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The lithofacies organization of fluvial channel deposits: a meta-analysis of modern rivers

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ABSTRACT

Environmental interpretations of subsurface fluvial successions are commonly based on facies observations from core and are often attempted by generalist geologists by reference to classic facies models. However, for fluvial channel deposits, the value of observations on lithofacies proportions for interpretations of depositional environment has yet to be assessed quantitatively. Here, a test is presented that is based on a comparative study of facies data from 77 reaches of 46 modern rivers. The analysis is undertaken on datasets from published case studies stored in a sedimentological database, with consideration of causes for observational bias, and with particular attention paid to sandy lithofacies. The observed variability in the proportion of facies assemblages in the channel deposits of sandy river systems is quantified for classes of environments categorized according to channel pattern (braided, low sinuosity, meandering), climatic setting (arid to perhumid), and discharge regime (ephemeral to perennial). By capturing the variability in facies organization within fluvial systems of certain types, these outputs serve as facies models that provide a measure of uncertainty to sedimentological interpretations. Concurrently, the statistical analysis presented enables a test of the significance of relationships between the relative proportions of channel lithofacies and parameters that either represent controlling factors (e.g., water-discharge characteristics) or covariates (e.g., channel pattern). For classes of river systems grouped by channel pattern, climate, and discharge regime, emerging features of facies organization can be identified. Statistically, it is observed that relationships exist (i) between channel pattern and the frequency of the preserved expression of bedforms, and (ii) between controls on river hydrology (climate, discharge regime and seasonal variability) and the record of upper and lower flow-regime conditions. Thus, the results corroborate existing qualitative facies models in some respects. However, observations of the relative dominance of facies in channel deposits demonstrate limited value for interpretations or predictions in subsurface or outcrop studies, as variability within each type of depositional system is significant. Corehole data of fluvial channel deposits may be commonly overinterpreted.

Keywords: fluvial facies models; channel pattern; braided; meandering; low sinuosity; discharge variability.

1 INTRODUCTION

It has often been claimed that attempting interpretation of the planform style of a river from one-dimensional samples of its deposits, such as those offered by cores and wireline logs, is inappropriate because of the lack of reliable diagnostic criteria (Jackson, 1977; Miall, 1985; Brierley, 1989a; Bridge, 1993a; Hickin, 1993; Ethridge, 2011; Hartley et al., 2015; Blum, 2016; Fielding et al., 2018). Notwithstanding, traditional fluvial facies models categorized according to channel patterns and depicted as idealized vertical sections are still widely used in applied contexts as a common reference for interpretations of subsurface data (e.g., Li et al, 2016; Sen et al., 2016; Attia et al., 2017). However, these facies models do not quantify the differences or similarities in facies architecture between different types of depositional systems, and neither do they convey uncertainty resulting from the variability seen in each type. These are major limitations in the application of facies models to the development of conceptual representations of the subsurface, and to rock-record interpretations of fluvial depositional environments more generally.

It is argued that other environmental classes (e.g., climate, dominant sediment-load type) might be better suited to the categorization of facies models (e.g., Miall, 1996; Fielding et al., 2009, 2018; Colombera et al., 2013; Plink-Björklund, 2015; Best and Fielding, 2019). The ideal set of facies models would result in more evidently contrasting styles of sedimentary architecture, expressed in the highest variability between classes of environments and in the lowest variability within each class; that is, they would be classified on the parameter that represents the strongest control – though this might vary depending on whether variability is considered for either a predictor (e.g., facies type) or a characteristic property of interest (e.g., sandbody geometry).

Thus, it ought to be possible to determine the predictive value of facies models via quantification, in a range of known examples, of the facies architectures they seek to represent. With regards to the occurrence and frequency of lithofacies in the channel deposits of fluvial systems, the opportunity to conduct an analysis of this type is offered by the many studies of the facies architecture of channel deposits of modern rivers that have been conducted since the 1960s. For modern rivers, observations can be made on processes and controlling factors that can only be inferred for ancient successions, thereby allowing links to be established between facies characteristics and planform channel morphology, reach climate, and discharge regime, with the proviso that any analysis based on data from modern depositional systems will not account for issues relating to preservational bias.

A comprehensive comparative study of which facies characteristics are related to types of fluvial systems, and to what degree, is to-date still lacking. By undertaking a study of this type, the aim of this work is to test whether a signature can be recognized in the facies organization of channel deposits for present-day fluvial depositional systems of different types, classified according to channel pattern, climatic setting, and discharge regime. The following specific objectives are sought:

- to assess the ability to discriminate types of currently active fluvial depositional systems, classified by environmental categories, based on the relative proportion of facies seen in limited samples of channel deposits, with a particular focus on the frequency of sandy facies in sand-bed rivers;
- to provide facies models that act as templates for geological interpretations that account for uncertainty related to geological variability; and
- to make inferences of the importance of possible controls on the dominance of processes and bedforms in fluvial channel sub-environments.

These objectives are met through a database-informed analysis of the channel deposits present in 77 reaches of 46 modern rivers, whereby quantitative comparisons can be undertaken to assess similarities or differences in facies organization across different types of fluvial systems.

2 DATASETS AND METHODS

The current work takes the form of a meta-analysis, i.e., a statistical synthesis of the results of different studies on a subject (Borenstein et al., 2009). By bringing together all or most available research on a topic in a format suitable for comparisons, meta-analyses can yield more insight than any single case study or narrative review, allowing the emergence of common threads. The main limitation of such an approach consists in the uncertainty as to whether the case studies are sufficiently similar to be combined, so as to enable meaningful comparisons. The comparative study presented here is aided by a database approach, whereby data from different sources can be integrated in the analysis because the database is populated following a standard aimed to ensure consistency in data definition.

2.1 Database

The sedimentological data are collated from many published sources and stored in a SQL relational database, the Fluvial Architecture Knowledge Transfer System (FAKTS; Colombera et al., 2012). FAKTS permits the digitization of the sedimentary architecture of fluvial systems, in the form of hard and soft data relating to genetic units that belong to three scales of observation, termed ‘depositional

elements', 'architectural elements' and 'facies units', in order of descending scale (Colombera et al., 2012, 2013). In FAKTS, data are stored on the geometry, spatial relationships, and hierarchical relationships of these units. FAKTS genetic units are assigned to subsets of fluvial systems, which can represent, for example, different reaches of the same river that differ with respect to their characteristics (e.g., channel pattern) or external controlling factors (e.g., climate). FAKTS' genetic units are classified on interpretative or objective classes, whereas case-study successions or rivers, and subsets thereof, are classified on parameters that describe the fluvial systems and their boundary conditions, and on metadata (e.g., attributes on data quality and type).
Facies units belong to higher-scale architectural or depositional elements that are classified according to the origin of their deposits: FAKTS can therefore be filtered to obtain outputs on the facies units that form channel deposits, i.e., that are contained in architectural elements recording channel deposition (e.g., bars, channel fills) or in depositional elements classified as channel bodies. Facies units in FAKTS represent packages with sub-bed-scale resolution characterized by given textural and structural properties, on which they are classified. Facies units are delimited by bounding surfaces that mark a change in lithofacies, a major change in palaeocurrent direction, or that represent erosional contacts or element boundaries (cf., second- or higher-order surfaces of Miall, 1996; see Colombera et al., 2013). The facies classification scheme adopted in FAKTS extends the scheme by Miall (1996); a summary of the facies types recognized in the channel deposits studied herein is given in Table 1.

Table 1. Classes of lithofacies recognized in the studied channel deposits, modified after Miall (1996; cf., Colombera et al. 2013).

