Signature of controlling factors on the large-scale architecture of fluvial depositional systems: a comparative study

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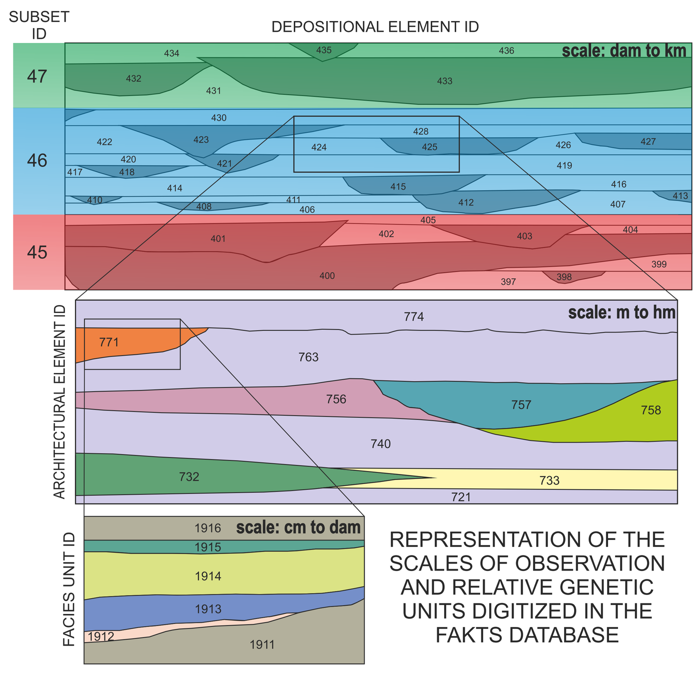
The proportion, size, geometry, distribution and clustering of channelized geobodies in fluvial sedimentary systems are related to a range of variables (e.g. subsidence rates, frequency and magnitude of base-level changes, sediment-supply rates, avulsion rates), which are themselves controlled by system boundary conditions (e.g. tectonic setting, prevalent climatic regime within both basin and catchment, catchment geology). Models of channel stacking patterns based on field observations attempt to qualitatively describe the relationships between controls and stratigraphic products, most often in a sequence stratigraphic framework. As the effect of individual controls cannot be isolated in the stratigraphic record in the absence of reliable constraints, numerical models or analogue physical models are commonly employed to investigate the sensitivity of architectural features to each single parameter. However, numerical models are limited by the choice of the boundary conditions that are thought to control system evolution, likely resulting in biased results. By contrast, physical models are subject to scaling problems.
Here we present results of a project based on the collation of architectural data from ancient and modern fluvial depositional systems into a relational database, which stores hard and soft data referring to genetic units organized in a hierarchical scheme. At the largest scale, the system characterizes fluvial architecture in terms of depositional elements classified as channel-complexes or floodplain elements; the segmentation of stratigraphic volumes into these units is established on the basis of clear-cut, although flexibly applied, geometrical criteria. Stratigraphic volumes are then classified on a range of attributes describing environmental parameters (e.g. relative distality, drainage pattern type) and several orders of controls (e.g. subsidence rates, tectonic setting). One of the principal aims of implementing this database approach is to establish a method for the determination of the relative role played by each controlling parameter in determining resultant fluvial sedimentary architecture.
The database includes real-world case studies, and each of them is subject to several controls (e.g. subsidence rate) and linked dependent variables (e.g. aggradation rate), typically resulting in complex overprints and feedback mechanisms. Since for each case history these variables are only partially classified in the database system, due to a lack of constraints on part of the boundary conditions of the included case studies, the objective assessment of the sensitivity of each studied fluvial system to individual controls is not possible. However, the quantitative evaluation of architectural changes can yield evidence of the dominant controls if a large number of partially-classified datasets are available for performing comparative studies. Large-scale architectural characters are then presented for different systems, in terms of channel-complex proportions and geometry, highlighting commonalities and differences existing between systems having different environmental parameters and external controls. Additionally, given that three orders of genetic units are hierarchically stored in the database (depositional elements, architectural elements and lithofacies), geometrical characters can be linked to the internal organization of the depositional elements, which can be internally characterized in terms of lower-order genetic units. Thus, it is possible to quantify the multi-storey or multi-lateral character of fluvial channel-complexes, recognizing the clustering of channel-fills and barforms that compose them. Moreover, as genetic-unit transitions are also stored, it is additionally possible to identify and quantify spatial trends (e.g. floodplain extent between two channel-complexes, style of vertical stacking of channel-complexes and nature of their lateral offset). Thus, this database approach is enabling the improved quantification of channel-complex connectivity, an important consideration in reservoir modelling.

