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A meta-study of relationships between fluvial channel-body stacking pattern and aggradation rate: Implications for sequence stratigraphy

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ABSTRACT

A quantitative comparison of 20 literature case studies of fluvial sedimentary successions tests common assumptions made in published models of alluvial architecture concerning (1) inverse proportionality between channel-deposit density and floodplain aggradation rates, and (2) resulting characteristics of channel-body geometries and connectedness. Our results do not support the relationships predicted by established stratigraphy models: the data suggest that channel-body density, geometries and stacking patterns are not reliable diagnostic indicators of rates of accommodation creation. Hence, these architectural characteristics alone do not permit the definition of accommodation-based 'systems tracts' and 'settings', and this calls into question current sequence stratigraphic practice in application to fluvial successions.

INTRODUCTION

The proportion, geometry and spatial distribution of sedimentary bodies produced by in-channel deposition in fluvial successions are often cited to be dependent on floodplain aggradation rate, based on the assumption that slower rates of aggradation facilitate floodplain reworking by migrating and avulsing rivers (Allen 1978; Bridge and Leeder 1979). Consequently, channel-body density is commonly expected to inversely correlate with aggradation rate, thereby also affecting the geometry and connectedness of channel deposits. These assumptions are often made on the basis of results from a suite of numerical models known as the Leeder-Allen-Bridge (LAB) models of alluvial architecture (Leeder, 1978; Allen 1978; Bridge and Leeder 1979).

Because results from the LAB models have been incorporated into influential sequence-stratigraphy models (e.g., Wright and Marriott, 1993; Shanley and McCabe 1994), these tenets dominate thinking in fluvial sequence stratigraphy . The distinction of 'low-accommodation' versus 'high-accommodation' systems tracts in fluvial successions is routinely undertaken based solely on the degree of channel amalgamation (Catuneanu et al., 2009).

More generally, the LAB model concepts have had a significant impact on rock-record interpretations. As aggradation rates are intimately linked with lithospheric kinematics, eustastic fluctuations and catchment processes, obtaining a validation or rejection of assumptions commonly made by advocating the LAB models has profound implications, for example on the appropriateness of the use of stratigraphic variations in channel-body characteristics as proxies for absolute sea-level change or variations in subsidence rates.

Thus, it is important to test the expected relationships between aggradation rate and channel-body density, geometry and stacking pattern in the rock record. To perform a meaningful test of the expected responses, 20 field examples have here been compared with respect to the proportion, geometries and vertical connectivity of channel deposits, for different values of aggradation rate and under different conditions of change in aggradation rates.

METHODS

A comparative study is undertaken based on literature-derived data collated from 20 ancient fluvial depositional systems into a relational database – the Fluvial Architecture

Knowledge Transfer System (FAKTS) – which digitizes classified sedimentary units in a hierarchical scheme (Colombera et al., 2012; supplementary material). At the largest scale of observation FAKTS characterizes fluvial architecture in terms of units termed 'depositional elements' and classified as 'channel complex' or 'floodplain' units, depending on the interpreted origin of their deposits. Geometric attributes are used to characterize each individual depositional element, and the spatial relationships between each of them are stored in the form of transitions (e.g., unit 2 vertically stacked on unit 1; unit 3 updip of unit 4). The subdivision of stratigraphic volumes into depositional elements is based in part upon the application of geometric criteria; this provides a way to assign amalgamated channel bodies objectively into discrete units (see supplementary material). The floodplain domain is subdivided into geometric packages that vertically and laterally neighbor the channel complexes.

Within the database, stratigraphic volumes to which depositional elements belong are classified on several attributes, of which one is average aggradation rate, based on data compiled from the literature. For this work, the division of the successions into intervals is driven by the existing temporal constraints. Values of aggradation rates attributed to the stratigraphic intervals are variably based on published geochronometric data, correlation of biostratigraphically constrained strata and on magnetostratigraphic control.

For outcrop datasets comprising 2D or pseudo-3D architectural panels depicting the sedimentary architecture of strata composed of channel and floodplain deposits, depositional-element proportions are based on cross-sectional areas estimated as the product of the lateral and vertical extent of the elements; thickness-based proportions are instead derived from 1D datasets.

This approach is subject to several limitations. Full control on spatial variability of architectural products and of the boundary conditions that govern the deposystems is lacking.