Code	Characteristics
G-	Gravel with undefined structure and undefined additional textural characteristics.
Gmm	Matrix-supported, massive or crudely bedded gravel.
Gmg	Matrix-supported, graded gravel.
Gcm	Clast-supported, massive gravel.
Gci	Clast-supported, inversely graded gravel.
Gh	Clast-supported, horizontally or crudely bedded gravel; possibly imbricated.
Gt	Trough cross-stratified gravel.
Gp	Planar cross-stratified gravel.
S-	Sand with undefined structure.
St	Trough cross-stratified sand.
Sp	Planar cross-stratified sand.
Sr	Current ripple cross-laminated sand.
Sh	Horizontally bedded sand.
Sl	Low-angle (<15˚) cross-bedded sand.
Ss	Faintly laminated, cross-bedded, massive or graded sandy fill of a shallow scour.
Sm	Massive sand; possibly locally graded or faintly laminated.
Sd	Soft-sediment deformed sand.
F-	Fine-grained sediment (silt, clay) with undefined structure.
Fl	Interlaminated very-fine sand, silt and clay; might include thin cross-laminated sandy lenses.
Fsm	Laminated to massive silt and clay.
Fm	Massive clay.
Fr	Fine-grained root bed.
C	Coal or highly carbonaceous mud.

The sedimentological data analysed in this study relate to 77 classified fluvial reaches from 46 modern rivers, and have been derived from 60 literature sources consisting of scientific articles or dissertations (Table 2; Fig. 1). The datasets employed in this study do not represent all the available literature on the facies of channel deposits in modern rivers. Rather, the chosen datasets have been selected because they contain data on facies observations that can be confidently coded in the database, and therefore compared in a geologically meaningful way. The original datasets consist of sedimentological descriptions (vertical logs, two-dimensional panels) of the lithofacies that form channel deposits of different types (e.g., active barforms, channel fills), as seen along natural exposures or excavated trenches, or in core. Original classifications of grainsize and sedimentary structures are relied upon for assigning facies types in the database. The database output employed in this work comprises estimations of the proportions of facies types in channel deposits in the studied river reaches, either computed based on their frequency and geometry where at least 6 facies units per subset are present (cf., Colombera et al., 2013), or as reported in the literature sources.

Table 2. Rivers and case studies considered in this work. Discharge regime, channel pattern and Thornthwaite and Köppen (in brackets) climate types are reported for the locations of the studied reaches. The channel sub-environments that have been sampled in the original datasets are also reported, classified on the terminology used in the respective literature sources. The facies data types for each studied river are reported as vertical logs ('1D log') or two-dimensional panels ('2D') measured on natural exposures or excavated trenches, or as cores ('1D core'). Some of the case studies are denoted as follows: (*) all or part of studied deposits relate to a planform phase that differs from the current one; the channel pattern is classified as seen at time of deposition; (†) studied deposits include currently abandoned channel belts or terraces, as old as Upper Pleistocene in age; the studied reaches are classified on conditions at time of deposition; (‡) the distinction between channel and overbank deposits is tentative.

River	Location	Data sources	Channel pattern	Climate	Discharge regime	Original sub-environment	Dataset type
Amazon	Brazil	Rozo et al. (2012)	Meandering (*)	Humid (Aw)	Perennial	Point bar	1D log
Araguaia	Brazil	Bayer and de Campos Zancopé (2014)	Meandering (*)	Moist subhumid (As)	Perennial	Side bar, point bar, alluvial deposits	1D log
Barwon	Australia	Taylor and Woodyer (1977); Woodyer et al. (1979)	Meandering	Semiarid (BS)	Perennial	Point bench	1D log
Bermejo	Argentina	Sambrook Smith et al. (2016)	Meandering	Humid (Cf)	Perennial	Point bar, concave-bank bench	1D core
Bijou Creek	USA	McKee et al. (1967)	Low sinuosity	Semiarid (BS)	Ephemeral	Channel	1D log
Brahmaputra	India	Sonowal et al. (2018)	Braided	Humid (Cw)	Perennial	Bank-attached bar	1D log
Brahmaputra (Jamuna)	Bangladesh	Bristow (1993); Best et al. (2003)	Braided	Humid (Aw)	Perennial	Channel, mid-channel braidbar	2D, 1D core
Burhi Gandak	India	Singh and Singh (2005)	Meandering	Dry subhumid (Cw)	Perennial	Point bar	1D log
Calamus	USA	Bridge et al. (1986; 1998)	Braided (*)	Dry subhumid (Df)	Perennial	Midstream bar, channel bar, channel fill	1D core
Cheyyar	India	Resmi et al. (2017)	Low sinuosity	Dry subhumid (Aw)	Ephemeral	-	1D log
Chhoti Gandak	India	Singh and Singh (2005)	Meandering	Dry subhumid (Cw)	Perennial	Point bar	1D log
Congaree	USA	Levey (1977)	Meandering	Humid (Cf)	Perennial	Point bar	1D log
Daule	Ecuador	Smith (1987)	Meandering	Dry subhumid (BS)	Perennial	Point bar	1D core
Embarras (Athabasca)	Canada	Calverley (1984); Smith (1987)	Meandering	Semiarid (Df)	Perennial	Point bar	1D core
Fort Nelson	Canada	Hickin (1986)	Meandering	Semiarid (Df)	Perennial	Point bar	1D core
Ganges	India	Singh (1977); Singh and Bhardwaj (1991); Shukla and Singh (2004); Singh et al. (2007)	Braided	Dry subhumid (Cw)	Perennial	Sand bar, braid bar	2D
Gash (‡)	Sudan	Abdullatif (1989)	Braided	Arid (BW)	Ephemeral	Channel fill	2D
Ghaghara	India	Singh and Singh (2005)	Braided	Dry subhumid (Cw)	Perennial	Lateral bar	1D log
Gomti	India	Shukla and Singh (2004)	Meandering	Dry subhumid (Cw)	Perennial	Point bar	2D
Great Gandak	India	Singh and Singh (2005)	Braided	Dry subhumid (Cw)	Perennial	Braid bar	1D log

