given bounding-surface orders are taken into account.

To obtain meaningful 1D transition statistics, 2D- and 3D-dataset transitions can be filtered through a special query that performs random selections in order to force the sampling to be one dimensional.

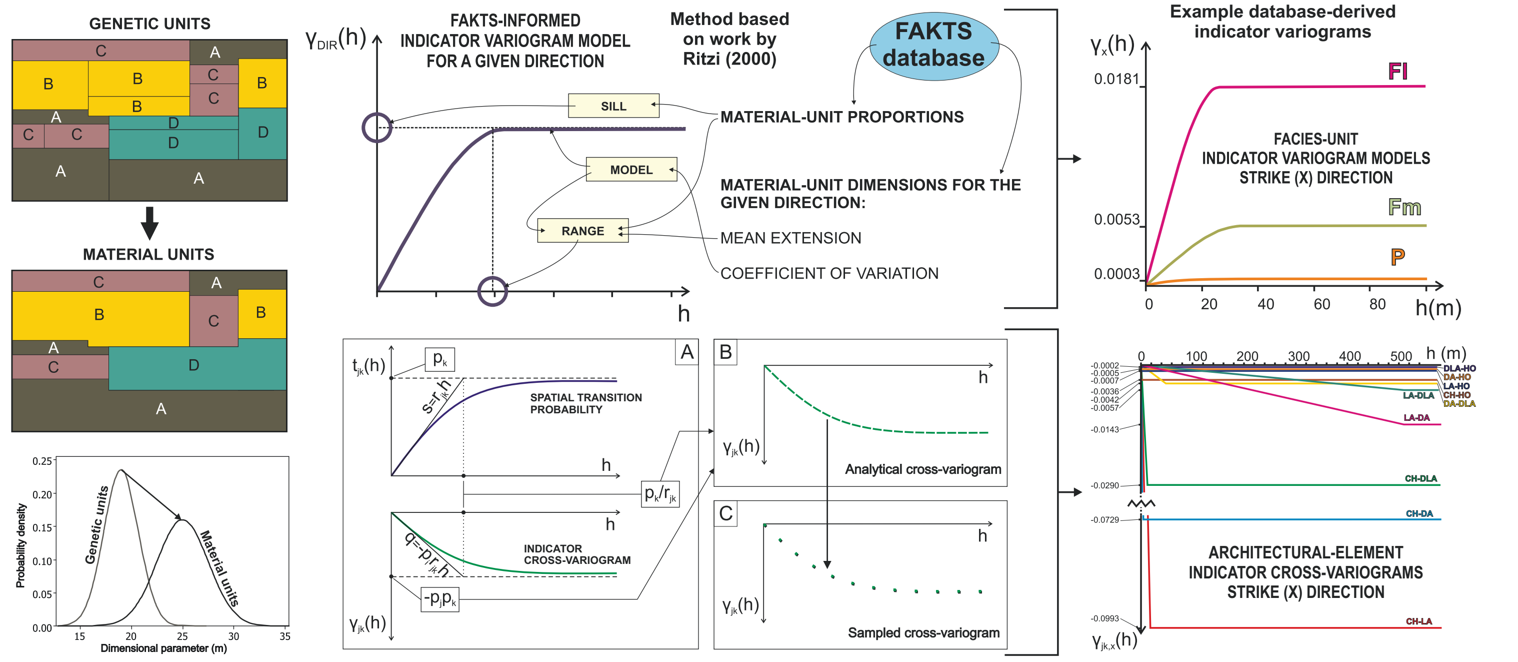


MATERIAL-UNIT PROPERTIES

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 grain-size value, or on the basis of a 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.

Material unit properties (proportions, central tendency and dispersion of extent in a given direction, transition statistics in a given direction) can then be employed for the derivation of model indicator auto- and cross-variograms (model type, range, sill).



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Digital reproduction of clastic sedimentary architecture by means of relational databases: characterization and prediction of fluvial and deep-marine reservoirs

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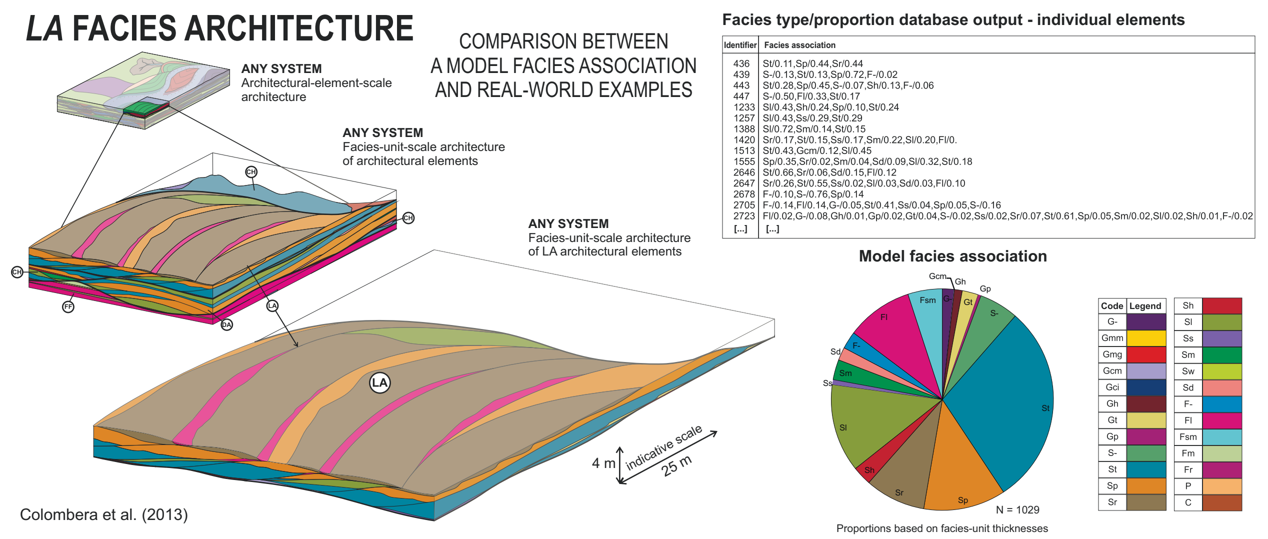
ANALOG CHOICE

Reservoir-analog information can either be derived from (i) individual depositional systems that are thought to best match with the reservoir of interest in terms of either architecture or depositional boundary conditions, or both, or (ii) from a suite of depositional systems that share architectural characteristics or system parameters with the reservoir, and whose quantified architectural properties are distilled into a database-informed facies model, which can effectively be employed as a synthetic reservoir analog. The process of standardization of sedimentary architecture – through rigorous definition of genetic-unit hierarchy, classification and attributes – permits the synthesis of architectural data, such that meaningful information can be obtain by merging different datasets in quantitative facies models.

Architectural databases as the ones shown here can effectively be used to highlight the uniqueness of depositional systems, since each depositional system and each genetic unit within them are stored singularly in the database and can be individually retrieved for comparison (cf. example on the right), thereby providing a more flexible benchmark for reference than traditional facies models. This type of database system can therefore reconcile the 'facies model' and the 'reservoir analog' schools of thought.

Such individual or synthetic analogues can then be employed to guide subsurface interpretations and predictions by assisting core interpretation, quality-checking well-to-well correlation panels of reservoir-quality sandstones, and conditioning pixel- or object-based stochastic reservoir models, as illustrated in some examples here.

