PS A Relational Database for the Digitization of Fluvial Architecture: Toward Quantitative Synthetic Depositional Models*

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Abstract

Facies models for fluvial depositional systems aim to summarize the sedimentological features of a specific fluvial type (e.g. braided, ephemeral) through a process of distillation of several real-world examples, in order to provide conceptual frameworks that are straightforwardly applicable to subsurface prediction problems. However, such models are often based on few case studies and are qualitative in nature, thereby resulting in poor predictive power. Our aim is to generate quantitative depositional models for fluvial systems that are based on the synthesis of many different case histories and continuously refined by adding data when they become available.

A relational database for the storage of data relating to fluvial architecture has been devised, developed and populated with literature- and field-derived data from studies of both modern rivers and their ancient counterparts preserved in the stratigraphic record. The database scheme characterizes fluvial architecture at three different scales of observation, corresponding to many genetic-unit types (large-scale depositional elements, architectural elements and facies units), recording all the essential architectural features, including style of internal organization, geometries, spatial distribution and reciprocal relationships of genetic units. The database classifies datasets - either in whole or in part - according to both controlling factors (e.g. climate type, tectonic setting) and context-descriptive characteristics (e.g. river pattern, dominant transport mechanism). The data can therefore be filtered on the parameters according to which they are classified, allowing the exclusive selection of data relevant for the model.

To demonstrate the value of the approach, an example synthetic depositional model for braided fluvial systems in arid/semiarid basins is presented here, and some of its features are compared with analogous data from other settings. Resultant models are based on outcrop studies of the Permian Organ Rock Fm., Triassic Moenkopi Fm., Jurassic Kayenta Fm. (all from Utah), the Chester Pebble Beds Fm. and Helsby Fm. (both Cheshire Basin, UK), together with literature-derived data. In comparison to traditional facies models, the improved usefulness of synthetic models derived from this database approach to subsurface predictions is evident, as their quantitative content is particularly suitable to inform well-to-well correlations and to constrain stochastic reservoir models.

A relational database for the digitization of fluvial architecture: toward quantitative synthetic depositional models

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ABSTRACT

Facies models for fluvial depositional systems aim to summarize the sedimentological features of a specific fluvial type (e.g. braided, ephemeral) through a process of distillation of several real-world examples, in order to provide conceptual frameworks that are straightforwardly applicable to subsurface prediction problems. However, such models are often based on few case studies and are qualitative in nature, thereby resulting in poor predictive power. Our aim is to generate quantitative depositional models for fluvial systems that are based on the synthesis of many different case histories and continuously refined by adding data when they become available.

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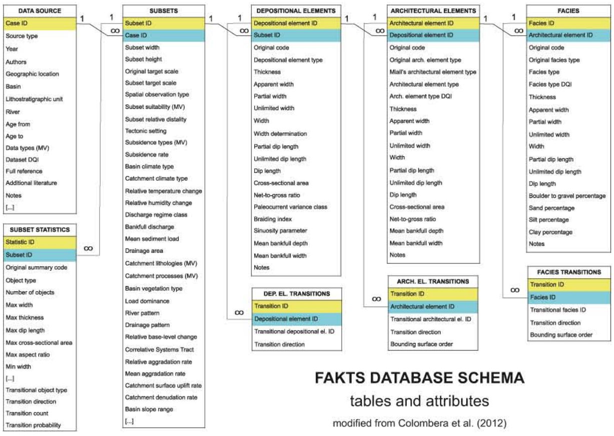
FAKTS DATABASE: overview

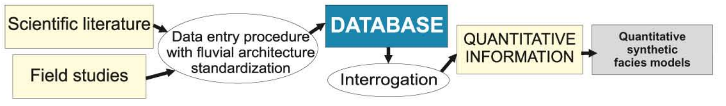


FAKTS DATABASE SCHEMA

tables and attributes

modified from Colombera et al. (2012)