DATABASE, AIMS AND METHOD

The **Fluvial Architecture Knowledge Transfer System** (FAKTS) is a relational database devised as a tool for translating numerical and descriptive data and information about fluvial architecture coming from fieldwork and peer-reviewed literature, from both modern rivers and their ancient counterparts in the stratigraphic record. The stratigraphy and the geomorphology of ancient successions and modern rivers are translated into the database schema in the form of genetic units belonging to different scales of observation, nested in a hierarchical fashion. Each order of unit is assigned a different table and each object within a table is given a unique numerical identifier that is used to keep track of the relationships between the different objects, both at the same scale (transitions) and also across different scales (containment). Each single dataset is split into a series of stratigraphic windows called subsets that are characterized by homogeneous attributes, such as internal and external controls. Thus, the database scheme records all the major features of fluvial architecture, including style of internal organization, geometries, spatial distribution and reciprocal relationships of genetic units, classifying datasets – either in whole or in part – according to both controlling factors such as climate type and tectonic setting, and context-descriptive characteristics (e.g. channel/river pattern, dominant transport mechanism).
A more detailed description of FAKTS structure is given in Colombera et al. (2012).

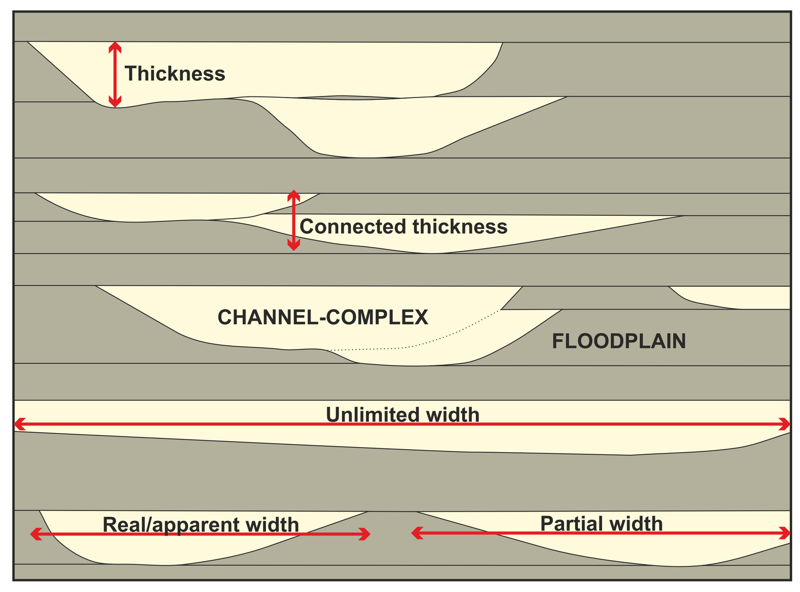


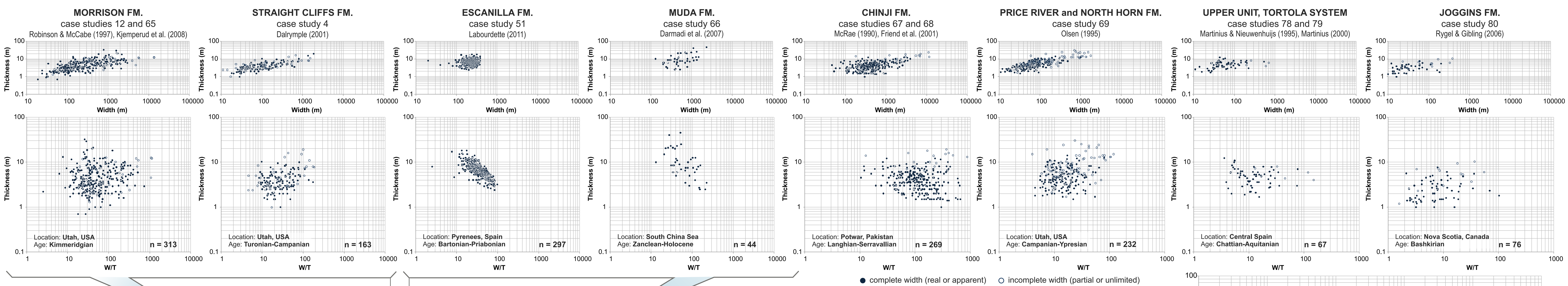
REPRESENTATION OF THE SCALES OF OBSERVATION AND RELATIVE GENETIC UNITS DIGITIZED IN THE FAKTS DATABASE