Kosi	India	Singh et al. (1993)	Braided, low sinuosity	Dry subhumid (Cw)	Perennial	Side bar, mid-channel bar, bar, chute channel	2D, 1D log
Kuiseb (‡)	Namibia	Ringrose et al. (2018)	Low sinuosity, undefined	Arid (BW)	Ephemeral	Point bar, (mega island)	1D log
Luni	India	Carling and Leclair (2019)	Low sinuosity	Arid (BW)	Intermittent	-	1D log
Mahi	India	Sridhar and Patidar (2005); Sridhar (2007); Sridhar et al. (2013)	Braided, low sinuosity (*)	Semiarid (BS)	Perennial	Point bar, channel fill	2D, 1D log
Markanda (†, ‡)	India	Parkash et al. (1983)	Low sinuosity	Semiarid (Cw)	Ephemeral	-	1D log
Mississippi	USA	Frazier and Osanik (1961); Jordan and Pryor (1992); Bouma and Bouma (1994)	Meandering	Humid (Cf)	Perennial	Thalweg, point bar, abandoned channel	2D, 1D log, 1D core
Muskwa	Canada	Hickin (1986)	Meandering	Semiarid (Df)	Perennial	Point bar	1D
Neales	Australia	Lang et al. (2002; 2004)	Low sinuosity	Arid (BW)	Ephemeral	Lateral bar	1D log
North Thompson	Canada	Leclerc and Hickin (1997)	Meandering	Humid (Ds)	Perennial	Point bar	1D core
Palar (†)	India	Resmi et al. (2017); Resmi and Achyuthan (2018a, b)	Braided, undefined	Dry subhumid (Aw)	Ephemeral, undefined	-	1D log
Paraná	Argentina	Reesink et al. (2014)	Braided	Humid (Cf), moist subhumid (Cf)	Perennial	Mid-channel bar	1D core
Platte	USA	Rogers (1994); Horn et al. (2012)	Braided	Moist subhumid (Df)	Perennial	Laterally accreted macroform	2D, 1D core
Powder River	USA	Ghinassi et al. (2019)	Meandering	Semiarid (BS)	Perennial	Point bar	2D, 1D log
Red River	Canada	Brooks (2008)	Meandering	Dry subhumid (Df)	Perennial	Oblique accretion deposits	1D core
Río Colorado–Río Capilla	Bolivia	Donselaar et al. (2013); Li (2014); Li et al. (2014); Perdomo Figueroa (2017)	Meandering, undefined	Semiarid (BW)	Ephemeral	Point bar, accretionary bar, concave bank	1D log
Sandover (Mueller Creek) (†)	Australia	Tooth (1999)	Low sinuosity	Arid (BW)	Ephemeral	-	1D log
Saskatchewan	Canada	Campbell and Hendry (1987)	Meandering	Dry subhumid (Df)	Perennial	Meander lobe	1D log
South Esk	UK	Bridge et al. (1995)	Meandering	Humid (Cf)	Perennial	Point bar	1D core
South Saskatchewan	Canada	Ashworth et al. (2011); Lunt et al. (2013)	Braided	Dry subhumid (Df)	Perennial	Compound bar, bar, abandoned channel	1D core
Squamish	Canada	Brierley (1989a, b)	Braided, Meandering, undefined	Perhumid (Cf)	Perennial	Compound bar, diagonal bar, bank-attached bar, lateral bar, point bar	1D log
Trinity (†)	USA	Garvin (2008)	Meandering	Humid	Perennial	Point bar, channel fill	1D log
Vistula	Poland	Lejzerowicz et al. (2014)	Braided	Moist subhumid (Df)	Perennial	Sandbar	1D log
Wabash	USA	Jackson (1976)	Meandering	Humid (Cf)	Perennial	Point bar	1D log
Wadi Al-Hamd	Saudi Arabia	Ghandour et al. (2016)	Low sinuosity	Arid (BW)	Ephemeral	Channel fill	1D core
Wadi El Arish (†, ‡)	Egypt	Sneh (1983)	Undefined	Arid (BW)	Ephemeral	Confined floodplain	1D log
Willapa	USA	Smith (1987)	Meandering	Perhumid (Cs)	Perennial	Point bar	1D core

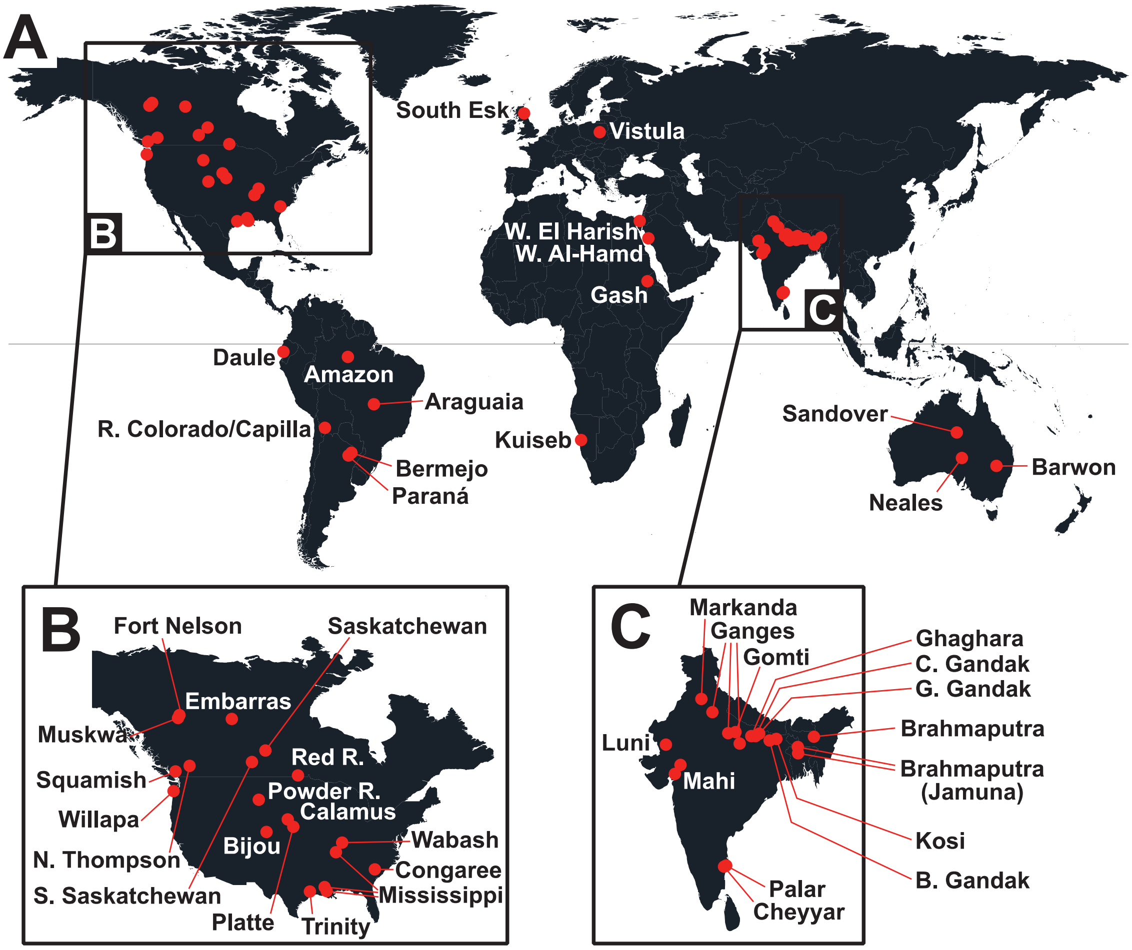


Figure 1. (A) Geographic distribution of the rivers considered in this work, with inset maps for North America (B) and the Indian sub-continent (C).

2.2 River classifications

In FAKTS the sedimentological data are tied to attributes that characterize the river systems and their tectonic, climatic and eustatic boundary conditions (Colombera et al., 2012, 2013). In this work, the datasets are filtered on attributes that describe the channel pattern, host climate zone, and discharge regime of modern rivers. Stretches of the same river that exhibit different channel patterns, that are characterized by different discharge regime, or that are contained in different climate zones, are treated as separate subsets of data in the statistical analysis.

2.2.1 Channel pattern

The channel patterns of the studied reaches are classified into single-thread ‘meandering’, single-thread ‘low-sinuosity’, and ‘braided’ classes. River reaches with wandering channel patterns have been excluded from the analysis. Meandering and low-sinuosity rivers are differentiated here based on the commonly used threshold of 1.5 sinuosity (Leopold and Wolman, 1957). Braided reaches are characterized by channel belts with multiple channels, which split around bars, at least at low river stage (Bridge, 1993b). In agreement with Bridge (1993b), anastomosing planforms are treated as a type of river pattern, i.e., as a property relating to the planform organization of channel belts. Accordingly, anastomosing planforms are not mutually exclusive to the adopted classes of channel patterns and have hence been excluded from this analysis. The considered reaches are classified by channel pattern at the time of deposition; in a small number of cases, the studied sediments – as old as Upper Pleistocene in age – are reported to have accumulated during phases in which planforms differed from the ones of the present-day river courses (Table 2).