Approach



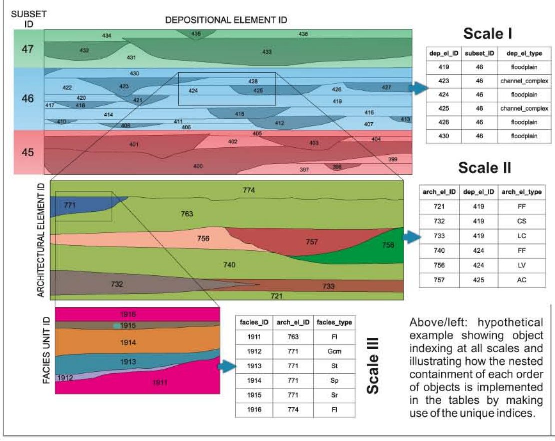
The **Fluvial Architecture Knowledge Transfer System** (FAKTS) is a relational database storing fluvial architecture data populated with literature- and field-derived case studies from modern rivers and ancient successions. The database scheme characterizes fluvial architecture at three different scales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

SCOPE Here we aim to demonstrate how FAKTS can be used to derive filtered quantitative information that can be used for the compilation of synthetic depositional models of fluvial architecture associated to specific system parameters; a relatively detailed model is presented for braided dryland fluvial systems, showing how some architectural features change through the intermediate steps of the filtering process.

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 implemented as subsets. In addition, FAKTS stores all the metadata that refer to whole datasets, describing the original source of the data and information including the methods of acquisition employed, the chronostratigraphic stages corresponding to the studied interval, the geographical location, the names of the basin and river or lithostratigraphic unit, and a dataset 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).

Multi-scale genetic-unit nesting

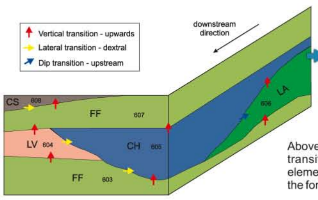


Above/left: hypothetical example showing object indexing at all scales and illustrating how the nested containment of each order of objects is implemented in the tables by making use of the unique indices.

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).

Genetic-unit transitions

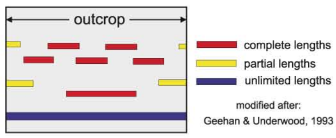


arch_el_ID	trans_el_ID	trans_direction	bound_surf_order
603	604	vertical	4th
603	605	lateral	5th
603	605	vertical	5th
603	606	vertical	5th
604	605	lateral	4th
604	607	vertical	4th
605	606	dip	4th
605	607	vertical	4th
606	605	vertical	4th

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.

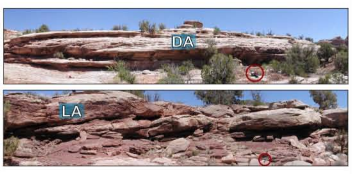
Rakaia River channel-belt (New Zealand.) From Google Earth™.

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.

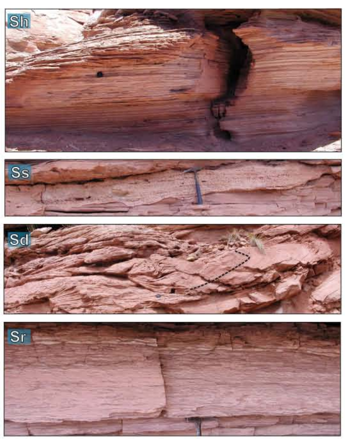


Above: example preserved architectural elements (DA and LA barforms) from the Lower Jurassic Kayenta Formation at Sevenmile Canyon (SE Utah, USA).

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

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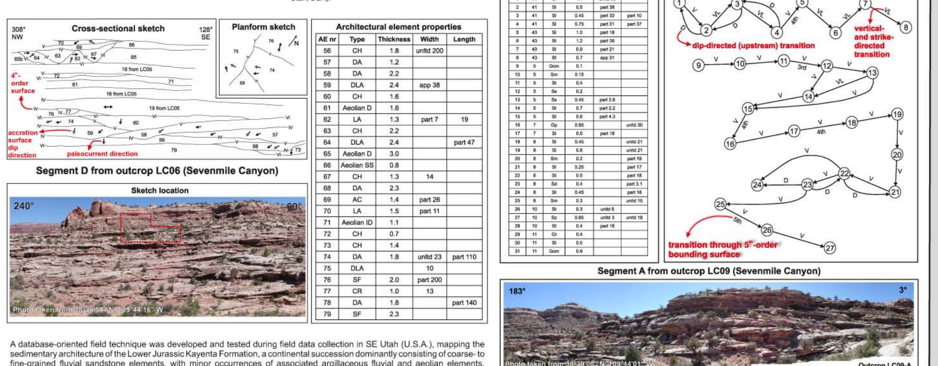
FIELD TECHNIQUES