LA FACIES ARCHITECTURE



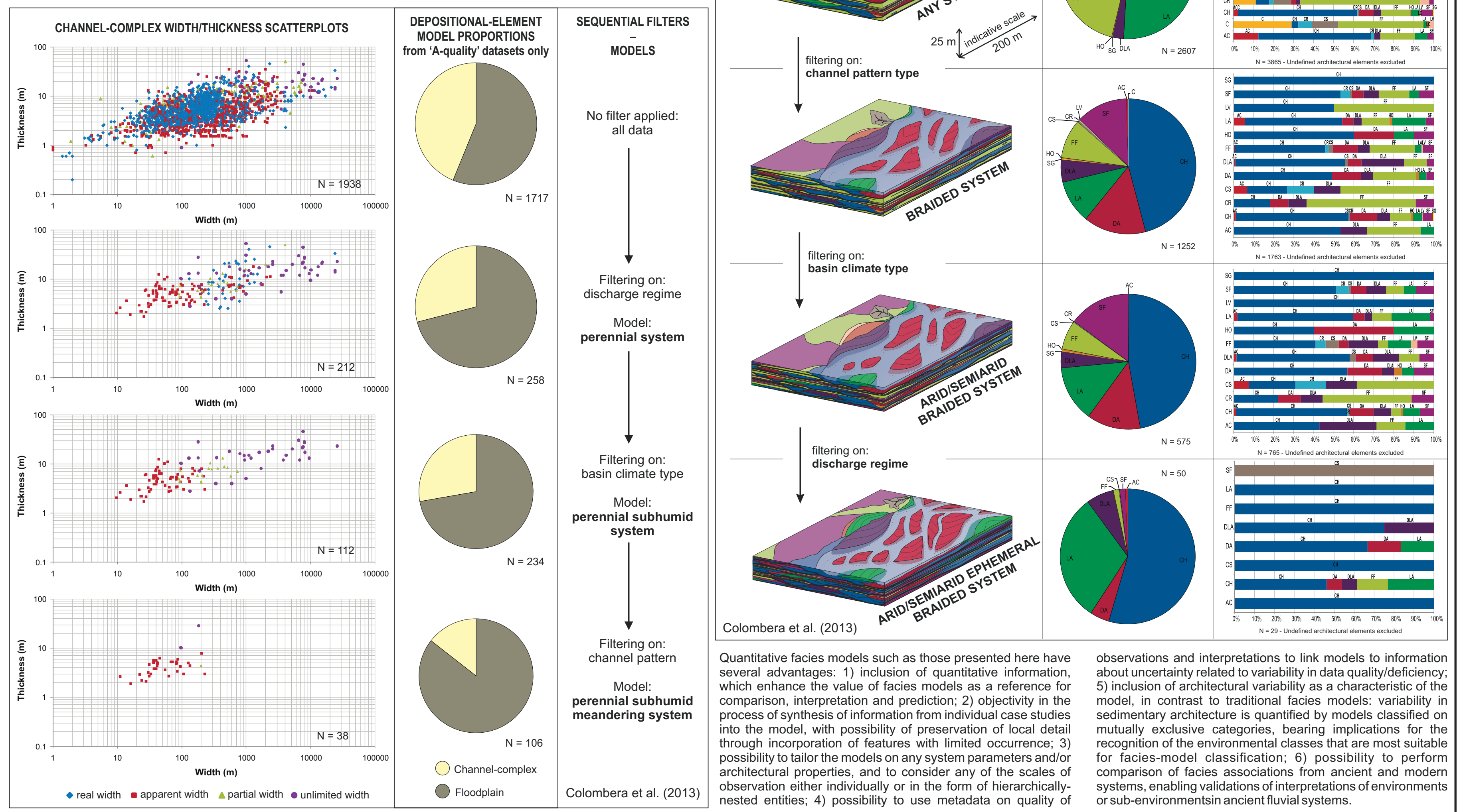
QUANTITATIVE FLUVIAL FACIES MODELS: GUIDES TO SUBSURFACE INTERPRETATION AND PREDICTION

The generation of database-informed facies models is illustrated here by employing the FAKTS database to build some example fluvial facies models. These facies models consist in sets of quantitative information relating to selected architectural properties, categorized on any combination of architectural properties (e.g. sandy river, high net-to-gross system) and system parameters (e.g. braided river, subhumid system).

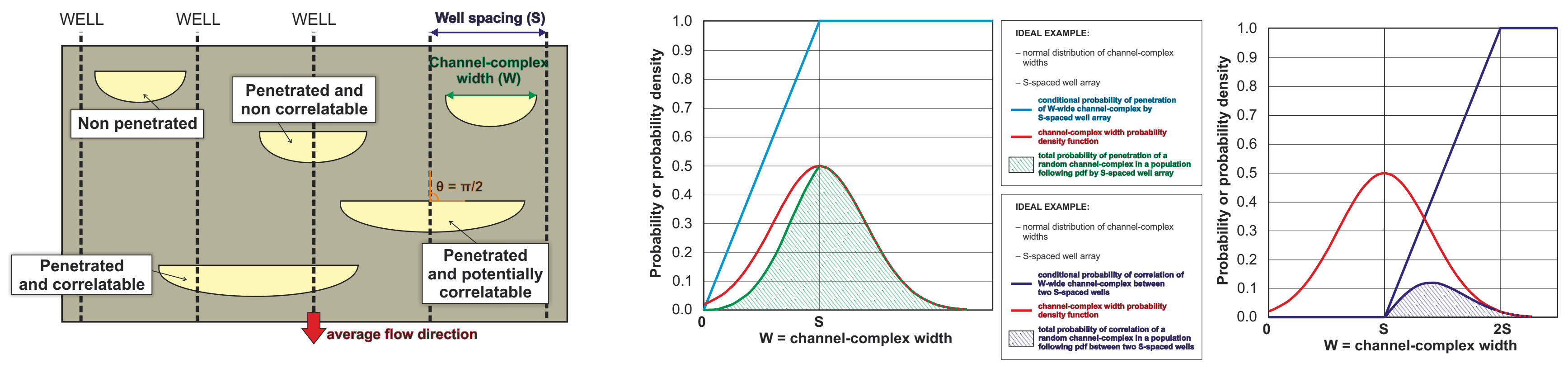
Firstly, the generation of quantitative fluvial facies models involves a sequential application of filters to the knowledge base that allows only case studies that developed under appropriate boundary conditions to contribute to any particular model.

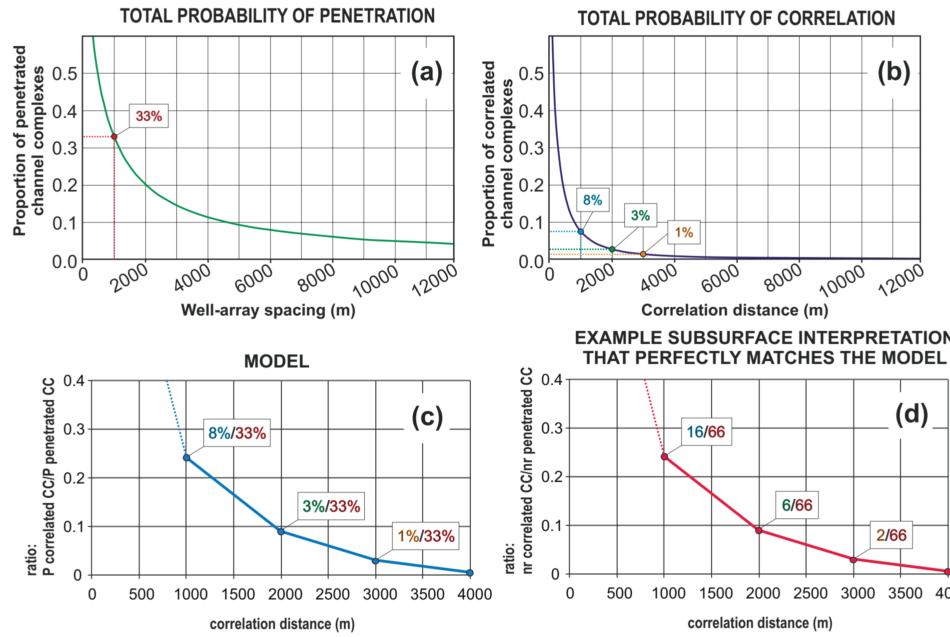
Secondly, the database output on genetic-unit proportions, geometries and spatial relationships derived from suitable systems needs to be synthesized into the model by following standard procedures that consider the types of observations available.

Examples of the end result of this method are shown on the right and below; these facies models are linked to different deposystem categories, and relate different types of information associated with different scales of observation.



CORRELABILITY MODELS FOR GUIDING WELL CORRELATIONS





Assuming orthogonal penetration of a well array with constant spacing S into channel complexes, it is possible to combine analytical expressions for the conditional probability of penetration and correlation of a channel complex with width W with database-derived probability density functions of channel-complex width to obtain total probabilities of channel-complex penetration and correlation, which can be integrated and expressed as functions of well-spacing and correlation distance respectively.