2.2.2 Basin climate

In FAKTS, the local climate under which each river reach develops is recorded according to both the Thornthwaite and Köppen-Geiger climate classification systems (Table 2). The classes in the Thornthwaite system reflect local moisture availability, based on the balance between precipitation and potential evapotranspiration (Thornthwaite, 1948). This balance is quantified by a moisture index, which is positive when precipitation exceeds potential evapotranspiration. The classes in the Köppen-Geiger system reflect regional vegetation associations, and are based on temperature and precipitation statistics (Köppen, 1936). In this study, climate types are only classified for the sites where the river reaches were studied, and these climates might differ considerably from the dominant climates in the respective catchment areas. Climate classification for the studied river is based on available sources reporting global to regional climate zones (e.g., Feddema, 2005; Kottek et al., 2006; Peel et al., 2007). In the current work, the six Thornthwaite climate types (arid, semiarid, dry subhumid, moist subhumid, humid, and perhumid, in order of increasing moisture availability) are used for the statistical study, in relation to their hydrological significance. Arid, semiarid, and dry subhumid climates are characterized by water deficiency, and are grouped as 'dryland' climates in some of the subsequent analysis.

2.2.3 Discharge regime

In FAKTS the river reaches are also classified on categories of discharge regime, which describe the temporal continuity of stream flow (cf., Hudson-Edwards, 2007), as: (i) perennial, for rivers that maintain flow permanently; (ii) intermittent, for rivers that do not maintain flow during dry intervals; and (iii) ephemeral, for rivers that only maintain flow during or in the immediate aftermath of precipitation events. The stream-discharge classification for the studied river is based on available published sources and unpublished reports.

2.2.4 Other attributes

Additional attributes for some of the studied river reaches that are employed in the analysis include: (i) a measure of seasonality in water discharge that consists of the ratio between the monthly water discharge for the month when the river carries the largest flow (as averaged over the number of years for which data are available) and the mean annual discharge, as proposed by Leier et al. (2005) and referred to as 'discharge peakedness'; (ii) the size of the catchment areas of the rivers upstream of the studied reaches. Values of discharge peakedness are based on data from gauging stations, and are only assigned where these are located in proximity of the studied reaches. The data are derived from available published sources (Leier et al., 2005; Pomeroy et al., 2005; Bauch, 2009; Rokaya, 2014; Pechlivanidis et al., 2015; de Araujo Gomes et al., 2017; Roy and Sinha, 2017) and publicly accessible databases (UNESCO RivDIS–Global River Discharge Database, Vörösmarty et al., 1998, https://nelson.wisc.edu/sage/data-and-models/riverdata; R-HydroNET v.1.0, Vörösmarty et al., 1998, www.r-hydronet.sr.unh.edu/english; R-ArcticNET v4.0, Lammers et al., 2001, http://www.r-arcticnet.sr.unh.edu/v4.0; Atlas of Indo-Gangetic Plains, http://www.iitk.ac.in/gangetic/; USGS National Water Information System, https://waterdata.usgs.gov).

2.3 Statistical analysis

Analysis of database outputs is performed with R (version 3.4.1) (R Core Team, 2018). Distributions and associated descriptive statistics of absolute facies proportions in channel deposits have been derived for samples corresponding to: (i) rivers, (ii) their distinct reaches, and (iii) reaches unaffected by problems of facies recognition, in which at least 60% of the sandy facies are classified on sedimentary structure; relative proportions of sandy facies are also determined. Ninety-five-percent confidence intervals of median proportions have been obtained with a bootstrap approach (a resampling technique for estimation of statistical parameters of a population), using the adjusted bootstrap percentile (BC_a) method (Efron and Tibshirani, 1986). Statistical analyses are undertaken to test hypotheses relating to differences in distributions across samples of different populations of river systems, and to determine correlation between variables. The Wilcoxon rank-sum test (Wilcoxon, 1945) is chosen to determine the statistical significance of differences in distributions across pairs of groups of river systems. This test is employed because it is non-parametric and allows handling highly skewed distributions of facies proportions in samples of channel deposits. The statistical significance of differences in facies proportions across groups is expressed by p-values. For pairs of continuous variables (facies proportions vs catchment areas or discharge peakedness), the Pearson correlation coefficient (R) is used to quantify sign and strength of linear relationships, whose statistical significance is expressed as p-values.

2.4 Limitations

The main limitations to the current study can be summarized as follows.

- The chosen range of facies types (Table 1) does not fully capture the breadth in sedimentary textures and structures and in the associated formative bedforms that might be recognized in fluvial channels and their deposits. For example, a class of 'scour-fill' sands is used that does not differentiate the deposits on the nature of the infill, whereas a category of 'low-angle cross-stratification' is adopted as a blanket term for sediments with varied origin and sedimentological characters (e.g., concave- vs convex-upward laminae; backsets vs foresets). In some cases it may not even be possible to translate a facies as originally described to any of the types in the chosen scheme. However, the chosen facies scheme is ideal for database compilation and meta-analysis because it is largely based on a popular, widely adopted classification (Miall, 1996), and contains a limited number of basic but fundamental lithofacies types. Original facies types adopted from the literature sources are stored in the database but have not been used in the current analysis.
- There exists potential bias related to the types of channel sub-environment being sampled, as depositional and post-depositional processes can vary significantly across the range of depositional niches recognized in fluvial channel belts. This variability is expected to be recognized at multiple scales, such as, for example, in contrasting facies architectures in the deposits of channel fills vs bars, active vs abandoned channels, bar-head vs bar-tail regions, etc. (see below). This problem can be partially accounted for in the development of facies models that embody modal facies proportions by relating facies observations to different hierarchies of sub-environments, as rendered possible by the hierarchical approach adopted in the database method employed (see below; cf., Colombera et al., 2013). However, this type of bias is likely the most significant source of uncertainty in the assessment of variability in facies proportions, which is the focus of this work.
- Sampling bias also exists because of the nature of most sedimentological observations available from studies of modern rivers, since these observations are usually made on natural and artificial cuts and cores. These will tend to sample preferentially the upper portions of the channel belts, which have lower preservation potential than the deeper basal parts of scour fills or channel fills, and might be placed on types of geomorphic elements for which data collection is logistically feasible.
- The representativeness of the datasets is likely to scale with the size of the sample, which is highly variable across the case studies, with the cumulative total measured length of sections ranging from less than 3 m to over 360 m per river. The representativeness of the studied deposits is also partly a function of the size of the samples (as total logged thicknesses) relative to the maximum bankfull depth of river channels, over which vertical facies trends commonly develop (Bridge, 1993b).
- Factors relating to the shape of river hydrographs and to interannual variability in water discharge were not examined. It is desirable to attempt further analysis with additional metrics of discharge variability and seasonality (cf., Baker, 1977; Puckridge and Sheldon, 1998; Cecil, 2003; Shamir et al., 2005; Fielding et al., 2018).
- Few of the studied rivers approximate a pristine natural state, and the influence of anthropogenic controls on river discharge may have varied over the time for which historical stream gauge data have been considered.

3 RESULTS

The studied rivers encompass braided, meandering and single-thread low-sinuosity planforms (Table 2; Fig. 2), and have developed under the influence of a wide range of climates, from arid to perhumid, and discharge regimes of perennial, intermittent and ephemeral types (Table 2; Fig. 3). The channel belts considered in this analysis occur in a variety of continental environments, including alluvial valleys, coastal plains – some of which are subject to the influence of marine processes – and fluvial fans – some of which form terminal systems in endorheic basins.