Example fieldwork data-collection results from the Lower Jurassic Kayenta Formation at Sevenmile Canyon (SE Utah, USA).



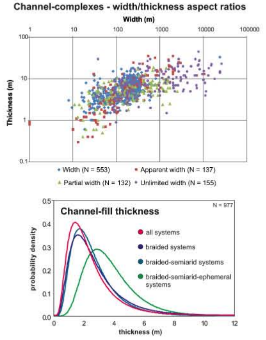
A database-oriented field technique was developed and tested during field data collection in SE Utah (U.S.A.), mapping the sedimentary architecture of the Lower Jurassic Kayenta Formation, a continental succession dominantly consisting of coarse- to fine-grained fluvial sandstone elements, with minor occurrences of associated argillaceous fluvial and aeolian elements, developed in the overall arid/semiarid climatic context of the Glen Canyon Group. Interpreted architectural elements were indexed by numeric identifiers, some of their properties (element type and dimensional parameters) were tabulated, and their spatial arrangement was sketched – in form of cross sectional and planform sketches – including bounding surface order (scheme by Miall, 1996) and paleocurrent information. Facies units were also indexed and their properties (facies type, dimensional parameters and identifier of the parent architectural element within which they occur) tabulated. As the number of facies units per outcrop is far larger than the number of architectural elements, the reciprocal relationships between facies units were not drawn as sketches but were instead depicted in transition diagrams, storing strike-, dip-, and vertical-directed transitions between facies units, including bounding surface order information. No scale or spatial significance is attached to the spatial distribution of the units – represented by circles coded according to the facies unit numeric identifiers – on the transition diagram in the figure above; the spatial relationships are exclusively expressed by means of arrows representing transitions along the indicated direction. So, similarly to what is done in the database itself, the unique numeric identifiers were used to keep track of the transitions between facies units and of the containment of facies units in architectural elements. The same type of transition diagram is applicable to the architectural element scale, and the 'table-and-diagram' approach is also applicable at the depositional element scale. In contrast to sedimentary logging or the construction of drawn architectural panels, this field technique does not generate standalone representations, such as those commonly expressed as drawn architectural panels. Rather, all the data required for database use are acquired in a more time-efficient manner in comparison to such traditional methods, with data recorded in a format that is well suited for coding into the database structure.

FAKTS OUTPUT 1: genetic-unit geometries

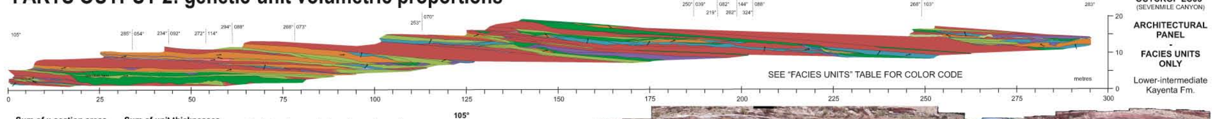
FAKTS can be queried in order to filter out the knowledge-base that is relevant to the synthetic model that one aims to generate, i.e. belongs to case studies with suitable boundary conditions.
In the first place, the FAKTS quantitative depositional model includes descriptors of dimensions and geometries of genetic units. FAKTS allows probability density functions of given dimensions or syntheses of aspect ratios for any genetic unit or genetic-unit type to be derived, choosing whether to include or not underestimated (partial and unlimited) and overestimated (apparent) dimensions.