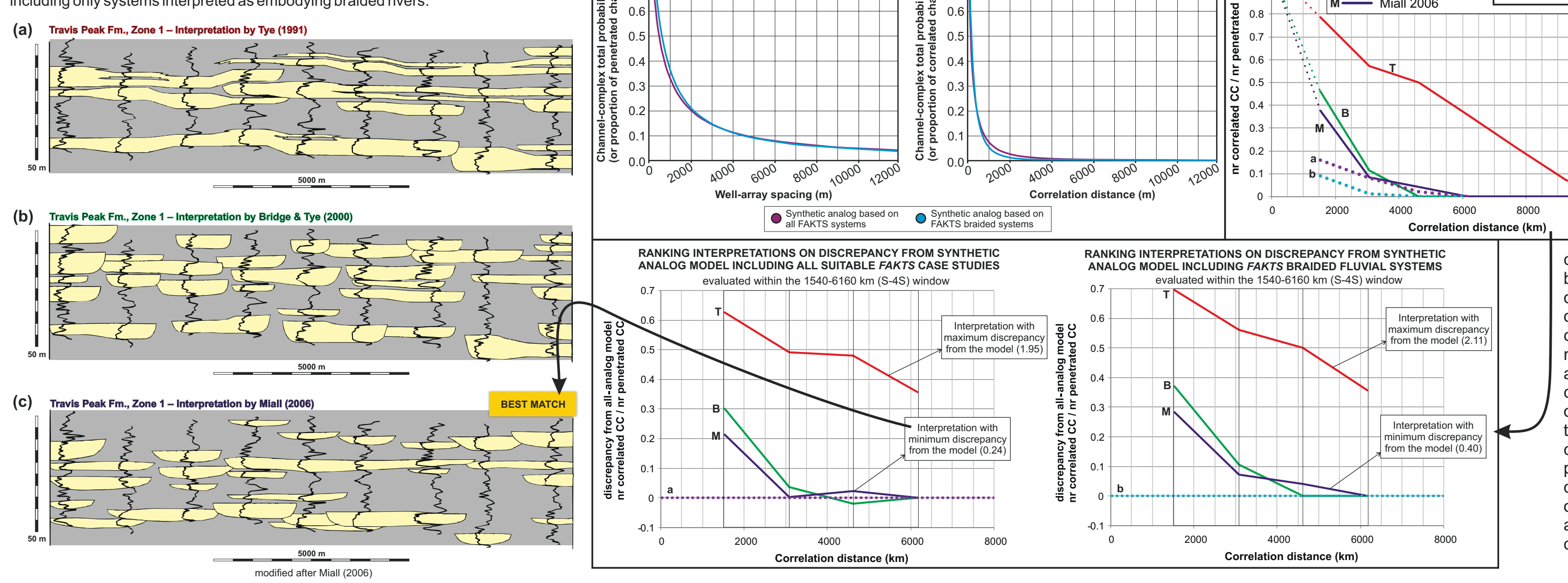
IDEAL EXAMPLE:
– well spacing = 1000 m
– penetrated channel complexes = 66

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

Evaluation of the realism of subsurface well-to-well correlation of the sandbodies is carried out by comparing the discrepancy between the correlability model and an analogous curve based on the ratio between correlated and penetrated channel complexes as represented in the correlation panel under evaluation. In effect, this process of quantitative comparison permits assessing whether well correlations are too optimistic or too pessimistic, as compared with suitable analogs, taking into account possible variability in sandbody size.

EXAMPLE SUBSURFACE APPLICATION

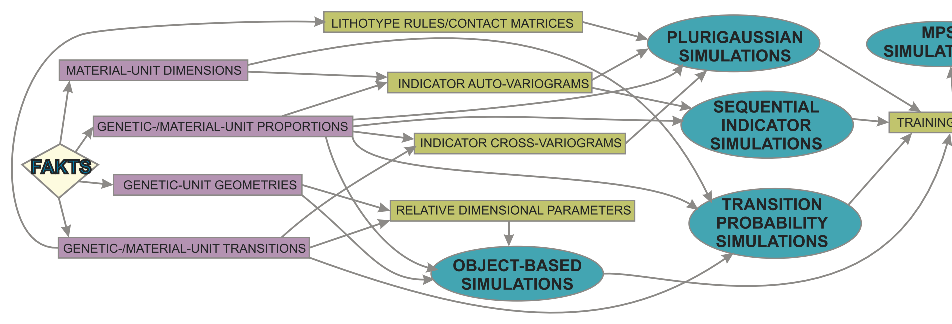
The method has been applied to rank three published alternative interpretations of a stratigraphic interval of the Travis Peak Formation (Texas, USA) in terms of realism of correlation patterns as compared to (i) all analogs recorded in FAKTS and considered suitable for large-scale architectural characterization, and (ii) a subset of them including only systems interpreted as embodying braided rivers.



comparison between database-derived correlability models and curves of correlability obtained for the 3 different correlation panels; quantification of discrepancy allows for quality ranking.

Quantitative facies models such as those presented here have several advantages: 1) inclusion of quantitative information, which enhance the value of facies models as a reference for comparison, interpretation and prediction; 2) objectivity in the process of synthesis of information from individual case studies into the model, with possibility of preservation of local detail through incorporation of features with limited occurrence; 3) possibility to tailor the models on any system parameters and/or architectural properties, and to consider any of the scales of observation either individually or in the form of hierarchically-nested entities; 4) possibility to use metadata on quality of observations and interpretations to link models to information about uncertainty related to variability in data quality/deficiency; 5) inclusion of architectural variability as a characteristic of the model, in contrast to traditional facies models: variability in sedimentary architecture is quantified by models classified on the environmental classes that are most suitable for recognition of the environmental classes; 6) possibility to perform comparison of facies models, and to consider any ... systems, enabling validations of interpretations of environments or sub-environments in ancient fluvial systems.

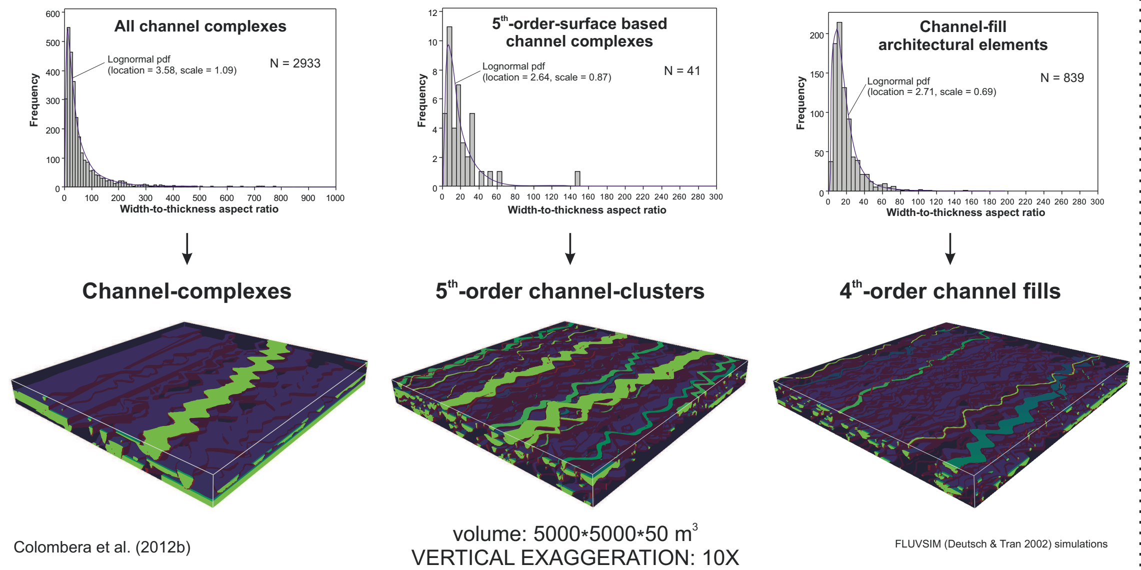
DATABASE CONSTRAINTS TO PIXEL- AND OBJECT-BASED GEOSTATISTICAL MODELS



The FAKTS database provides analog-derived input to object- and pixel-based methods for stochastic modeling of fluvial sedimentary architecture.

CONDITIONING OBJECT-BASED SIMULATIONS

To condition object-based stochastic reservoir models, FAKTS output on both absolute and relative dimensional parameters (see poster 1) can be queried for different hierarchical orders of genetic units (e.g. channel fill, 5th-order channel belt, channel complex), to match with the scale of simulation.