The general approach to the segmentation of alluvial architecture at the largest scale involves picking and indexing channel bodies, then breaking up the remaining floodplain deposits in floodplain objects that are juxtaposed to the channel bodies in a spatially coherent way. Large-scale depositional elements are classified as channel-complexes or floodplain segments and are distinguished on the basis of geometrical rules; the application of these rules is generally flexible, as the criteria devised for defining these objects may sometimes be difficult to apply due to data of both geometrical and geological nature that may be missing: such difficulties are recorded by data-ranking, data-type and target-scale attributes. In addition, these criteria cannot be followed altogether when data are derived from only summary results; this form of uncertainty is recorded by a data-ranking attribute. The geometry of FAKTS depositional elements is described by thicknesses, cross-gradient widths and downstream lengths; widths and lengths are classified as real, apparent, partial or unlimited (Geehan & Underwood 1993), as some observations are truncated at one limit of the observation window (partial lengths), whereas others at both ends (unlimited lengths).

FAKTS can be employed for the purpose of **assessing the sensitivity of fluvial architecture to its controls and quantifying relationships between associated architectural features**. Here we aim to investigate the architectural characters displayed by fluvial systems at the largest scale, described by FAKTS depositional elements. Thus, fluvial architecture is here characterized by the proportion, geometry and stacking pattern of channel-complex and floodplain depositional elements, and these characters are presented in the form of compilations from stratigraphic volumes (subsets) that are likewise classified by attributes describing system controls or descriptive parameters.

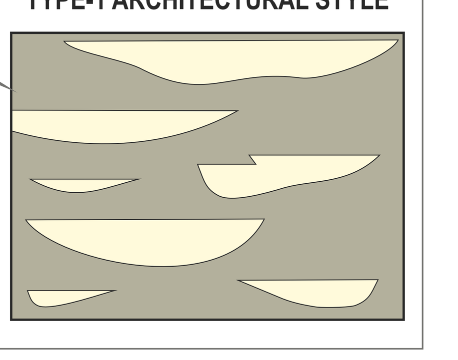
IDEALIZED PANEL EXEMPLIFYING GEOMETRICAL DEFINITION OF DEPOSITIONAL ELEMENTS AND DIMENSIONAL-PARAMETER TERMINOLOGY



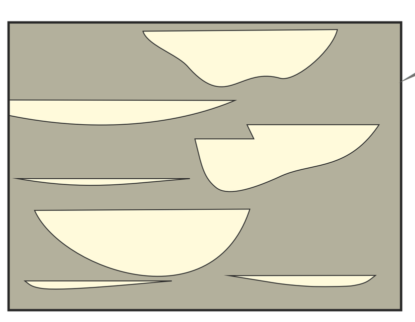


The large-scale architectural style of most of the systems is characterized by either not showing any clear correlation between the W/T aspect ratio and the thickness of the channel-complexes occurring in them, or by showing a very weak positive correlation, resulting in channel-complexes with a subtle tendency to display higher aspect ratios when thicker.