Channel-complexes - width/thickness aspect ratios

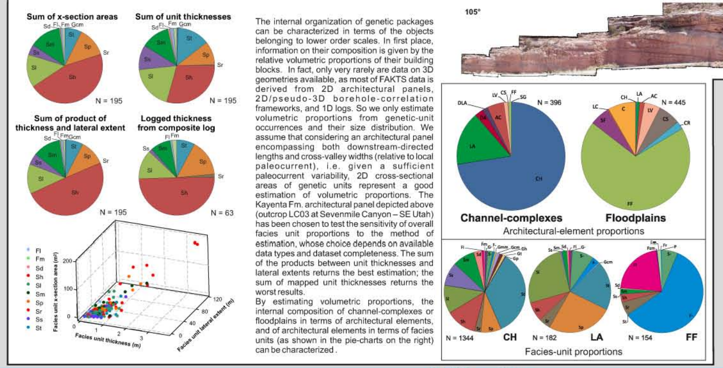
Channel-fill thickness



FAKTS OUTPUT 2: genetic-unit volumetric proportions

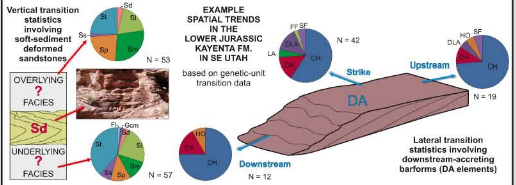


The internal organization of genetic packages can be characterized in terms of the objects belonging to lower order scales. In first place, information on their composition is given by the relative volumetric proportions of their building blocks. In fact, only very rarely are data on 3D geometries available, as most of FAKTS data is derived from 2D architectural panels, 2D/pseudo-3D borehole-correlation frameworks, and 1D logs. So we only estimate volumetric proportions from genetic-unit occurrences and their size distribution. We assume that considering an architectural panel encompassing both downstream-directed lengths and cross-valley widths (relative to local paleocurrent), i.e. given a sufficient paleocurrent variability, 2D cross-sectional areas of genetic units represent a good estimation of volumetric proportions. The Kayenta Fm. architectural panel depicted above (outcrop LC03 at Sevenmile Canyon – SE Utah) has been chosen to test the sensitivity of overall facies unit proportions to the method of estimation, whose choice depends on available data types and dataset completeness. The sum of the products between unit thicknesses and lateral extents returns the best estimation; the sum of mapped unit thicknesses returns the worst results.
By estimating volumetric proportions, 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 on the right) can be characterized.



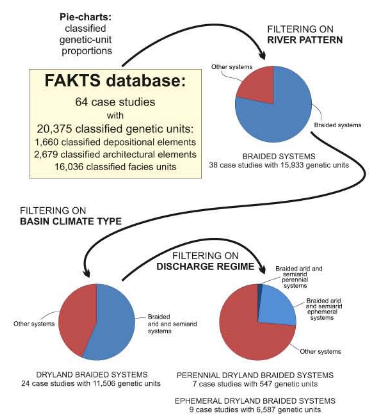
FAKTS OUTPUT 3: genetic-unit transition statistics

FAKTS can be interrogated to derive data on occurrences of transitions between genetic units, in order to obtain a quantitative description of spatial depositional trends in the form of a transition count matrix. 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.