Also, a limitation is associated with the inclusion of data from published summary datasets of channel-body geometries, because for these datasets the geometric criteria cannot be checked, making comparisons with other datasets less reliable. Stored average aggradation rates are affected by the variable degree and types of uncertainty to which the different temporal constraints are subject, i.e. connected with radiometric dating error, magnetostratigraphic correlation, biostratigraphic correlation, and, in some cases, to correlation of bounding surfaces outside the considered study areas (see digital repository, tab. DR2). Furthermore, aggradation rates have been averaged over different time scales for different stratigraphic volumes. Generally, however, stratigraphic volumes considered in this study are the product of deposition at the 10^{-1}-10^{1} Myr timescale, and are 10^{1}-10^{2} m thick: these spatial and temporal scales make the results comparable with volumes simulated by the LAB models. Also, aggradation rates have not been corrected for sediment compaction; as the abundance of fine-grained and organic deposits in floodplain settings renders overbank units generally more compactable than sand-prone channel bodies, differential compaction might alter any relationships that may exist between channel-body properties and aggradation rates. Further limitations are inherent in the variability in dataset quality. Uncertainty relates to restricted outcrop continuity or lack of 3D control, for example where channel-complex widths may not entirely be exposed due to outcrop termination, or may be exposed at different angles with the channel-body axis. The reliability of interpretations is also variable; notably, uncertainty may arise from recognition of channel and floodplain deposits in certain datasets, as based for example on photo-interpretation or subsurface studies.

RESULTS

We have compared the evolution of different fluvial successions that record vertical changes in channel-deposit proportions concurrent with temporal changes in overall aggradation rates (Fig. 1). Potential relationships between aggradation rate and channel-deposit proportion are also evaluated across all the successions; this is of use to assess whether accommodation itself is a parameter with general predictive value, such that it determines architectural differences observable between different sedimentary basins. This approach therefore also serves as a test of whether high- and low-accommodation ‘settings’ can be genuinely identified based on channel-body stacking density (Leckie and Boyd, 2003; Catuneanu, 2006).

The timescale dependency of aggradation rates is not expressly accounted for by either LAB or sequence stratigraphy models (Miall, 2014). Aggradation rates depend on the time over which they have been estimated, as the longer the time embodied by a succession, the higher the probability that it incorporates significant breaks in sedimentation or longer average durations of such hiatuses (Sadler, 1981). Thus, to enable comparisons between and within different timescales, results are presented by classifying stratigraphic volumes on the timescale over which aggradation rates were estimated (Fig. 1).

Of 20 deposystems considered, which cover different tectonic, physiographic and depositional settings and typify different scenarios of accommodation generation, 15 provide data on the proportion of channel and floodplain deposits; 9 of these are suitable for investigation of their temporal evolution (i.e., changes in aggradation rates through time are documented). Of 18 tracked variations (i.e., changes between two stratigraphic volumes within a system), 11 are particularly significant, as they involve pairs of stratigraphic volumes whose aggradation rate values are evaluated either over corresponding timescales or in such way that the largest aggradation rate value of the pair is estimated over a longer timescale (Fig. 1). Only 6/18 of any variations and 4/11 of timescale-relevant variations clearly display increase in aggradation rate matched by decrease in channel-body proportion, or vice versa.

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Considering data from all 36 volumes associated with the 15 systems studied (Fig. 1), no consistent trend exists between channel proportion and aggradation rate, as evaluated both across all volumes (Pearson's correlation coefficient = –0.043, p-value = 0.81) and for timescale-matching groups (cf. supplementary material).

The distributions of channel-complex thicknesses and widths from 21 stratigraphic volumes associated with 15 different systems were also studied (Fig. 2). The maximum thickness of each channel-complex has been considered, whereas width distributions have been constructed from data of real widths (i.e., channel-complex width orthogonal to mean paleoflow), apparent widths (i.e., element width seen obliquely to mean paleoflow) and measured widths of incompletely exposed elements (e.g., due to outcrop termination). No significant relationships are observed between mean channel-complex thickness and mean aggradation rate (Pearson's R = –0.130, p-value = 0.59), or between mean channel-complex width and mean aggradation rate (R = –0.054, p-value = 0.82).