TYPE-1 ARCHITECTURAL STYLE



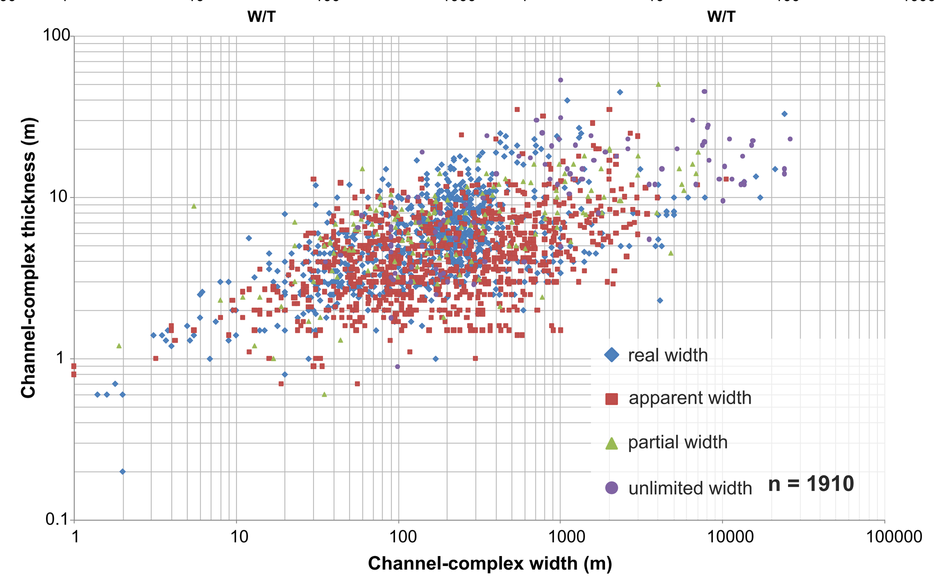
TYPE-2 ARCHITECTURAL STYLE

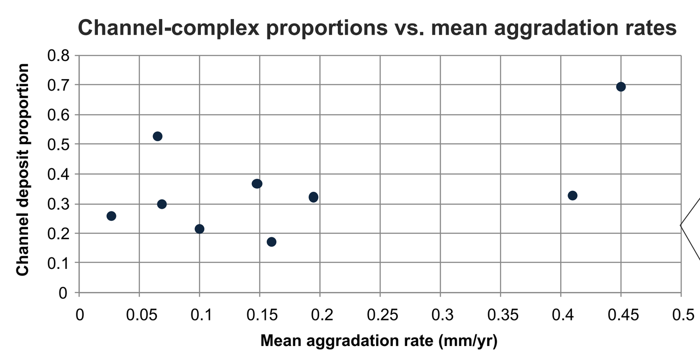


An alternative architectural style displaying a negative correlation between the W/T aspect ratio and the thickness of the channel-complexes may be possibly related to the topographic control on channel-belt extension and clustering, likely determined by degradation driven by tectonic activity in the Escanilla Fm. and by base-level falls in the Muda Fm.

CHANNEL-COMPLEX GEOMETRY: WIDTH/THICKNESS ASPECT RATIOS

A simple description of channel-body geometry is given by their width/thickness aspect ratios. FAKTS channel complexes can be considered as large-scale flow units, and their geometry can provide a first-order description of the geometrical heterogeneity of analogue reservoirs or aquifers. Also, analysing the behaviour of channel-complex geometry under different system boundary conditions may provide information on the dominant controls on large-scale fluvial architecture.