MODELING UNIT SPATIAL RELATIONSHIPS

FAKTS output on 3D genetic-unit spatial relationships can be employed to condition plurigaussian simulations (by informing lithotype rules or 'dynamic contact matrices') and transition-probability-based methods (see example below).

IN-CHANNEL ARCHITECTURAL-ELEMENT SPATIAL RELATIONSHIPS

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

Independent trials matrix – upstream direction

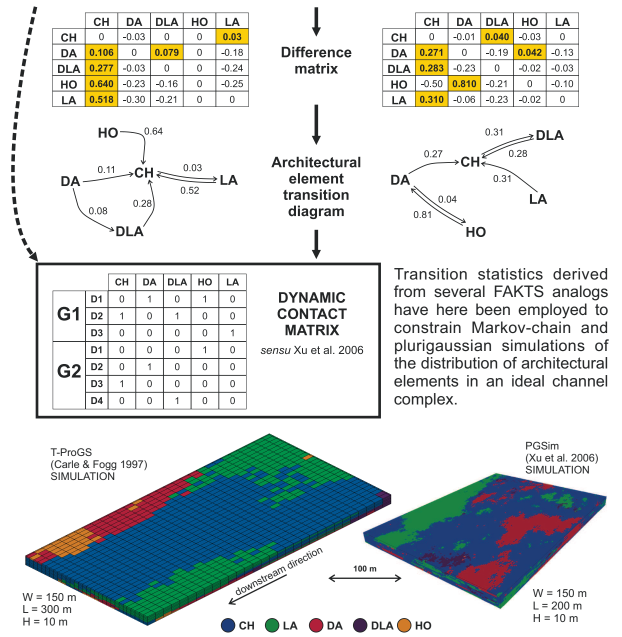
	CH	DA	DLA	HO	LA
CH	0	0.367	0.400	0.033	0.200
DA	0.604	0	0.250	0.020	0.125
DLA	0.617	0.234	0	0.021	0.128
HO	0.500	0.190	0.207	0	0.103
LA	0.547	0.208	0.226	0.019	0

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

Transition probability matrix – upstream direction

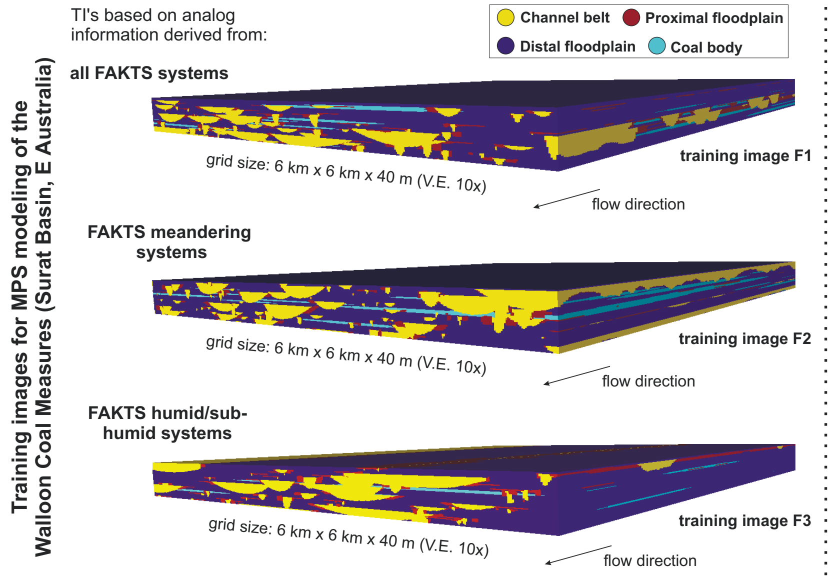
	CH	DA	DLA	HO	LA
CH	0	0.360	0.440	0	0.200
DA	0.875	0	0.063	0.063	0
DLA	0.900	0	0	0	0.100
HO	0	1	0	0	0
LA	0.857	0.143	0	0	0



Transition statistics derived from several FAKTS analogs have here been employed to constrain Markov-chain and plurigaussian simulations of the distribution of architectural elements in an ideal channel complex.

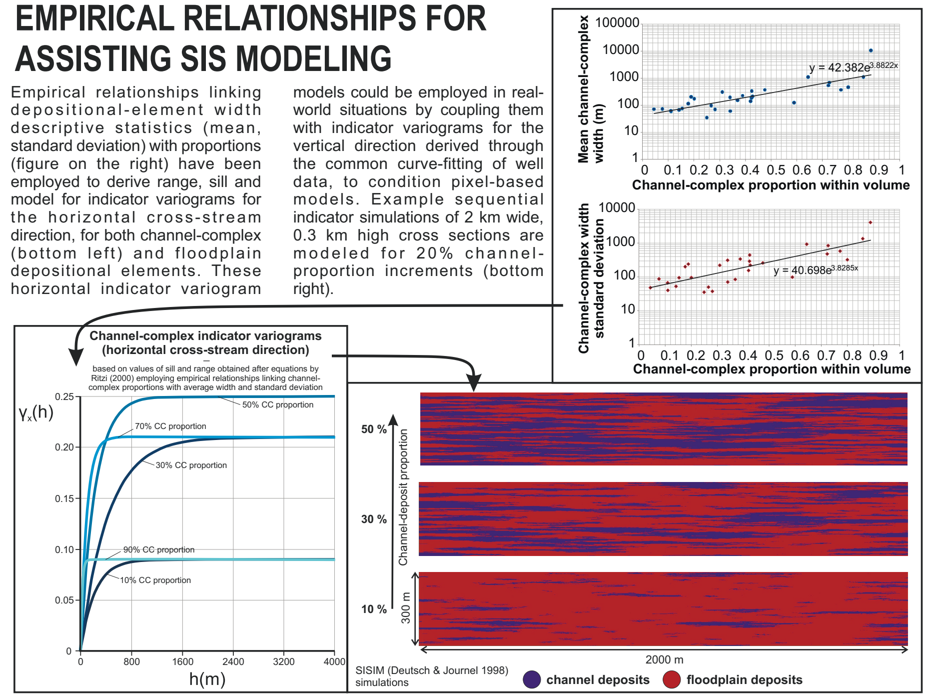
GENERATION OF MPS TRAINING IMAGES

After selection of relevant analogs and genetic units, database-derived output can be employed to fully constrain unconditional simulations (i.e. simulations that are not conditioned to direct data) of fluvial architecture so that the resulting realizations can be used as 3D training images for multiple-point statistics simulations. Notably, the database method allows for pixel- and object-based techniques to be combined.



EMPIRICAL RELATIONSHIPS FOR ASSISTING SIS MODELING

Empirical relationships linking depositional-element width descriptive statistics (mean, standard deviation) with proportions (figure on the right) have been employed to derive range, sill and model for indicator variograms for the horizontal cross-stream direction, for both channel-complex (bottom 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 derived through the common curve-fitting of well data, to condition pixel-based models. Example sequential indicator simulations of 2 km wide, 0.3 km high cross sections are modeled for 20% channel-proportion increments (bottom right).



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Digital reproduction of clastic sedimentary architecture by means of relational databases

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UNIVERSITY OF LEEDS

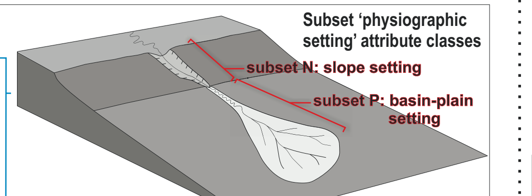
D-MAKS 2 DATABASE OVERVIEW

DEEP-MARINE CASE-STUDY CLASSIFICATION

Systems are defined as segments of slope to basin plain deep-water environment considered to the same feeder system. D-MAKS 2 stores systems and their component subsets (i.e. stratigraphic volumes with given suitability); the same system or subset may be the subject of different studies, which are included as different entities only in a separate table that records the contribution of different works to every subset. However, if the same stratigraphic volume has been described in different source works in a way that the data are suitable for different purposes (e.g. W/T plot of architectural-element geometries suitable for dimensional output and lithofacies-scale log suitable for facies-proportion output, for the same outcrop), data must be included in more than one subset. Two different tables, referring to systems and subsets, are used to separately classify systems and subsets; each table includes attributes describing both metadata (e.g. data *quality index*) and context-descriptive parameters or depositional-system controls.