Traditional stratigraphic models predict the development of more sheet-like channel bodies under slower aggradation. Counter to what is predicted by these models, FAKTS datasets for which temporal changes are documented demonstrate variations in mean channel-complex width to be more often of the same sign as changes in aggradation rate (i.e., more commonly, channel-complexes become on average wider as aggradation accelerates, and vice versa): comparison with Figure 1 reveals that this result likely relates to a positive relationship between channel-complex proportion and size (i.e., channel-complex size reflects the effect of channel-deposit amalgamation).

Data on the spatial arrangement of channel complexes within the stratigraphic volumes have been used to derive information about the degree of channel amalgamation and vertical channel-deposit connectivity. This information is provided by values of channel-complex 'connected thickness' – defined as the sum of the thicknesses of vertically stacked channel complexes, with the admissible condition of a channel complex being included in more than one stack. The connected thickness is a proxy for channel-body stacking density, which is commonly predicted to be higher for slower rates of aggradation. No evident relationship is found between the mean or maximum connected thickness and the mean aggradation rate, when evaluated across different systems (Fig. 3). Instead, for systems whose evolution is tracked, 5 of 6 variations in mean connected thickness have the same sign as changes in mean aggradation rate. Again this reflects the effect of increased channel-deposit proportions on amalgamation.

DISCUSSION

Terrestrial accommodation can be seen as the volume within the elevation difference between the long-term river equilibrium profile and the topography (Posamentier and Vail, 1988; Muto and Swenson, 2005; citations therein). However, in agreement with most authors, we practically quantify accommodation as a vertical distance, and we infer rates of creation of accommodation on the basis of aggradation rates (cf. ‘realized accommodation’; Cross, 1988; Muto and Steel, 2000).

For the studied fluvial systems, temporal variations in aggradation rate do not serve as good predictors of changes in channel-deposit proportion through the inverse relationship often implied by stratigraphic models. Furthermore, the results show that changes toward sheet-or ribbon-like channel-complex geometries do not appear to occur with corresponding decreases or increases in aggradation rate. Relationships between mean aggradation rate and channel-complex vertical connectivity also contradict those predicted by common stratigraphic models. These considerations suggest that sequence stratigraphic models that interpret temporal changes in channel proportions, geometry and stacking pattern in terms of changes in the rate of creation of accommodation may be of limited value. Recognition of ‘high’- or ‘low’-accommodation systems tracts (cf. Catuneanu et al., 2009) based solely on patterns of channel-body amalgamation may be misleading for interpretations of basin evolution, as floodplain cannibalization may not be the norm in causing high channel density and channel-body sheet-like geometries, at least when evaluated at the spatial and temporal scales to which the LAB models refer. Equally, the ability to infer the ratio between accommodation and sediment supply (A/S; e.g., Martinsen et al., 1999) on the basis of channel proportions requires re-evaluation, especially given that the rate of creation of terrestrial accommodation depends on sediment supply rate, in contrast to contexts where the concept of sea-level-based accommodation is applicable (cf. Prince and Burgess, 2013). The results presented here support the claim of Gibling et al. (2011) that it is dangerous to infer accommodation conditions from the degree of channel-body amalgamation, and further support a recommendation that terms such as high- or low-accommodation systems tracts be avoided, when their recognition is based solely on channel-body density. Instead, the use of non-genetic terms in absence of temporal constraints or evidence of specific controls is recommended. Moreover, the lack of relationships between channel-complex properties and aggradation rates across all studied stratigraphic volumes, whose mean aggradation rates collectively span two orders of magnitude, provides evidence against the practicability of inferring low- or high-accommodation settings as is commonly attempted (cf. Leckie and Boyd, 2003; Catuneanu, 2006).