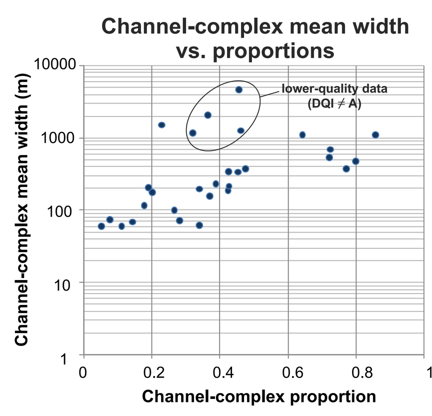


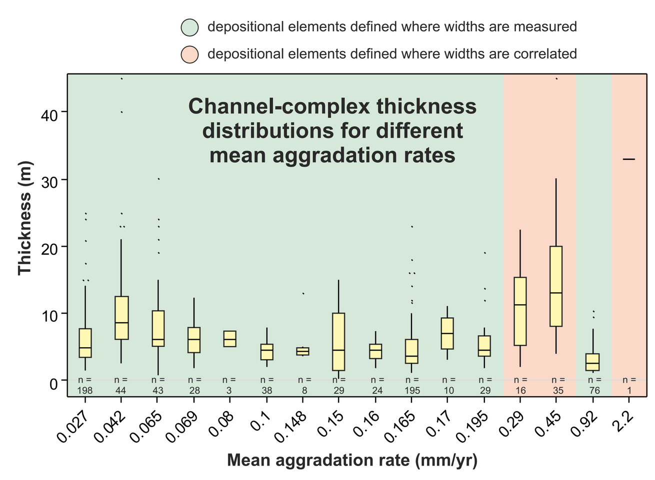


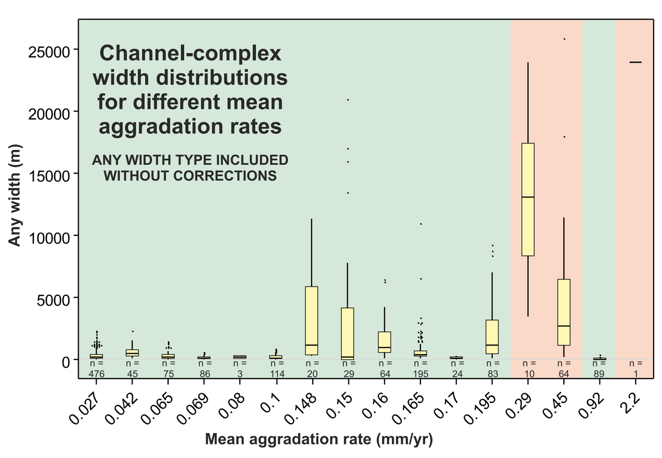
RESULTS 1: AGGRADATION RATES

Conceptual models for the evolution of large-scale fluvial architecture consider architectural changes as resulting from variations in the ratio between sediment supply and the rate of accommodation space creation (function of water discharges, sediment supply, subsidence/uplift, base-level changes); channel-belt lateral migration and avulsion are partially related to such controls and they can interfere in complex ways. Existing models describe architectural variations in terms of channel-body proportions, geometry and stacking pattern, in a floodplain background.
Aggradation rates are relatively easily estimated, and they are deemed to be directly proportional to the availability of accommodation space. A limitation in the results presented here is that aggradation rates are averaged over different time-scales for different stratigraphic volumes.

Several models predict a decrease in channel-deposit proportions with increasing accommodation and aggradation rates. Such a trend is not identifiable in FAKTS data derived from high-quality datasets, derived from 2D panels allowing proportions to be computed from the product of channel-complex thickness and width. This result agrees with observations by Ashworth et al. (1999), and, if further substantiated by data from other systems, may demonstrate that aggradation rate (or its changes) constitutes a poor predictor for the sedimentary architecture of fluvial systems (or its changes), maybe suggesting that such variations in fluvial architecture are variably sensitive to the controls to the changes in aggradation rates; e.g. an increase in accommodation availability dictated by a reduction in fluid discharge might influence channel migration or avulsion rates (and consequently proportions) differently to a rise in base level or increase in solid supply.