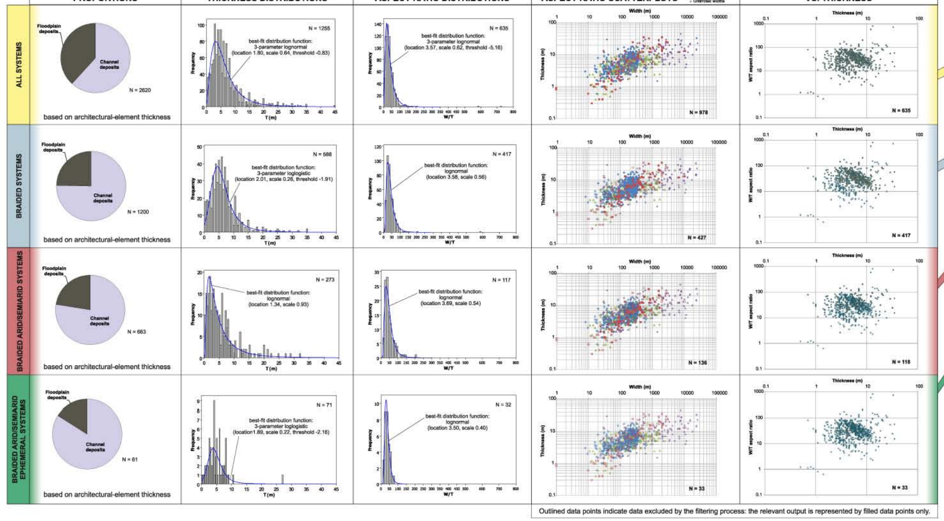


Braided arid/semiarid perennial systems	Sagavanirktok River	Tye (2004)
	South Saskatchewan River	FRG data – photointepretation
	Balfour Fm., Beaufort Gp.	Catuneanu & Elango (2001)
	Kayenta Fm.	Bromley (1991); Luttrell (1993)
	Ormskirk Sandstone Fm., Sherwood Sandstone Gp.	Meadows (2006)
	Sindong Gp.	Jo (2003)
Braided arid/semiarid ephemeral systems	Gash River	Abdullatif (1989)
	Thomson River (Cooper Creek)	FRG data – photointepretation
	Dinosaur Canyon Mb., Moenave Fm.	Olsen (1989)
	Kayenta Fm.	Miall (1988); North & Taylor (1996); Sanabria (2001)
	Mauch Chunk Fm.	Fillmore et al. (2010)
	Organ Rock Fm.	Cain (2009)
	Sindong Gp.	Jo (2003)
Braided arid/semiarid other systems	Salt Wash Mb., Morrison Fm.	Robinson & McCabe (1997)
	Kayenta Fm.	FRG data - fieldwork; Stephens (1994); Sanabria (2001)
	Bunter Pebble Beds (Chester Pebble Beds Fm. and Cannock Chase Fm.)	Steel & Thompson (1983)
	Omingonde Fm.	Holzförster et al. (1999)
	Hawksmoor Fm. and Hollington Fm. (Sherwood Sandstone Gp.)	FRG data - fieldwork
	Wilmslow Sandstone Fm. and Helsby Sandstone Fm., Sherwood Sst Gp.	FRG data - fieldwork
	Sherwood Sandstone Gp.	Cowan (1993)
	Westwater Canyon Mb. and Brushy Basin Mb., Morrison Fm.	Miall & Turner-Peterson (1989)
Braided other systems	Baghmati River	Friend & Sinha (1993)
	Brahmaputra (Jamuna) River	Bristow (1993); Best et al. (2003)
	Gandak River	Friend & Sinha (1993)
	Guarda Velha Fm.	Santos (pers. comm.)
	Majût Mb., Eriksfjord Fm.	Tirsgaard & Øxnevad (1998)
	Melka Kunture Fm.	Raynal et al. (2004)
	Middleton Fm. and Koonap Fm., Beaufort Gp.	Catuneanu & Bowker (2001)
	Olson Mb., Escanilla Fm.	Labourdette (2011)
	Oukaimeden Fm.	Fabuel-Perez et al. (2009a; 2009b)
	Rio Vero Fm.	Jones et al. (2001)
	Seglodden Mb., Båsnæring Fm.	Hjellbakk (1997)

CASE-STUDY FILTERING



DEPOSITIONAL-ELEMENT TYPE PROPORTIONS	CHANNEL-COMPLEX THICKNESS DISTRIBUTIONS	CHANNEL-COMPLEX WIDTH/THICKNESS ASPECT RATIO DISTRIBUTIONS	CHANNEL-COMPLEX ASPECT RATIO SCATTERPLOTS	CHANNEL-COMPLEX ASPECT RATIO VS. THICKNESS