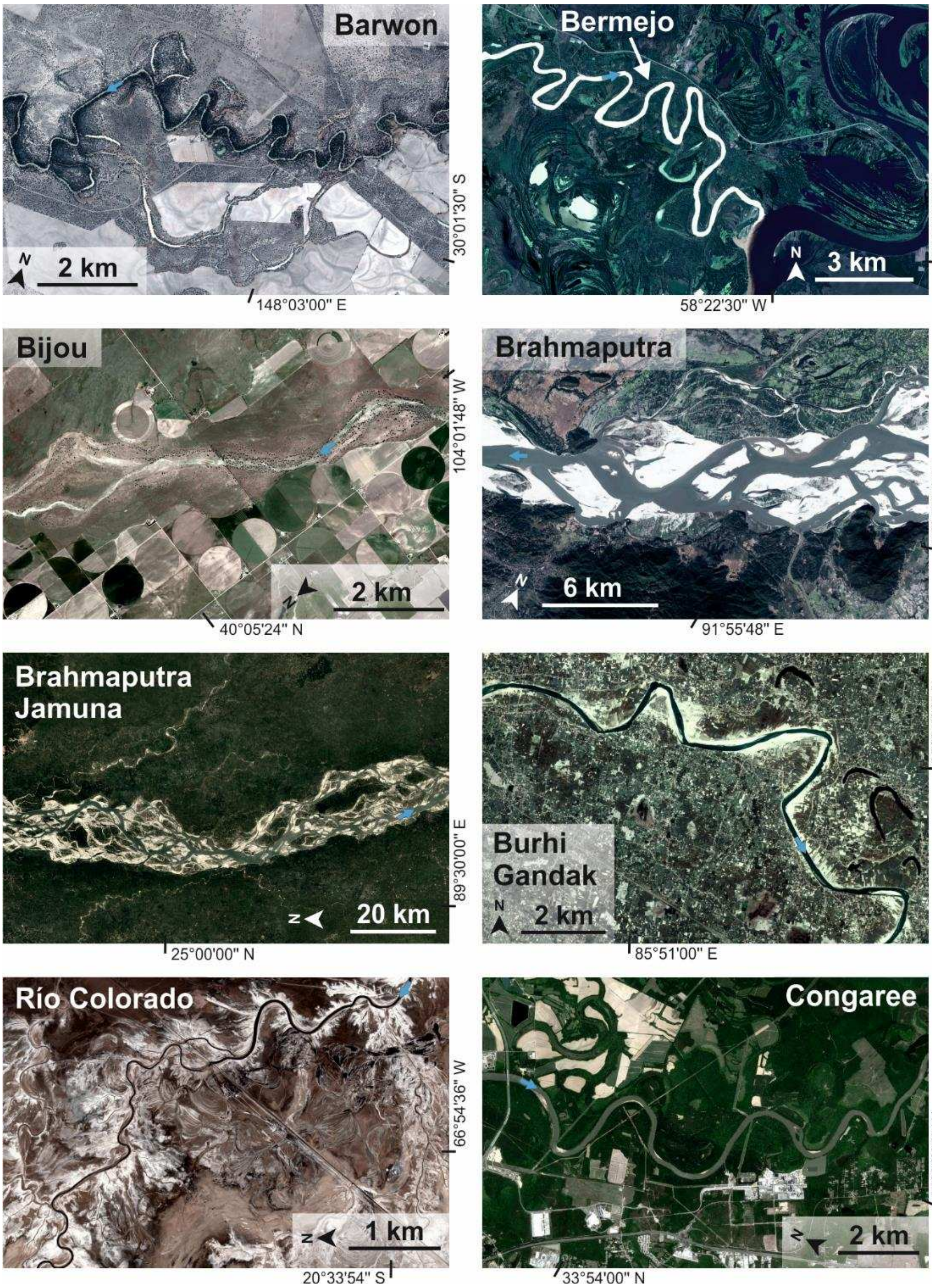
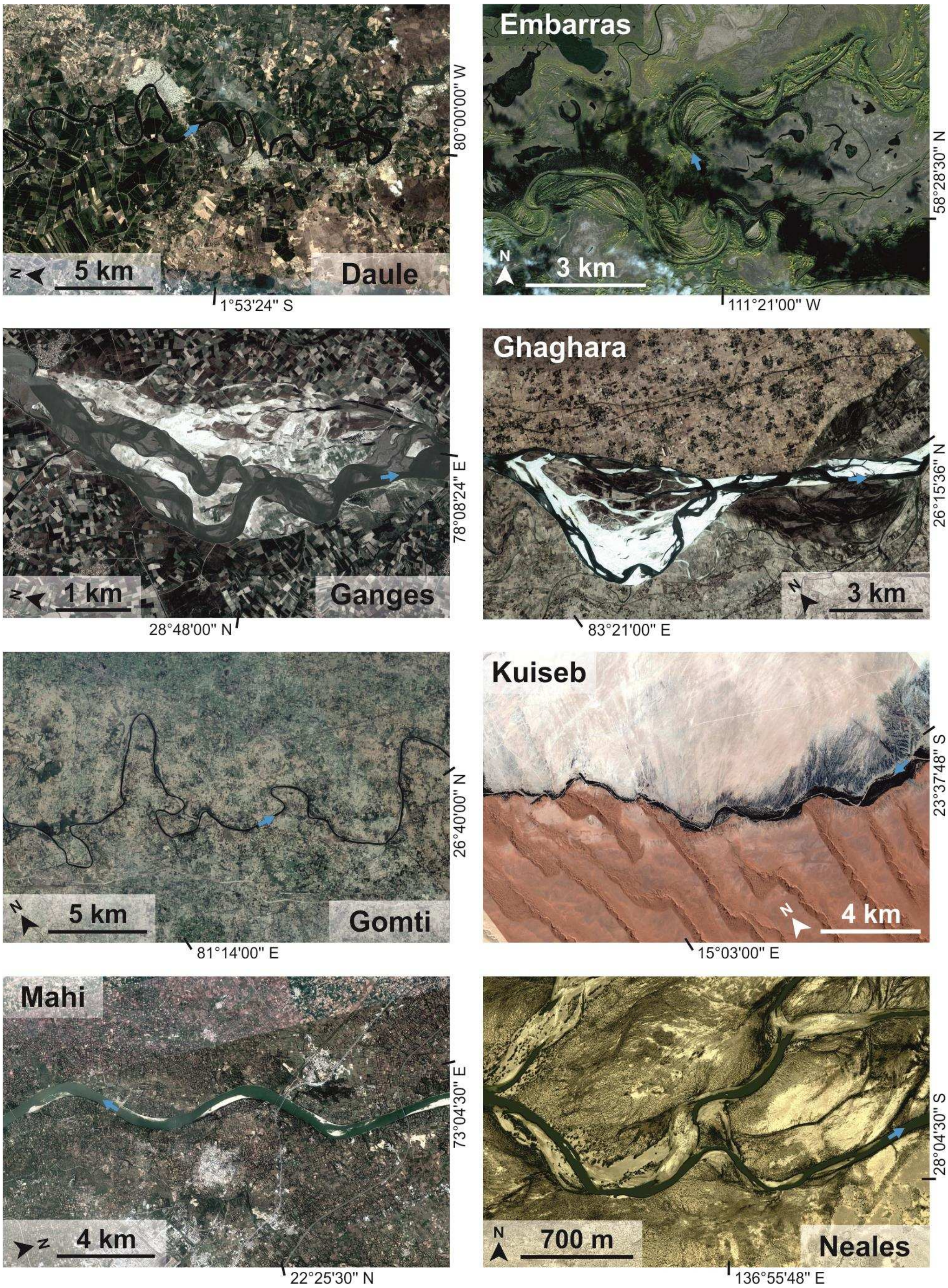


Figure 2. Satellite imagery of selected examples from the river reaches included in this study. Images from Google Earth©. Blue arrows indicate the direction of flow.