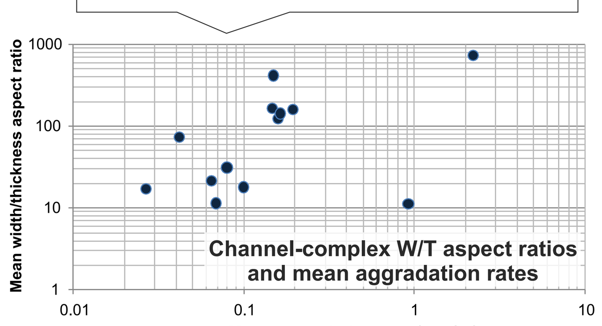


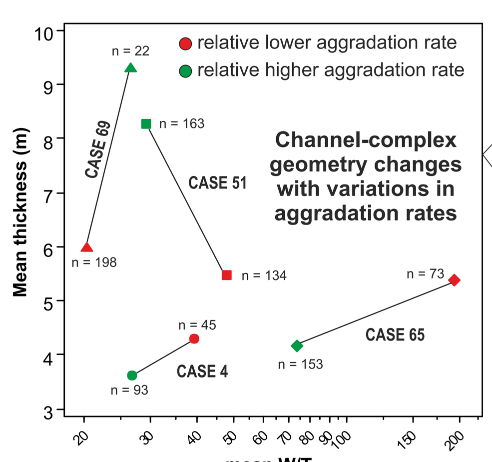




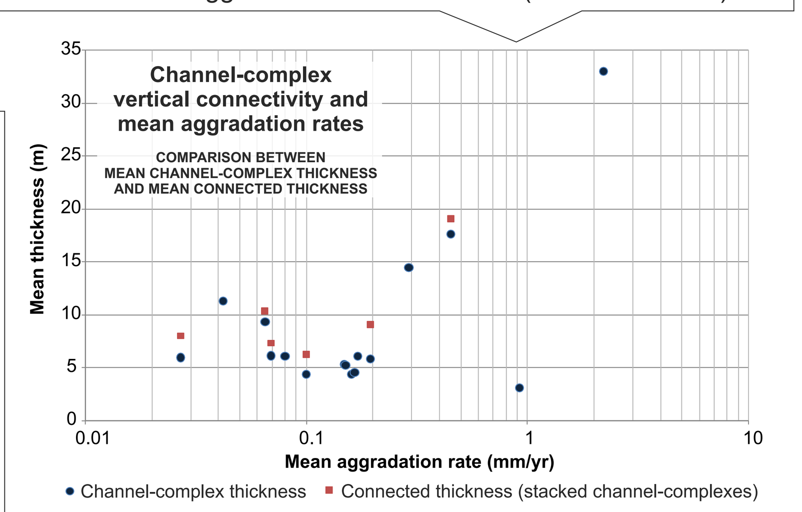
Since the juxtaposition between genetic units is stored in the form of transitions, FAKTS allows the recognition of channel complexes in touch with each other, therefore channel-complex stacking patterns and connectivity in the vertical, cross-gradient and down-gradient directions can be quantified. For example we can define a *connected thickness* as the sum of individual thicknesses in a series of stacked channel-bodies that are geometrically defined as different channel complexes. A strong positive correlation between connected thickness and aggradation rate is observed (Pearson r = 0.90).

A trend of increasing W/T with increasing aggradation rate is observed, showing a fairly strong positive correlation (Pearson coefficient r = 0.76).

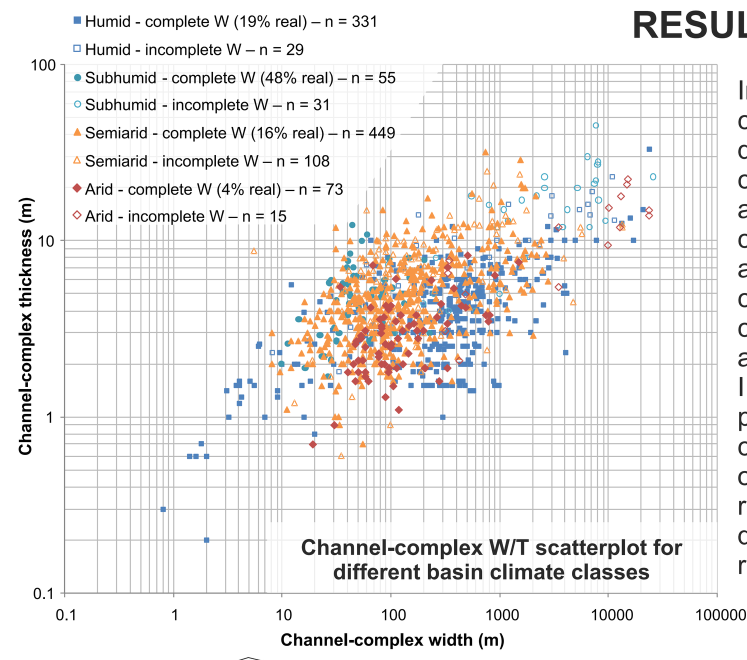




FAKTS enables the evaluation of the architectural evolution across stacked stratigraphic volumes subject to changes in controls or systems variables that can be expressed in terms of relative variations.
The four examples shown do not demonstrate any concordant change in channel-complex mean thickness or mean W/T ratio, as compared to adjacent volumes with different aggradation rates.