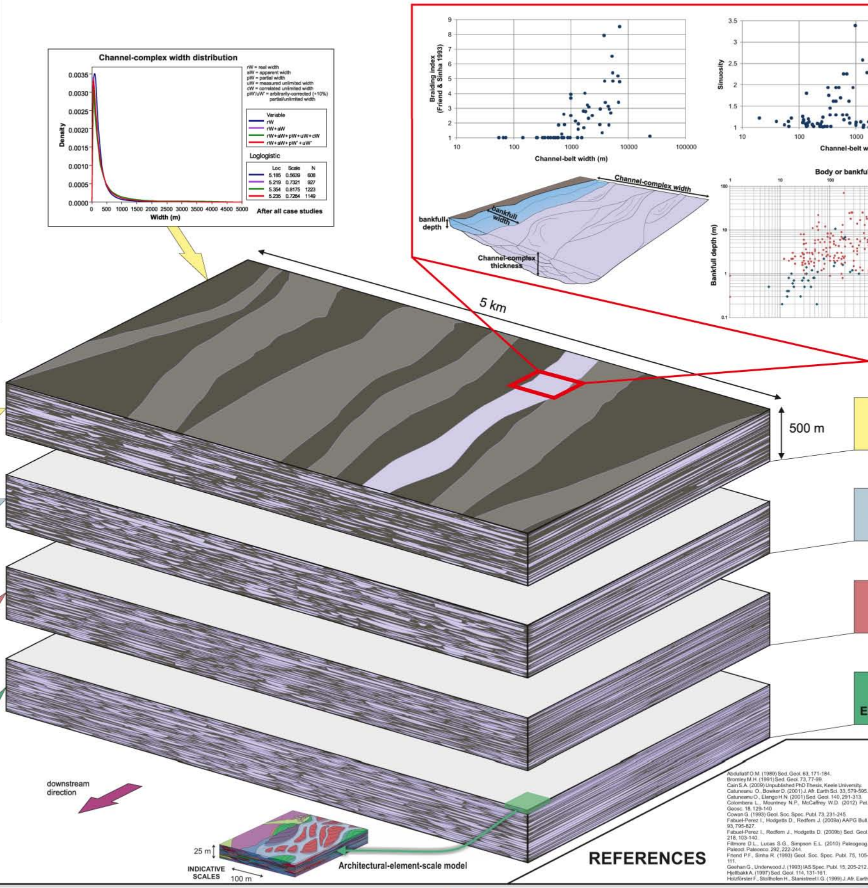
Outlined data points indicate data excluded by the filtering process: the relevant output is represented by filled data points only.

BLOCK-MODELS OF THE DEPOSITIONAL-ELEMENT-SCALE SEDIMENTARY ARCHITECTURE OF THE CHOSEN SYNTHETIC MODELS

The application of multiple filters to the data enables the generation – for every set of parameters – of synthetic models of fluvial depositional systems, which are represented by distinctive stacking patterns and lithosome geometries, modes of internal organization and reciprocal relationships, all of them referring to an ensemble of hierarchically-nested genetic units that are commonly recognized in fluvial systems (Colombera et al. 2012), integrating data from modern and ancient fluvial systems.

The ultimate goal is the infusion of quantitative data into otherwise qualitative facies models of fluvial sedimentary architecture.

At the largest scale, the architecture of the chosen synthetic fluvial systems is described in terms of depositional elements, categorized as channel-complexes or floodplain segments on the basis of geometrical criteria. Thus, at this scale, each model is fully characterized by depositional-element volumetric proportions, geometries and stacking patterns. Example models referring to systems associated to parameters on which the data were filtered are presented below.