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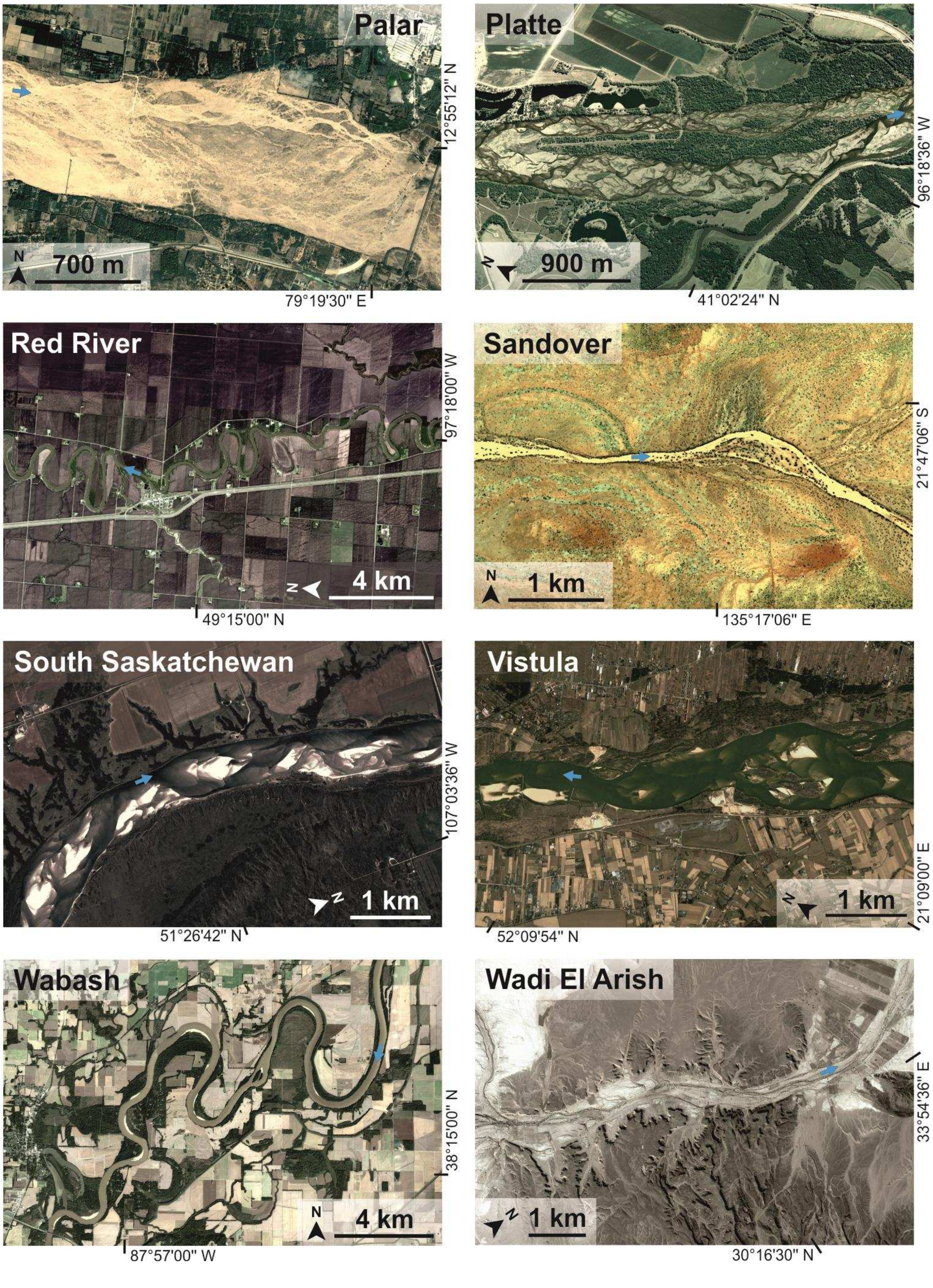

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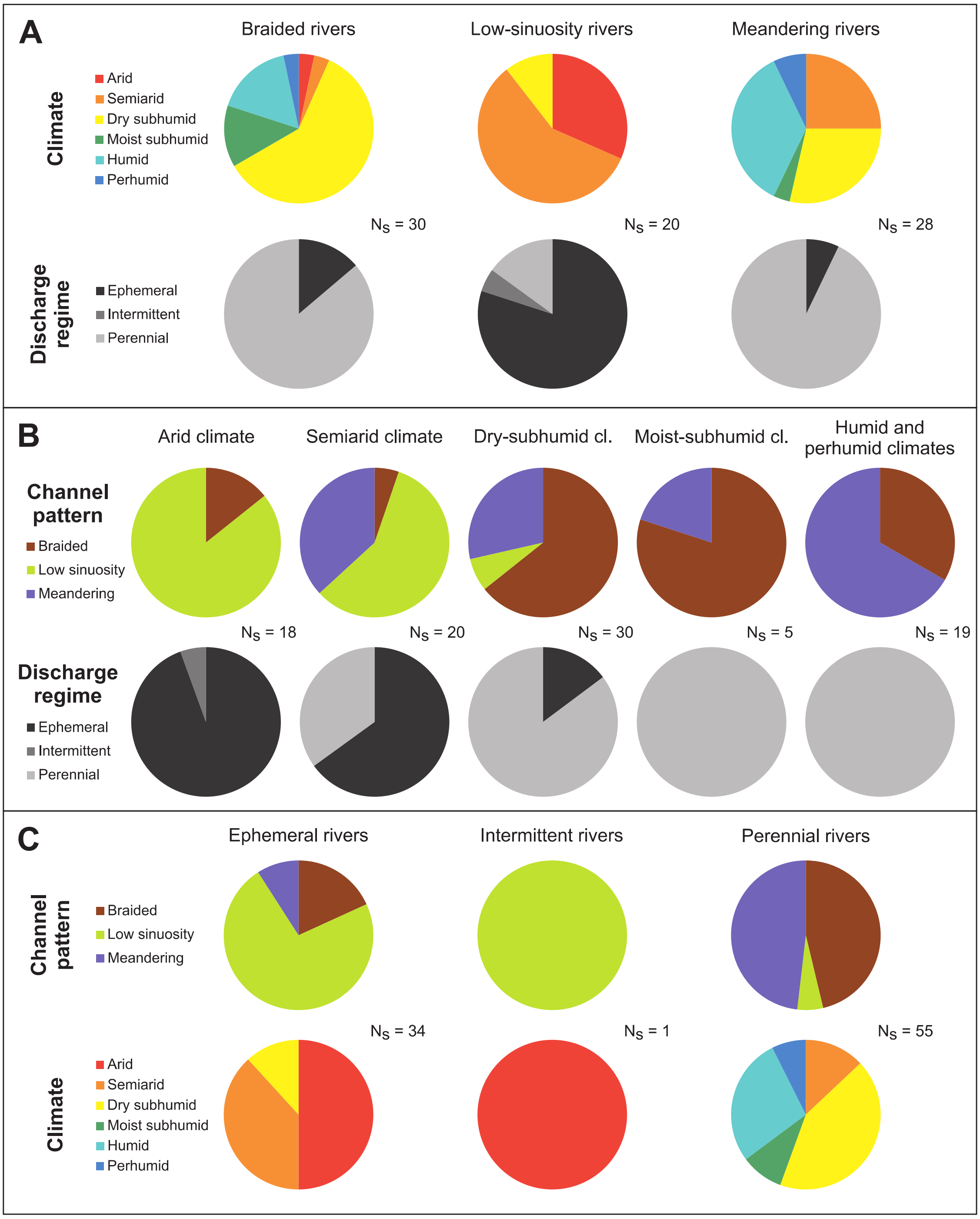

Figure 3. (A) Relative frequency of Thornthwaite climate types and classes of discharge regime for categories of channel pattern in the studied river reaches. (B) Relative frequency of classes of channel pattern and discharge regime for Thornthwaite climate types associated with the locations of the studied river reaches. (C) Relative frequency of channel patterns and Thornthwaite climate types for classes of discharge regime for the studied river reaches.