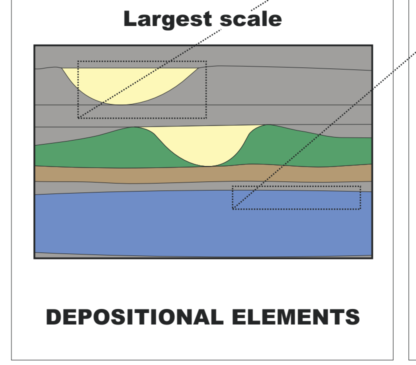
Example system or subset attributes
- tectonic setting
- dominant grain size
- feeder-system type
- aggradation rate
- basin confinement gradient
- [...]

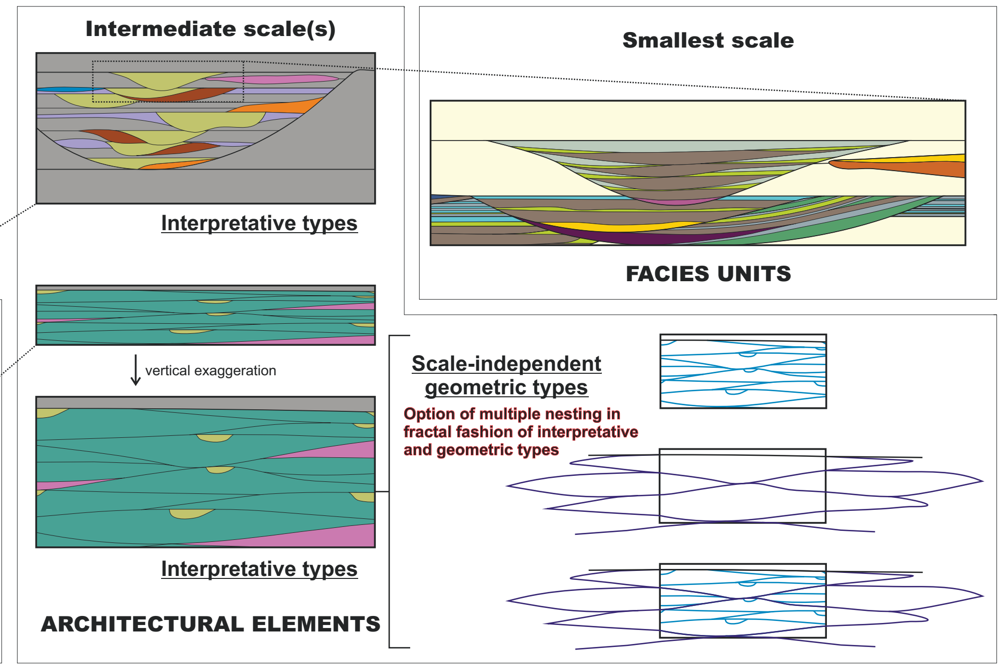
Subset 'physiographic setting' attribute classes



D-MAKS 2 GENETIC-UNIT HIERARCHY

In D-MAKS 2 three different orders of genetic units are considered; however, some geometric units can be multiply nested to span any order of physical scale actually observed: these geometrically-classified units can be multiply nested within each other, potentially defining a hierarchy of their own, and may contain genetically-classified units (or be contained in genetically-classified units), which would therefore anchor the scale of the geometric units to the scale of units with better-constrained genetic significance.

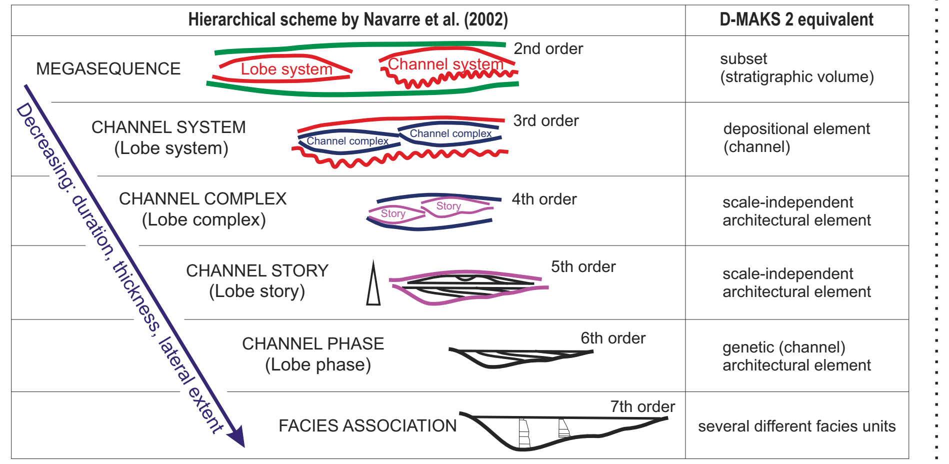


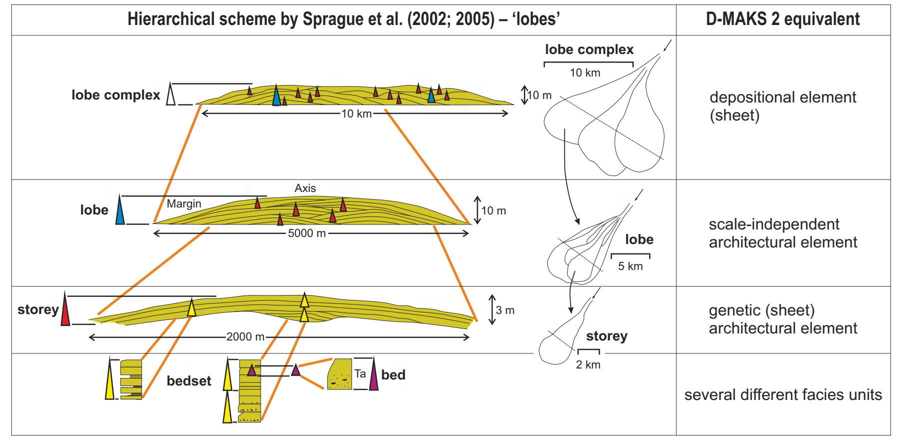


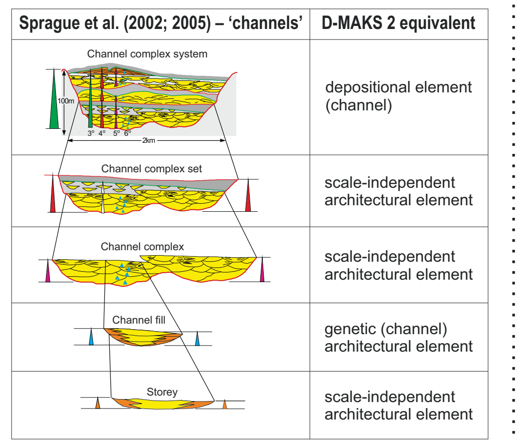
Depositional elements are defined mainly on geological criteria, which ensure that these elements represent the largest-scale sedimentary units recognizable in deep-marine environments (e.g. canyons, channel belts, master levees).
Architectural elements represent multi-bed intermediate scale sedimentary units. When classified on the subenvironment they represent, geological criteria are used to define scale-dependent interpretative types; when architectural elements are classified on geometry only, they can be adjusted to match with any physical scale that is observed in between the depositional-element and the bed scale, and can be multiply nested within each other in fractal fashion.
Facies units represent bed-scale to sub-bed-scale elementary volumes of sediment characterized by given sediment texture and structure, on the basis of which they are classified.

Conversion to other genetic-unit hierarchical schemes

Tentative translations between the hierarchical scheme adopted in D-MAKS 2 and hierarchical schemes used in the oil industry are available (see examples here). These involve one-to-many relationships between some of the D-MAKS hierarchical orders and some of the orders in other schemes, and the correspondence between different orders is in some cases separately considered for different genetic-unit types (channelized units or lobe/sheet units).