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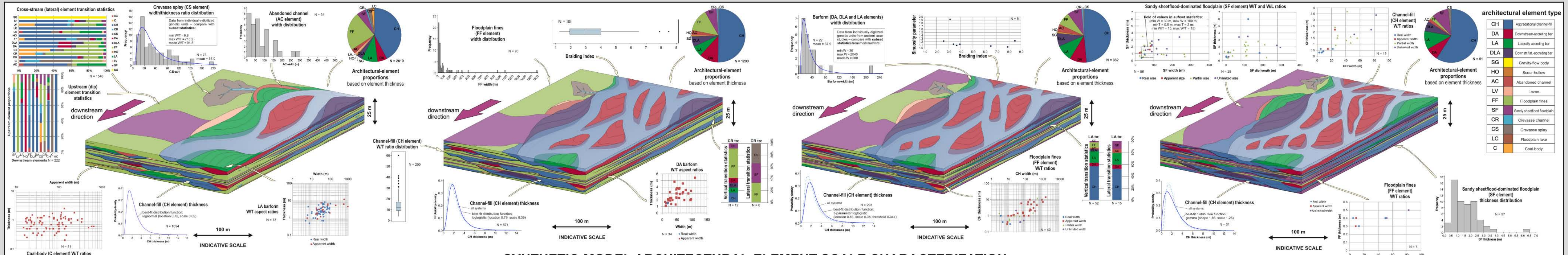
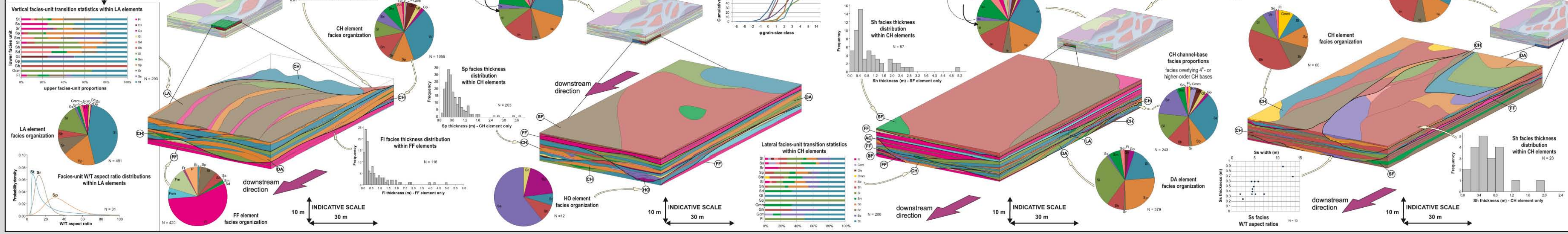


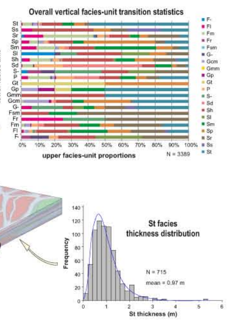
SYNTHETIC-MODEL ARCHITECTURAL-ELEMENT-SCALE CHARACTERIZATION

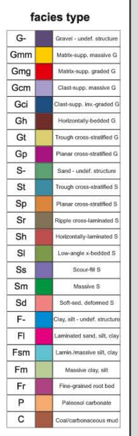
At an intermediate scale, model architecture is described in terms of architectural elements; the architectural characterization includes element proportions, geometries and juxtapositional trends.

At the smallest scale, model architecture is described in terms of facies units; the architectural characterization includes lithofacies proportions, geometries, grain size distribution and juxtapositional trends, referring to either the **whole model** or to **individual architectural elements**.