Decades of research on autogenic dynamics of fluvial systems and allogenic controls on their behavior have offered insight as to why the LAB models have limited applicability and thus current terrestrial sequence stratigraphy practice may be inadequate, and this is not attributable to one single explanation. For example, it is acknowledged that the LAB models do not account for the effect of the relationship between aggradation rate and avulsion frequency. As avulsions are favored by gradient advantage generated by channel-belt aggradation, avulsion frequency depends on the rate of generation of channel-belt superelevation, which is driven by differential sedimentation between channel belts and the adjacent floodplain, and appears to be scaled to aggradation rate (Heller and Paola, 1996). If avulsion frequency relates to aggradation rate following a direct proportionality to r^b, where r is aggradation rate and b>1, then an increase in channel density is expected in response to an increase in aggradation rate (Bryant et al., 1995; Heller and Paola, 1996). Furthermore, the proportion of channel deposits in a stratigraphic volume and the sheet- or ribbon-like geometry of channel bodies will also depend on channel size and rate of lateral migration (Bristow and Best, 1993). Upstream controls on sub-aerial accommodation include the rates of solid and liquid discharge to the fluvial system; so, depending on the relative dominance of the different drivers for the generation of accommodation, different scenarios involving changes in aggradation rate, formative channel size and rates of river mobility through migration and avulsion can be envisaged. This is also suggestive of how LAB-type responses can be determined by variations in the relative dominance of different river systems that deposit sediment in the same basin but variably respond to different sets of downstream and upstream controls and have different autogenic dynamics. These considerations do not aim to provide an exhaustive explanation of why and where the tested principles do not work, but simply to illustrate how fluvial systems respond in a complex manner to changes in a number of controlling parameters. It is the complex interplay of multiple controls that likely explains the results presented here.

CONCLUSIONS

Data from ancient sedimentary successions suggest that the evolution of fluvial systems subject to variable aggradation rates does not routinely follow the pattern expected by common stratigraphic models, whereby a negative relationship between aggradation rate and channel-deposit density is expected: observations on channel-body density, geometries and stacking patterns do not prove to be reliably diagnostic of rates of creation of accommodation. Consequently, the use of channel-body characteristics alone for the identification of high- and low-accommodation systems tracts and settings does not appear to be justified, calling into question fluvial sequence stratigraphy models and practices that draw heavily upon the principles tested by this study. Rejection of paradigms relating channel-body properties to accommodation states is relevant to a range of geologic disciplines, because research in many fields has often relied on them to interpret stratigraphic variations in channel-body stacking density in terms of changes in processes such as rates of crustal stretching or eustatic fluctuations.

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FIGURE CAPTIONS

Figure 1. Cross-plot of channel-body proportion and mean aggradation rate for different stratigraphic volumes. Each point represents a stratigraphic volume, and its shape indicates the timescale over which the aggradation rate was evaluated. Data representing intervals from the same depositional system are joined by arrowed lines to indicate temporal evolution. Each arrowed line represents a change (N = 18), pointing in the up-section stratigraphic direction. See digital repository for data and material on age uncertainty.

Figure 2. Box plots of channel-complex thickness (A) and width (B) distributions for different stratigraphic volumes, ordered by mean aggradation rate. The boxes are colored according to the timescale over which the aggradation rate was evaluated, as in legend. Width distributions also incorporate uncorrected values of apparent and incomplete observations (see text). The boxes represent interquartile ranges, the horizontal bars within them represent median values, and the spots represent outliers. Deposystem evolution can be deduced by referring to the case-study identifiers and Figure 1.

Figure 3. Cross-plots of minimum and mean channel-complex thickness and mean and maximum channel-complex ‘connected’ thickness against mean aggradation rate for different stratigraphic volumes. Each vertical line represents the thickness and connected thickness distribution of each stratigraphic volume. The numeric indices denote the FAKTS case-study successions used for this analysis: deposystem evolution can be deduced by referring to these case-study indices and Figure 1.

[1]GSA Data Repository item 2015xxx, containing method details, data and ancillary information is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

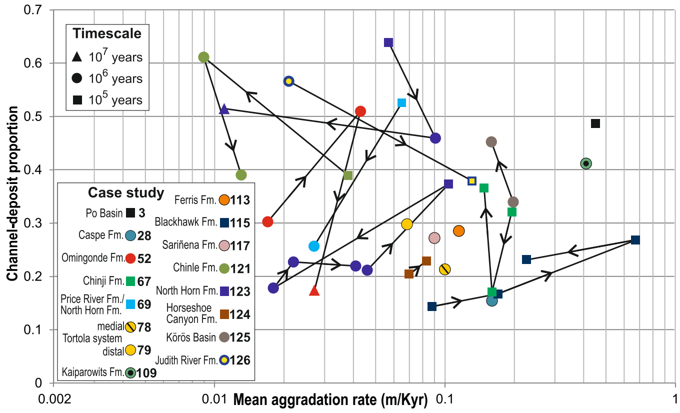

Timescale
10^7 years
10^6 years
10^5 years
Case study
Po Basin 3
Caspe Fm. 28
Omingonde Fm. 52
Chinji Fm. 67
Price River Fm./ North Horn Fm. 69
medial 78
Tortola system
distal 79
Kaiparowits Fm. 109
Ferris Fm. 113
Blackhawk Fm. 115
Sariñena Fm. 117
Chinle Fm. 121
North Horn Fm. 123
Horseshoe Canyon Fm. 124
Körös Basin 125
Judith River Fm. 126
Channel-deposit proportion
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.002
0.01
0.1
1
Mean aggradation rate (m/Kyr)