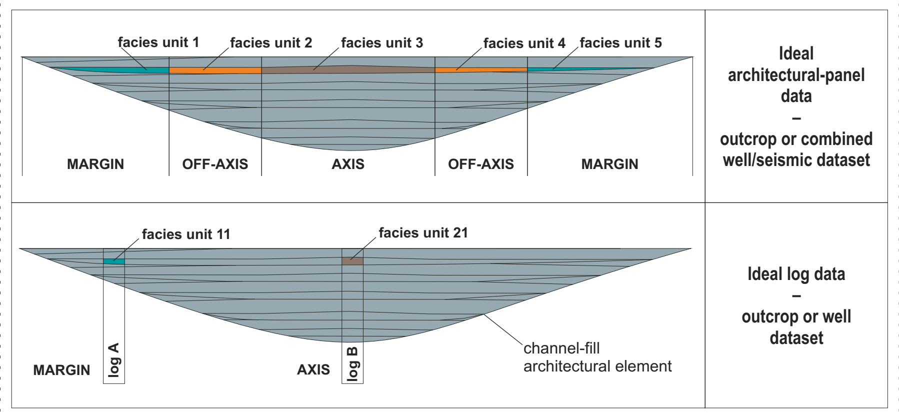


D-MAKS 2 GENETIC-UNIT SPATIAL RELATIONSHIPS

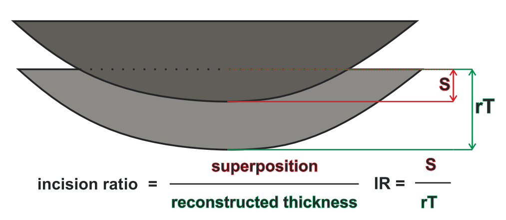
Transition axis	Conventional direction
Vertical	Upwards
Strike	Right-hand when facing downflow
Dip	Upstream

Contact type
Sharp non-erosional
Gradational
Erosional

Spatial relationships between genetic units are digitized as 3D transitions. In addition, the type of contact across which the transition occurs can be classified on the basis of a threefold classification of bounding surfaces.



To improve the characterization of architectural elements, a descriptor of the position of a facies unit within its parent architectural element (e.g. channel axis, lobe fringe) is included. If a facies unit crosses through the element in more than one position, artificial lateral transitions between sub-units are stored.

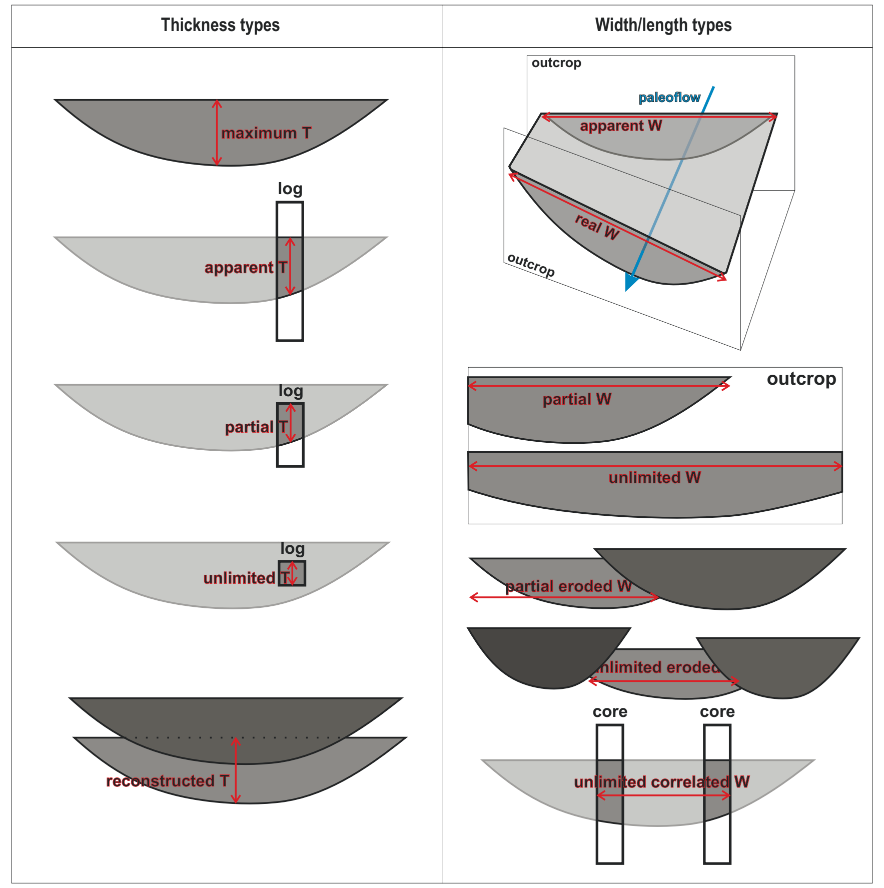


$$\text{incision ratio} = \frac{\text{superposition}}{\text{reconstructed thickness}} \qquad IR = \frac{S}{rT}$$

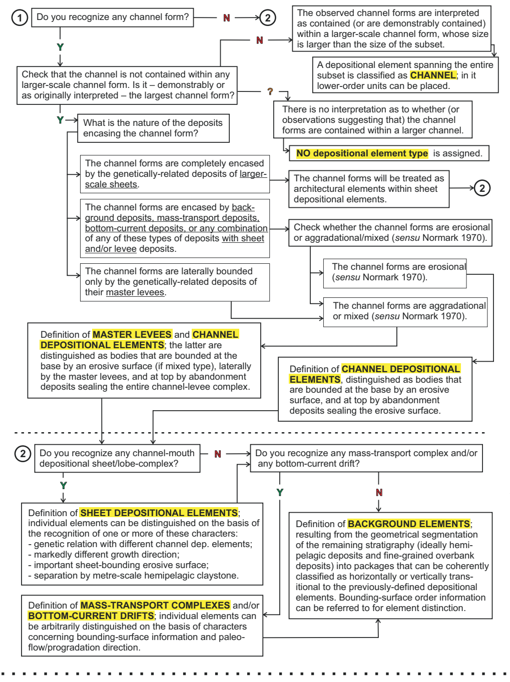
For depositional and architectural elements, information on the degree of incision of upper elements into lower elements across erosional surfaces is recorded in transition tables in the form of an *incision ratio* (see definition on the left).

D-MAKS 2 GENETIC-UNIT DIMENSIONAL PARAMETERS

Genetic-unit dimensional parameters ideally record maximum thickness, real strike width and real dip length, with reference to the average flow direction at the scale of the unit. However, as incomplete observations are the norm, the dimensional parameters are classified to account for (i) variable completeness related to the possible truncation at one or both limits of the observation window and (ii) variable completeness related to erosion. The original maximum thickness of a depositional or architectural element prior to erosion can be stored as 'reconstructed thickness'.



D-MAKS 2 LARGE-SCALE DEPOSITIONAL-ELEMENT CLASSIFICATION



To guarantee that genetic units from different datasets are consistently defined, such that database output can ultimately be compared or merged, in-house standards are referred to for genetic-unit hierarchy assignment and classification.
The sequential checking of the criteria outlined here aims to ensure consistency in data definition and entry at the largest scale; element-type attribution is not carried out (i.e. element-types are left undefined) whenever the required observable or interpretative elements on which the definitions are based are missing.
The standard adopted for depositional elements is summarized in the flow-chart on the left, which is referred to for the sequential application of the criteria during the data-entry process.
The instructions in the chart are meant to be applied afresh and independently for every subset.
It should be evident that, because of the physical and genetic scale to which these units correspond, depositional-elements are the most suitable descriptors of the sedimentary architecture mapped in seismic datasets, although they may also find wide application to modern-system datasets and may even be applicable to datasets associated with extensively-exposed outcrops.

D-MAKS 2 ARCHITECTURAL-ELEMENT GENETIC CLASSIFICATION

Different scale-constrained architectural elements are defined and assigned interpretive classes on combined observations on:
- external and internal geometries, their relationships with paleocurrent and growth directions, and nature of associated bounding surfaces;
- lithofacies associations;
- coarsening-/thickening-upwards (or fining-/thinning-upwards) trends;
- significant horizontal offset in position of 'axis' deposits;
- inferred genetic relationships with adjacent elements.