SYNTHETIC-MODEL FACIES-UNIT-SCALE CHARACTERIZATION



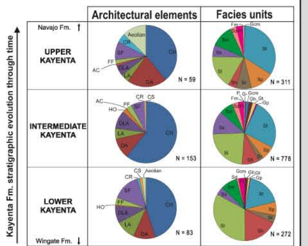


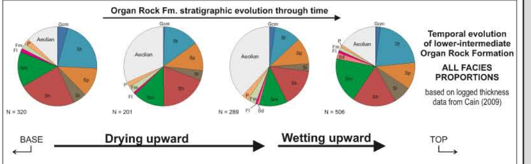


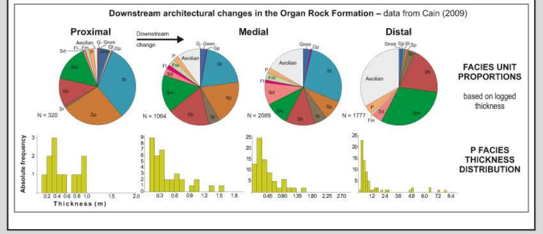
The example information referring to a quantitative facies model for braided ephemeral dryland river systems presented here is only meant to illustrate the approach: FAKTS does not currently have enough stored data referring to these systems to enable us to derive a fuller model characterization.
The scope of these illustrations is simply to show the potential of this database approach for the generation of quantitative facies models. The main strengths of this method are its multi-scale and quantitative nature, the capability to obtain a true objective integration of different case studies and the possibility to filter models on many different boundary conditions, describing internal context-descriptive parameters (e.g. braided systems) and external controls (e.g. climate type).
Although FAKTS allows the simultaneous use of different classifications for the same genetic unit, FAKTS' major drawback probably lies in the interpretative character of its building blocks.

CHARACTERIZATION OF THE TEMPORAL AND SPATIAL EVOLUTION OF FLUVIAL SYSTEMS

FAKTS is able not only to derive a range of information that collectively defines quantitative facies models of fluvial systems, but also to derive information on the temporal and spatial evolution of architectural features from individual case studies, as the data can be stored in relative temporal and spatial frameworks.
Performing quantitative comparative studies between different systems can reveal general spatial and temporal trends for similar systems (e.g. variations in architectural features associated to proximal-to-distal changes, timing of architectural variations associated to autogenic fluvial-fan progradation).
The examples provided here relate architectural changes to the temporal and spatial evolution of the Lower Jurassic Kayenta Fm. and the Permian Organ Rock Fm. from SE Utah (USA). Importantly, the possibility to classify each stratigraphic segment according to boundary conditions interpretable as external controls on fluvial systems (e.g. relative basin humidity in the example below) and their resulting architecture permits tentative discrimination between autogenic evolution and allogenic forcing. The quantitative evaluation of the sensitivity of fluvial architecture to changes in its controlling factors is also a far-reaching objective of the FAKTS project.







CONCLUSIONS

Here we have demonstrated how the FAKTS database can be employed for the generation of quantitative depositional models of fluvial systems. As these models describe the sedimentary architecture of fluvial systems in terms of occurrence, proportions, distribution, geometry and spatial relationships of genetic bodies, a database-derived model is entirely analogous to a traditional facies model. However, a number of advantages stem from this approach, the main ones include:
I) the **quantitative nature** of the architectural information associated to each model;
II) the construction of the model on a standardized set of **hierarchically-nested genetic units**, which facilitates comparisons between different models;
III) the **objective integration of different case histories**, by filtering data on the suitable attributes describing boundary conditions and qualifying dataset appropriateness for providing a given type of information.
Database-informed quantitative depositional models are expected to have higher predictive power, as some of the main drawbacks of traditional facies models (e.g. qualitative nature, end-member models based on individual studies) are overcome.

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A relational database for the digitization of fluvial architecture: toward quantitative synthetic depositional models

FRG

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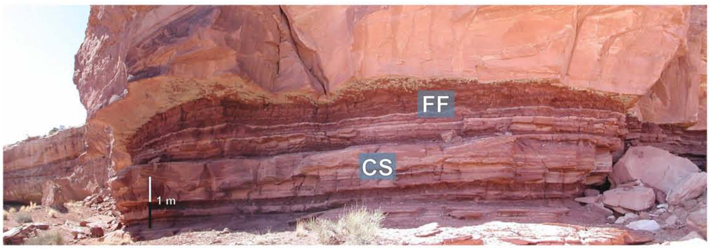
EXAMPLE ARCHITECTURAL STYLES FROM THE JURASSIC KAYENTA FORMATION AND THE PERMIAN ORGAN ROCK FORMATION (SE UTAH, USA)

Above: Kayenta Fm. at Sevenmile Canyon (SE Utah).

Below: Organ Rock Fm. at Indian Creek (SE Utah).



Architectural elements from the Lower Jurassic Kayenta Fm. at Sevenmile Canyon (SE Utah).

Sheetflood-dominated (and partially aeolian) distal portion of the Organ Rock Fm., at Farley Canyon (SE Utah).

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