Figure 1

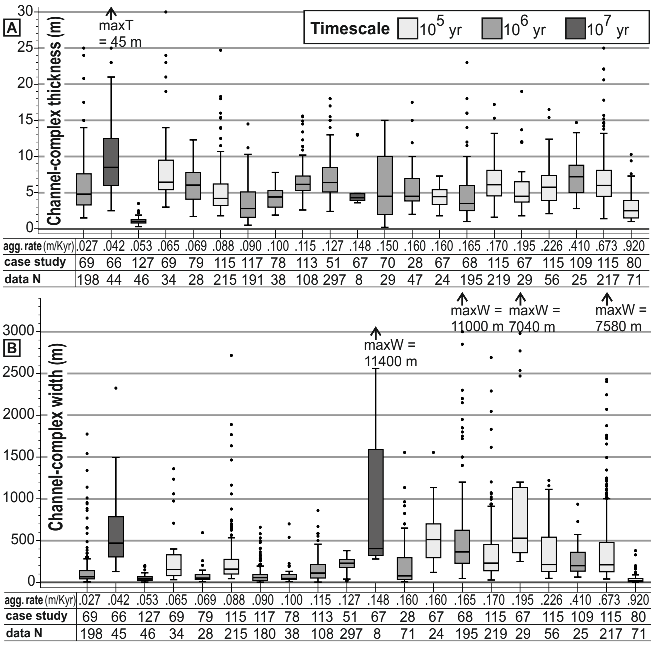
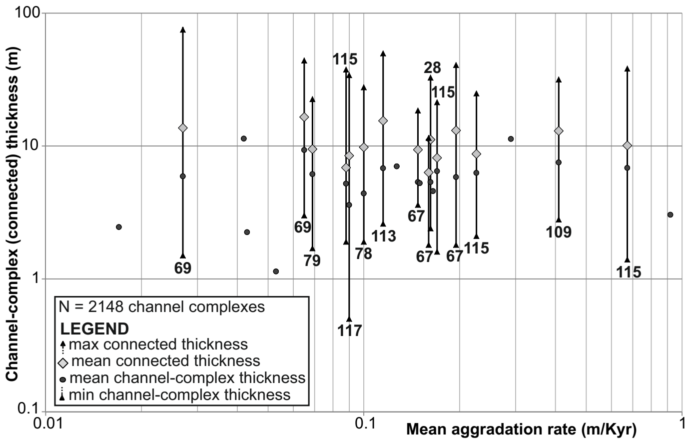

A
Channel-complex thickness (m)
Timescale 10^5 yr 10^6 yr 10^7 yr
maxT = 45 m
agg. rate (m/Kyr) .027 .042 .053 .065 .069 .088 .090 .100 .115 .127 .148 .150 .160 .160 .165 .170 .195 .226 .410 .673 .920
case study 69 66 127 69 79 115 117 78 113 51 67 70 28 67 68 115 67 115 109 115 80
data N 198 44 46 34 28 215 191 38 108 297 8 29 47 24 195 219 29 56 25 217 71
B
Channel-complex width (m)
maxW = 11400 m
maxW = 11000 m
maxW = 7040 m
maxW = 7580 m
agg. rate (m/Kyr) .027 .042 .053 .065 .069 .088 .090 .100 .115 .127 .148 .160 .160 .165 .170 .195 .226 .410 .673 .920
case study 69 66 127 69 79 115 117 78 113 51 67 28 67 68 115 67 115 109 115 80
data N 198 45 46 34 28 215 180 38 108 297 8 71 24 195 219 29 56 25 217 71

Figure 2



100
10
1
0.1
0.01
0.1
1
Channel-complex (connected) thickness (m)
Mean aggradation rate (m/Kyr)
69
69
79
115
117
78
113
67
28
115
67
67
115
109
115
N = 2148 channel complexes
LEGEND
max connected thickness
mean connected thickness
mean channel-complex thickness
min channel-complex thickness

Figure 3