TYPE	DESCRIPTION
Aggradational channel fill	Aggradational infill of the smallest recognizable channel form composed of one or more dominantly vertically-stacked accretion increments.
Inclined-accretion channel fill	Infill of a channel form by accretion increments stacked on each other along downlapping surfaces dipping towards the axis of a channel.
Internal levee	Thin-bedded wedge-shaped aggradational form that thins away from the margins of a channel fill, confined within a channel-belt by erosional surface or master levees.
External-levee element	Thin-bedded component of a master levee, it forms a wedge-/prism-shaped aggradational body that thins away from the margins of a channel belt.
Frontal turbidite-dominated sheet	Sedimentary/geomorphic product of deposition at the same channel terminus by one or several turbidity-flow events, typically in the form of a sheet or low-relief lobate mound; typically composed of turbidites, may also contain debrites.
Lateral turbidite-dominated sheet	Sedimentary/geomorphic product of deposition by turbidity-flow events that either overtopped a channel margin or occured downflow of a crevasse channel.
Debris-flow body	Aggradational form produced by debris-flow settling, including lobes/sheets and ridges/levees; this body may also contain genetically-related turbidites.
Slump	Aggradational form resulting by a single slump emplacement.
Slide	Aggradational form resulting by a single slide emplacement.
Mudstone/heterolithic sheet	Elements obtained subdividing the remaining stratigraphy into geometric packages of fine-grained hemipelagic/overbank deposits; bounding-surface information can be also considered for element definition.

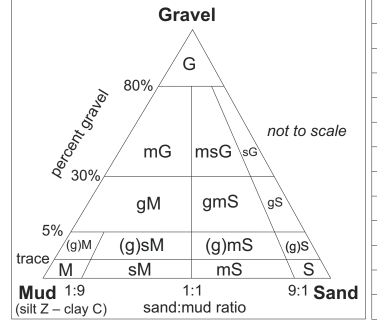
D-MAKS 2 SCALE-INDEPENDENT GEOMETRIC-UNIT CLASSIFICATION

The architectural elements can be classified on the predefined shape types, included in the table on the right. These classes are used to categorize geometrically-defined scale-independent – and possibly fractally-nested – units, but can also be applied to genetically-defined architectural elements to better characterize their geometries.

TYPE	CHARACTERISTICS
channel	ribbon shape, possibly sinuous, concave-up base, flat top
ridge	ribbon shape, flat base, convex-up top
scoop	semi-lenticular shape, concave-up base, flat top
mound	semi-lenticular shape, flat base, convex-up top
lens	lenticular shape, concave-up base, convex-up top
sheet	tabular shape, flat base, flat top, steep sides
wedge	shape tapering horizontally, with inclined base/top

D-MAKS 2 FACIES-UNIT CLASSIFICATION

GRAIN-SIZE CLASSES based on Folk (1954; 1980)

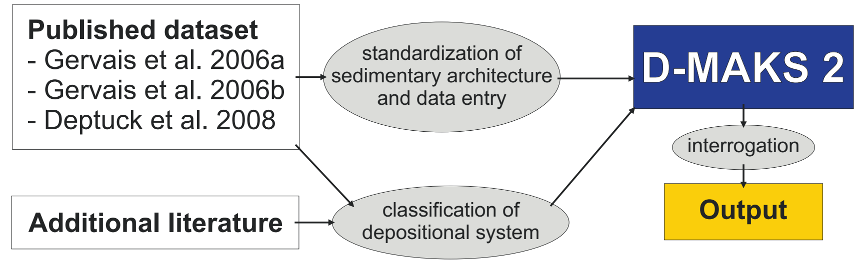


DOMINANT INTERNAL STRUCTURES
Massive
Unidirectional ripple cross-lamination
Planar-horizontal lamination
Low-angle cross-bedding
Trough cross-bedding
Planar cross-bedding
Flaser bedding
Wavy bedding
Lenticular bedding
Banding
Chaotic
Slump folding
Convolution

In contrast with FAKTS, to allow for more varied output to be obtained, soft data on the texture and sedimentary structures of a facies unit are included in different fields:
- dominant internal structure;
- fabric support;
- grading;
- additional internal structures;
- bed-plane structures;
- imbrication (Y/N);
- injection (Y/N).

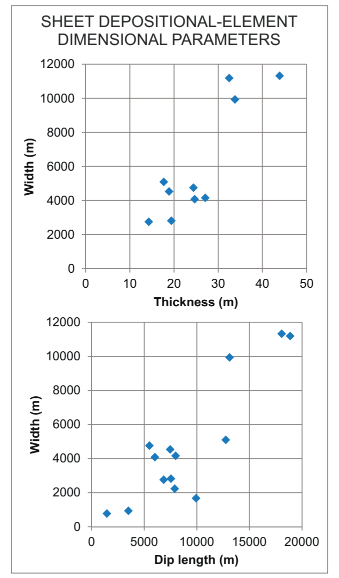
EXAMPLE *D-MAKS 2* OUTPUT

A PILOT CASE STUDY: THE PLEISTOCENE GOLO SYSTEM (CORSICA)

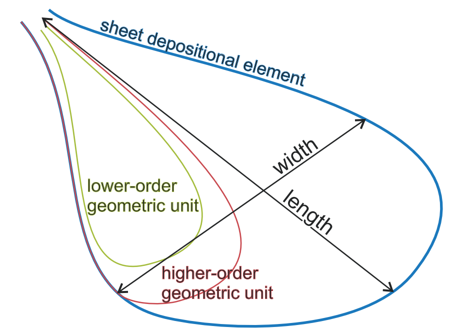


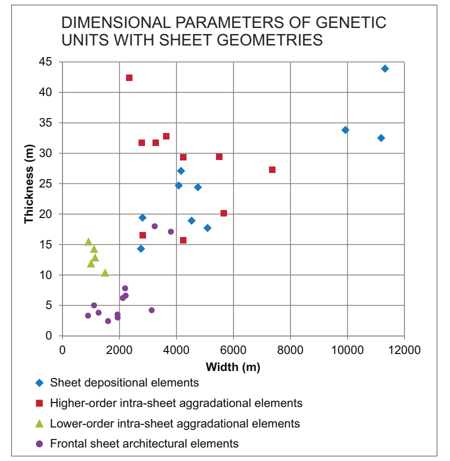
A few pilot case studies need to be added to the database as a preliminarily test of the consistency of genetic-unit defining criteria and the robustness of the devised data-entry practice; also, this provides a possibility to determine the feasibility of database interrogation as a way to obtain the expected output, in view of the differences in database design with respect to FAKTS.
Only one case study is currently included in D-MAKS 2: it consists in a dataset composed of 2D seismic lines and cores from the Pleistocene of the Golo Basin, on the eastern Corsican margin. All the papers containing data from the same dataset were considered (Gervais et al. 2006a; 2006b; Deptuck et al. 2008).

GENETIC-UNIT HIERARCHY AND DIMENSIONAL PARAMETERS



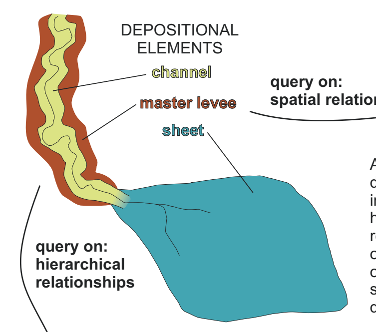
Similarly to FAKTS, D-MAKS 2 allows for the derivation of dimensional parameters associated with various hierarchical orders and classes of genetic units, readily permitting the investigation of relationships between geometrical parameters with which, for example, to aid subsurface predictions of sandstone lateral extent.
Importantly, D-MAKS 2 allows users to simultaneously consider information referring to both scale-dependent and scale-independent elements. To give a flavor of how this can be achieved, the scatter plot on the lower right reports the width and thickness of genetically-defined frontal-sheet architectural elements, in purple, and of sheet depositional elements, in blue, together with data from two orders of genetic units that are contained within sheet depositional elements and that sometimes also contain frontal-sheet architectural elements. These 'fractal-type' geometric units are also lobe-shaped and compensational but occupy intermediate hierarchical orders.