Channel deposits are defined here as sediments deposited by a channel in a channel belt, within the bankfull elevation. In accordance with this view, bar-top deposits are considered as being channel deposits in the analysis presented here (cf., Bridge and Tye, 2000). Yet, even in modern rivers, differentiating between channel and floodplain sedimentation may not be straightforward, and what is defined as channel deposition might differ between perennial or intermittent rivers and ephemeral rivers. For example, in ephemeral rivers channel banks might be ill defined, and channel activity tends to be mostly restricted to periods of flood-generating stormflow that is concomitant with overland flow. For three of the studied rivers, the distinction between channel and overbank deposits, based on the available descriptions, is only tentative (Table 2).

The studied channel deposits are dominantly represented by channel fills and macroforms of different types (Table 2). The expected variability in the relative frequency of lithofacies across channel sub-environments is evident when comparing the total proportions of facies occurring in active and abandoned aggradational channel fills and in barforms of any form (Fig. 4). Whereas active channel fills represent the preserved product of river-bed aggradation, abandoned-channel deposits represent the infill of extant channel forms that are disconnected from the river's base flow, whose accumulation typically takes place during and after channel cutoff or avulsion (Nanson and Croke, 1992; Toonen et al., 2012). Barforms represent landforms and associated deposits that record macroform growth accompanied by stream-bed migration, such as point bars and braid bars (Miall, 1996; Bridge, 2006). The compound facies proportions for these element types provide a quantitative description of characteristics of the facies arrangements that conform to what is typically presented in qualitative facies models for these sub-environments (cf., Bridge, 2006). This includes: (i) increased proportion of fine-grained deposits and ripple cross-laminated sands in bars, relative to active-channel fills, which might in part represent a signature of deposition on bar tops and bar tails; (ii) higher proportion of silt, clay and organic deposits in abandonments, which yet contain sandy beds; and (iii) marked dominance of trough and planar cross-stratified sands in the fills of active channels that may largely record thalweg deposition (Fig. 4). This inherent facies variability is a potential cause of bias and will affect the comparisons presented below.

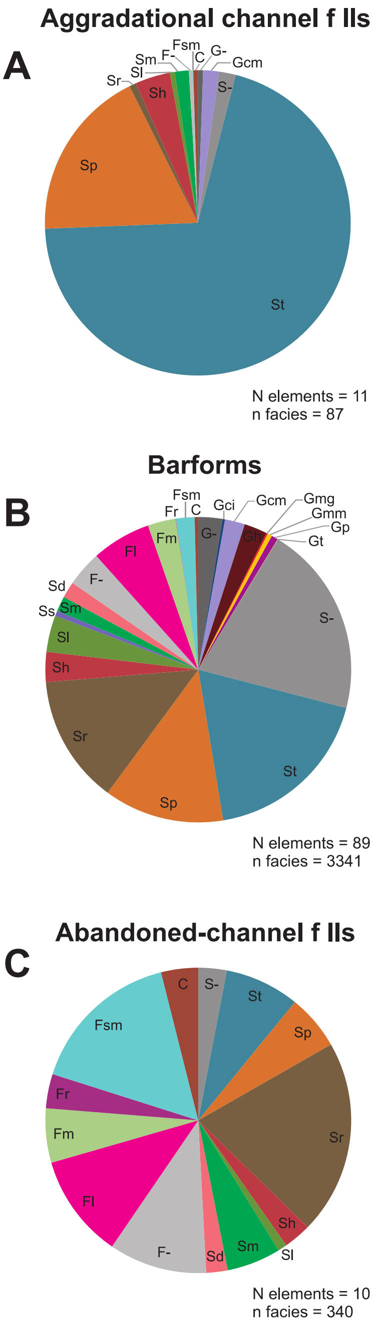

Figure 4. Total proportions of facies types in the channel deposits of the studied rivers, assessed by sub-environments of deposition: active aggradational channel fills (A), barforms (B), abandoned-channel fills (C). See Table 1 for facies codes.

Data on facies proportions serve to provide a summary of the relative predominance of types of depositional and post-depositional processes, and of possible formative bedforms – net of their short-term (i.e., in sub-recent times) preservation potential. In this perspective, database outputs on facies proportions in channel deposits are analysed within samples that consist of rivers or river reaches, and with consideration of attributes on which these samples are classified, in terms of channel pattern, climate type, and streamflow discharge at the studied locations. Considering the 46 studied rivers (Figs. 5, 6A) as the samples for which facies proportions are evaluated results in the largest amount of data in each sample, but in the smallest number of samples. Facies proportions are therefore also alternatively considered as obtained for each of the 69 database subsets representing individual river reaches whose available datasets contain at least 6 facies units (Fig. 6B). When distributions in facies proportions in channel deposits across rivers and reaches are considered, it is noted that mean and median values of facies percentages are consistent with what is usually represented in facies models for channel deposits of sand-prone river systems (Fig. 6), notably as expressed in the preponderance of sands with planar and trough cross-stratification and ripple cross-lamination (cf., Walker, 1976; Miall, 1996; Bridge, 2006). The variability in the abundance of each facies in the studied channel deposits is significant, however, indicating that a study of what ultimately controls this variability is warranted. To this end, because the majority of the studied rivers are characterized by channel deposits in which sandy facies constitute the largest fraction of grainsize (Fig. 5), data from the mud-dominated Red River and the gravel-dominated Saskatchewan have been excluded, and database outputs have been separately produced for the reaches of the 44 sand-bed rivers, which are the focus of the work presented below. Furthermore, it can be assumed that in some cases the dominant sedimentary structure of a lithofacies is not classified merely because of issues of recognition due to limitations in data quality. To account for this, some of the subsequent analyses are separately undertaken by excluding datasets of sand-bed river reaches for which sedimentary structures are not classified in most lithofacies; as a result, in the considered reaches, the proportion of sandy facies that are not classified with respect to sedimentary structures is always less than 40% of all sandy deposits in the reach. In addition, the relative proportions of sandy lithofacies types are also considered independently (cf., Fig. 5). Below, quantitative facies models are presented that quantify the distribution in proportion of sandy facies in samples of these types, for families of river and reaches classified according to their channel pattern, climate type, and discharge regime.

Figure 5. Proportions of grainsize classes in lithofacies of the river reaches included in this study, and relative proportion of sandy facies types. B = braided; L = low sinuosity; M = meandering. T denotes the sum of the thicknesses of all measured facies units for each river. See Table 1 for facies codes.