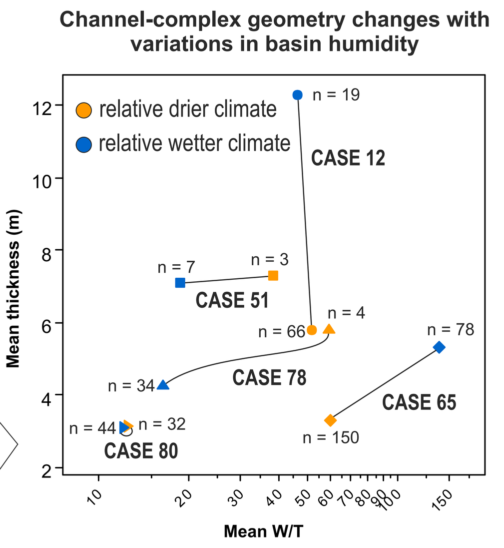


RESULTS 2: BASIN CLIMATE TYPE



Information concerning basin and catchment climate types are separately stored in the database. However, information on catchment climate is seldom available for ancient case histories, and very rarely it is coupled with an estimate of the catchment areal extent, on which a multivariate comparative study aiming at detecting a climatic signature in large-scale fluvial architecture could possibly be based.
In addition, limitations in the results presented here are given by (i) the fact that climate types for ancient systems are based on proxies having a variable degree of reliability (ranked by FAKTS using data-quality indices), and (ii) the fact that climate regime classes may be the result of averaging over different time scales.

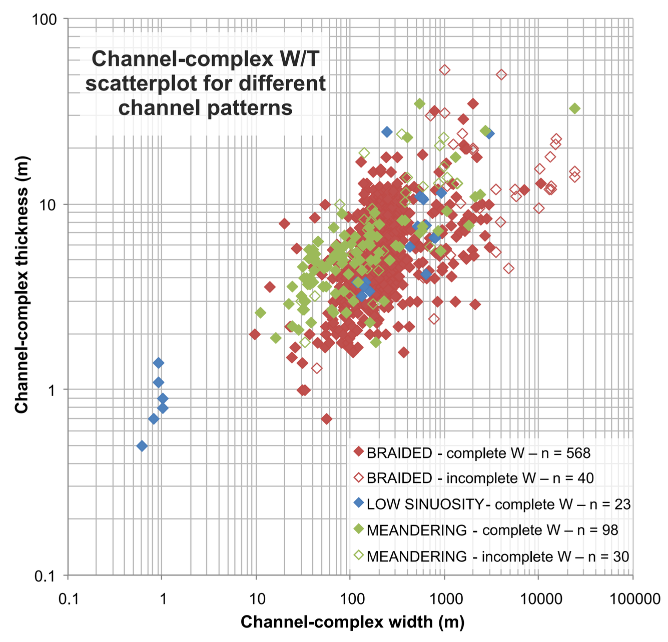
Although the climatic regime of the basin is also known to exert an important control on fluvial architectural features, no trend is identifiable from wetter to drier systems for channel-complex geometries, although different data distributions – probably due to other overriding controls, less likely connected to different climate-related hydrological or sediment-delivery behaviours – can be recognized.

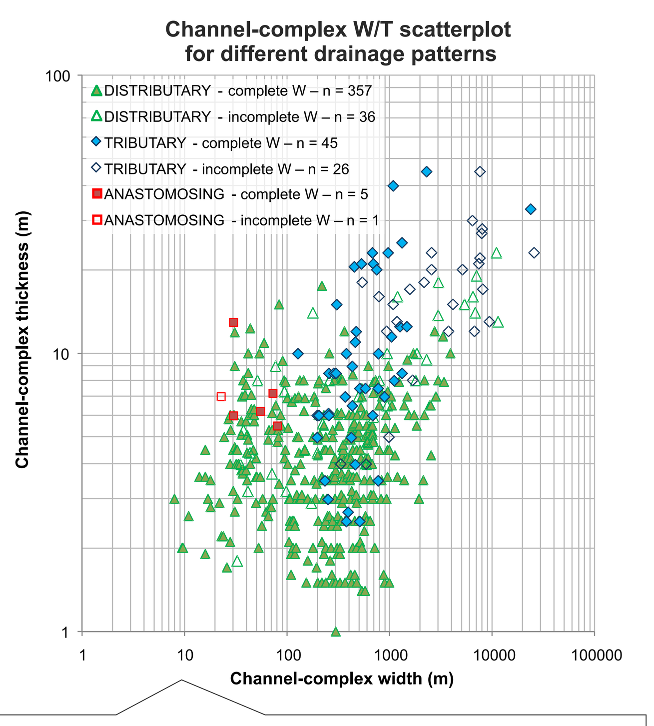


FAKTS records relative changes in basin humidity whenever they are observed across stratigraphic volumes. The five examples shown on the right show divergence, as they do not demonstrate any concordant change in channel-complex mean thickness or mean W/T ratio, when comparing adjacent volumes with different basin humidity.