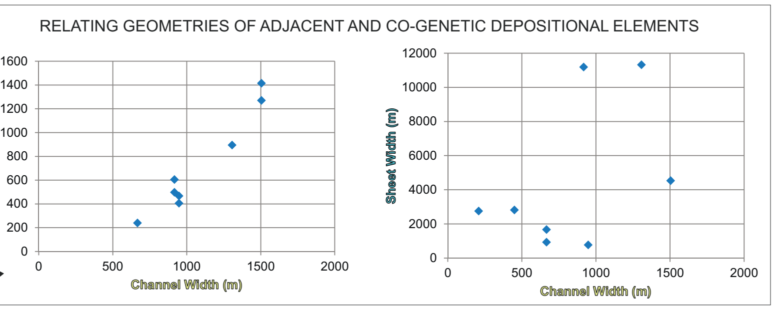




RELATING GEOMETRICAL PARAMETERS OF GENETICALLY-ASSOCIATED UNITS

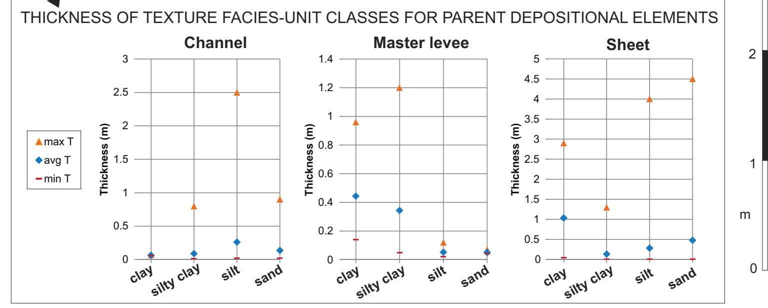
Similarly to FAKTS, D-MAKS 2 can be applied to the study of relationships existing between architectural properties associated with different but genetically-related sedimentary units. For example, information on the spatial relationships (adjacency) between sedimentary units and on the nature of associated bounding surfaces can be used to obtain database output with which to characterize co-genetic channel, master-levee and sheet depositional elements (see graphs on the right).

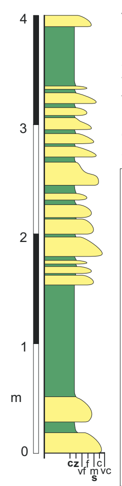


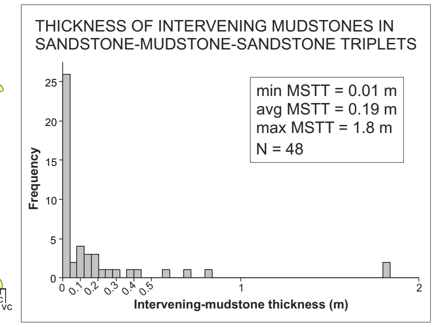


Also, to better characterize architectural styles, database output can be filtered exploiting information on the containment of a unit with its higher-scale parent genetic unit, or on the recognition of occurrence of a given type of lower-order unit within it. For example (see below), output on the thickness of facies units for different grain-size classes can be tailored on the types of depositional elements in which they occur.

As with FAKTS, by keeping track of spatial relationships between genetic units within a hierarchical level it is possible to query the database for rock volumes made of amalgamated genetic units that share a given attribute value (material units). More generally, it is possible to query the database for user-defined associations of sedimentary units, whose architecture can therefore be characterized quantitatively (e.g. statistics on thickness of mudstone sandwiched between two sandstones, see below).

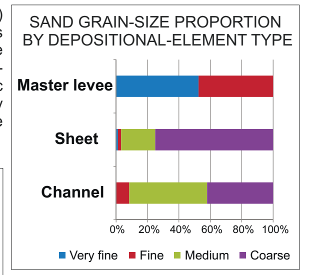


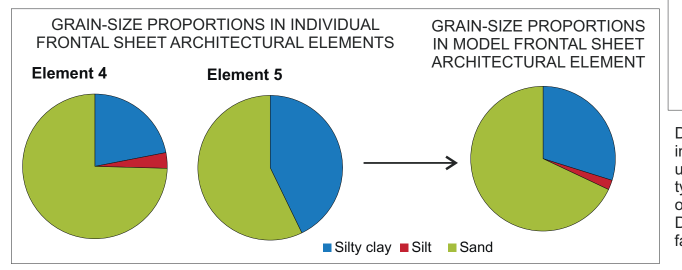




INTERNAL ORGANIZATION OF GENETIC UNITS

Just like for FAKTS, the internal organization of genetic packages can be characterized in terms of the objects belonging to lower-order scales that compose them.
Information on their composition is given by the relative volumetric proportions of their building blocks. For example, the internal composition of frontal-sheet architectural elements (as shown in the pie-charts below) or of types of depositional elements (as shown in the bar chart on the right) can be quantified in terms of proportions of facies-unit grain-size classes. Again, volumetric proportions can be estimated from variably combining genetic-unit occurrence frequencies with dimensional parameters.

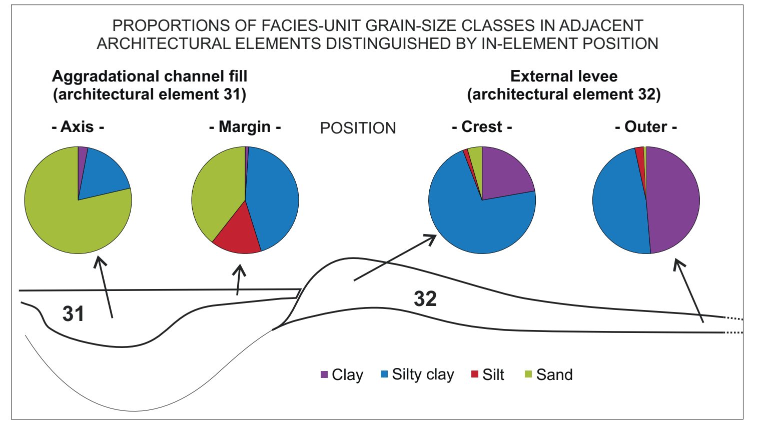




D-MAKS 2 permits deriving this type of information for either individual genetic units, or for models of given genetic-unit types, which are based on the synthesis of information from several units.
D-MAKS 2 effectively reconciles the facies model and analog approaches.

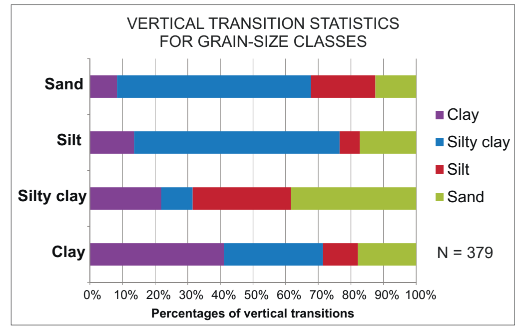
FACIES VARIABILITY WITHIN AND ACROSS GENETIC UNITS

As in FAKTS, database output can be derived to quantify the internal organization of spatially-related units (see example on the right).
However, differently from FAKTS, to account for the wider range of scales that deep-marine systems exhibit compared with fluvial ones, D-MAKS 2 keeps track of the spatial arrangement of facies-unit within different positions of the architectural elements: this means that the system enables a better characterization of lateral variations within the same element/sub-environment.



GENETIC-UNIT TRANSITION STATISTICS

Similarly to FAKTS, D-MAKS 2 can be queried to derive statistics that quantify spatial transitions between genetic units, in order to obtain a quantitative description of vertical or horizontal depositional trends. For example, the bar chart on the right reports facies-unit vertical transitions statistics relating grain-size classes from the Golo Basin cores.
To further characterize genetic units internally, transition statistics can be filtered so that only transitions observed within the type of depositional or architectural element investigated and across given bounding-surface types (i.e. gradational, sharp non-erosional, erosional) are taken into account.
To obtain meaningful 1D transition statistics, 2D- and 3D-dataset transitions can be filtered through a special query that performs random selections in order to force the sampling to be one dimensional.



CONCLUSIONS

The FAKTS and D-MAKS 2 databases are employed as systems for the digital reproduction of all the essential features of fluvial and deep-marine clastic sedimentary architecture. They account for the style of internal organization, geometries, grain size, spatial distribution, and the hierarchical and spatial reciprocal relationships of sedimentary units. The databases classify depositional systems – or parts thereof – according to both controlling factors and context-descriptive characteristics.
Upon interrogation, these databases return output consisting of user-defined sets of quantitative information on particular characters of sedimentary architecture, as derived from a suite of analogs, whose analogy to a particular reservoir can be considered in terms of architectural properties and/or depositional-system parameters.

The database output can be applied to fluvial and deep-marine reservoir characterization and prediction. The databases are meant to serve as tools with which to achieve the following primary goals:

- guide well correlation of fluvial and deep-marine sandstones;
- condition object- and pixel-based stochastic reservoir models;
- predict the likely heterogeneity of geophysically-imaged geobodies;
- inform interpretation of lithologies observed in core.

In addition, the databases will be employed as tools with which to pursue pure-science research questions.

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