RESULTS 3: CHANNEL AND DRAINAGE PATTERNS

Channel-complex geometries are likely related to the modes of clustering of channel belts in fluvial systems and to the geometrical nature of the channel-belts themselves.
Channel complexes of systems with braided channel patterns appear to be on average thicker and wider than channel-complexes from meandering systems.
However, FAKTS case studies from braided systems have a higher proportion of channel deposits than their meandering counterparts (67% against 35% as based on depositional-element proportions).





The three different populations of channel-complex geometry according to system drainage pattern are characterised by distinctive data distributions; channel-complexes in distributary systems have generally smaller mean width and thickness and have a higher variance in width, in comparison to tributary systems.
Systems with distributary patterns include deltaic systems; some ancient systems interpreted and classified by the authors as distributary may actually be fluvial fans characterized by having a radial distribution of channel-belts emanating from the apex and controlled by nodal avulsions, instead of a true distributary drainage pattern (North & Warwick 2007).

CONCLUSIONS

The FAKTS database now includes a significant amount of architectural data, but its application to improve our understanding of the sensitivity of large-scale fluvial architecture to different controls is restrained by several limitations:

1) datasets consisting of compilations of numerical geometry data do not allow geometrical criteria to be checked, making data comparison less reliable; such data can anyway be excluded by filtering on Data Quality Index;
2) interpretations may be based on weak proxies or incorrect; many case studies are poorly understood in terms of system boundary conditions, limiting studies aimed at the comprehension of the dynamics of sedimentary architecture;
3) some boundary conditions (e.g. aggradation rates, basin humidity) may have varied through time significantly and at high frequency, thus rendering average values non-indicative; in addition, such values may have been averaged over different time-scales.

Although this tells us that results must be applied with caution, some interesting outcomes are nevertheless observed:

1) different systems show marked differences in the geometry of fluvial channel complexes, highlighting the **importance of choosing the best analogues** to subsurface systems;
2) **no evidence is seen to support some existing models** relating channel-complex proportions, widths and vertical connectivity to aggradation rates;
3) channel-complex **geometry classified according to channel and drainage patterns shows distinctive populations**.

Multivariate analysis would ideally be applied provided that sufficient case studies with well-constrained boundary conditions become available.

REFERENCES

Ashworth P.J., Best J.L., Peakall J., Lorsong J.A. (1999) IAS Spec. Publ. 28, 333-346.
Colombera L., Mountney N.P., McCaffrey W.D. (2012) Petr. Geosc. 18, 129-140.
Dalrymple M. (2001) Petr. Geosc., 7, 115-122.
Darmadi Y., Willis B.J., Dorobek S.L. (2007) J. Sed. Res. 77, 225-238.
Friend P.F., Raza S.M., Geehan G., Sheikh K.A. (2001) J. Geol. Soc. 158, 163-177.
Geehan G., Underwood J. (1993) IAS Spec. Publ. 15, 205-212.
Kjemperud A.V., Schomacker E.R., Cross T.A. (2008) AAPG Bull. 92, 1055-1076.
Labourdette R. (2011) AAPG Bull. 95, 585-617.
Martinius A.W. (2000) J. Sed. Res. 70, 850-867.
Martinius A.W., Nieuwenhuijs R.A. (1995) Petr. Geosc. 1, 237-252.
McRae L.E. (1990) Jour. Geol. 98, 433-456.
North C.P., Warwick G.L. (2007) J. Sed. Res. 77, 693-701.
Olsen T. (1995) NPF Spec. Publ. 5, 75-96.
Robinson J.W., McCabe P.J. (1997) AAPG Bull. 81, 1267-1291.
Rygel M.C., Gibling M.R. (2006) J. Sed. Res. 76, 1230-1251.

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