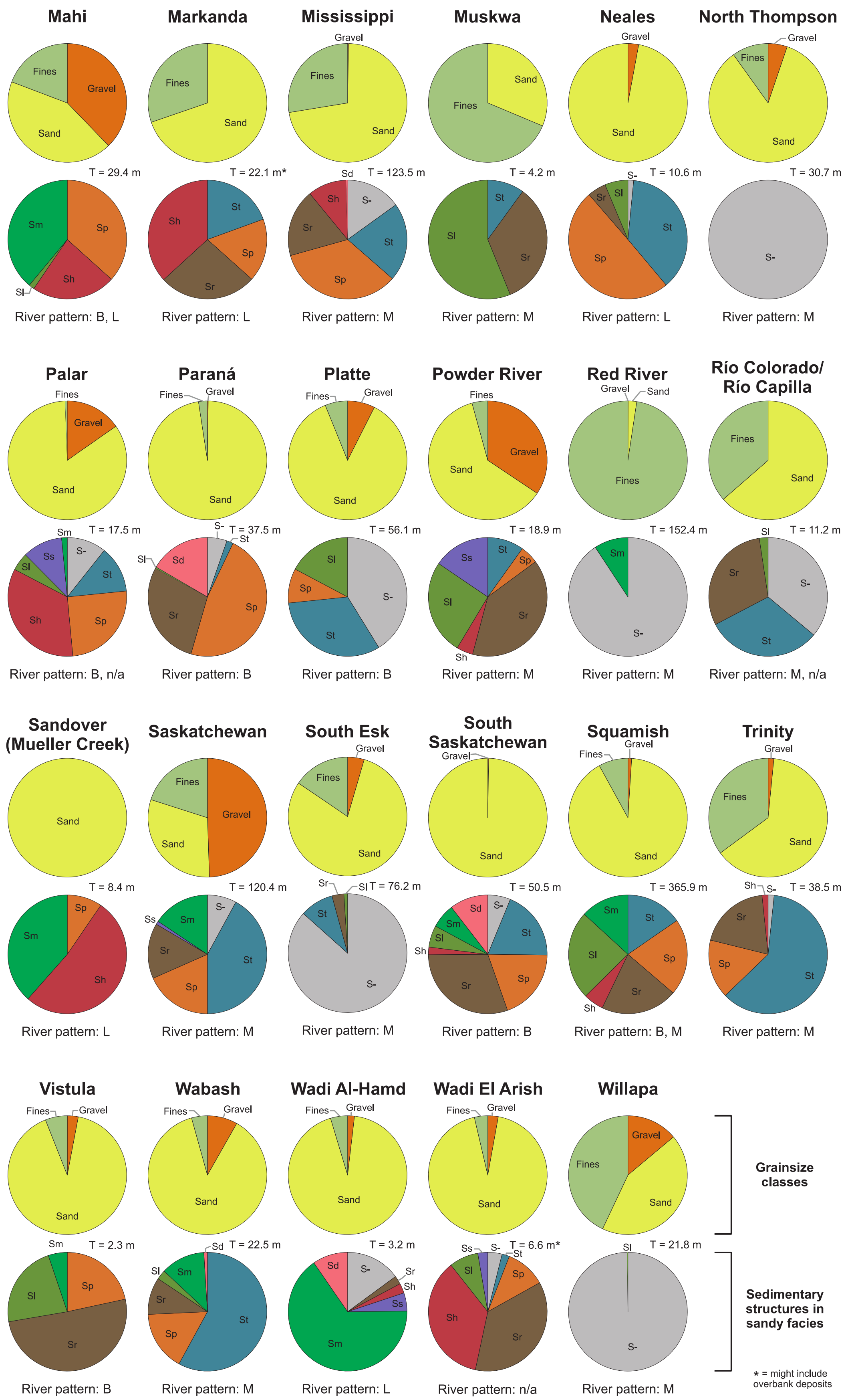

Figure 5. [Continued[

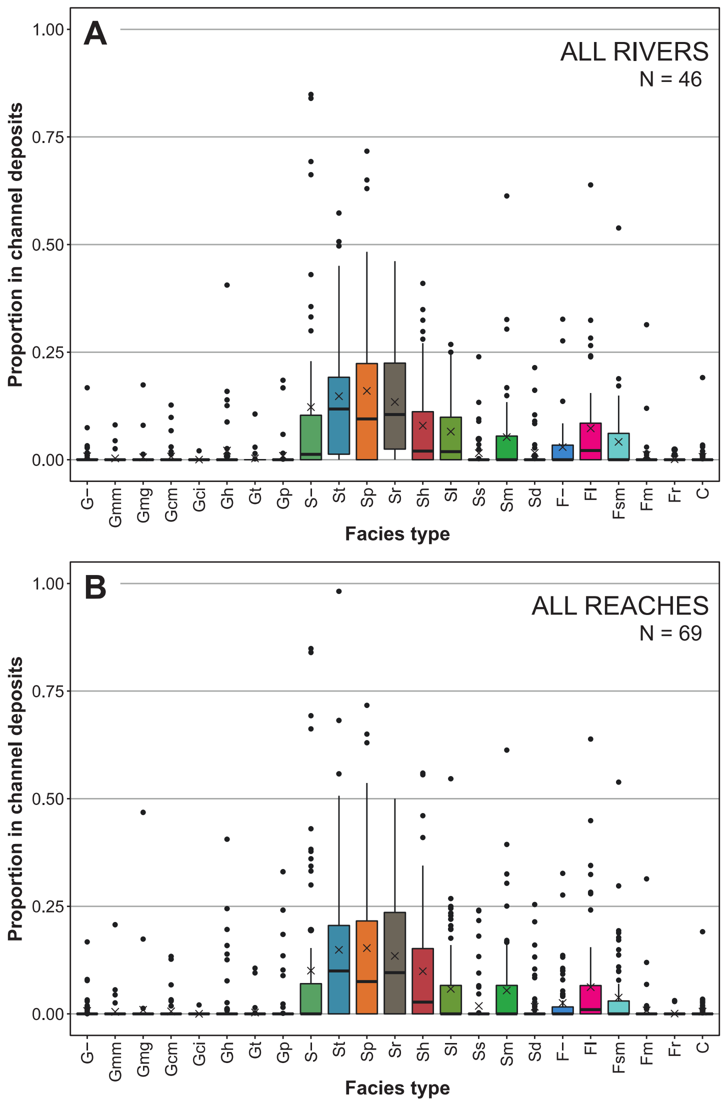

Figure 6. Distributions in facies proportions in the channel deposits of the studied rivers, assessed by river (A), and by river reach (B). See Table 1 for facies codes.

3.1 Facies proportions and channel patterns

Distributions and descriptive statistics relating to the proportion of sandy facies (cf., Table 1) are presented for samples consisting of 42 of the studied sand-bed rivers, i.e., those that are classified according to channel pattern (Figs. 7A, 8A); proportions of sandy facies are also presented for their distinct reaches (Figs. 7B, 8B), and for a selection thereof unaffected by problems of facies recognition (corresponding to reaches in which at least 60% of the sandy facies are classified on sedimentary structure; Figs. 7C, 8C); the relative abundance of sandy facies across all reaches is also shown (Figs. 7D, 8D). Facies-proportion statistics are separately obtained for: (i) families classified as displaying a channel pattern being braided, meandering, or single-thread low-sinuosity (Fig. 7); (ii) families of high- (meandering) and low-sinuosity (braided, single-thread) rivers (Fig. 8). For all sandy facies types, Wilcoxon rank-sum tests are performed to test the significance of differences between their distributions in datasets for high- and low-sinuosity fluvial systems (Table 3). Ninety-five-percent confidence intervals of median facies proportions in high- and low-sinuosity rivers are reported in Fig. 9.

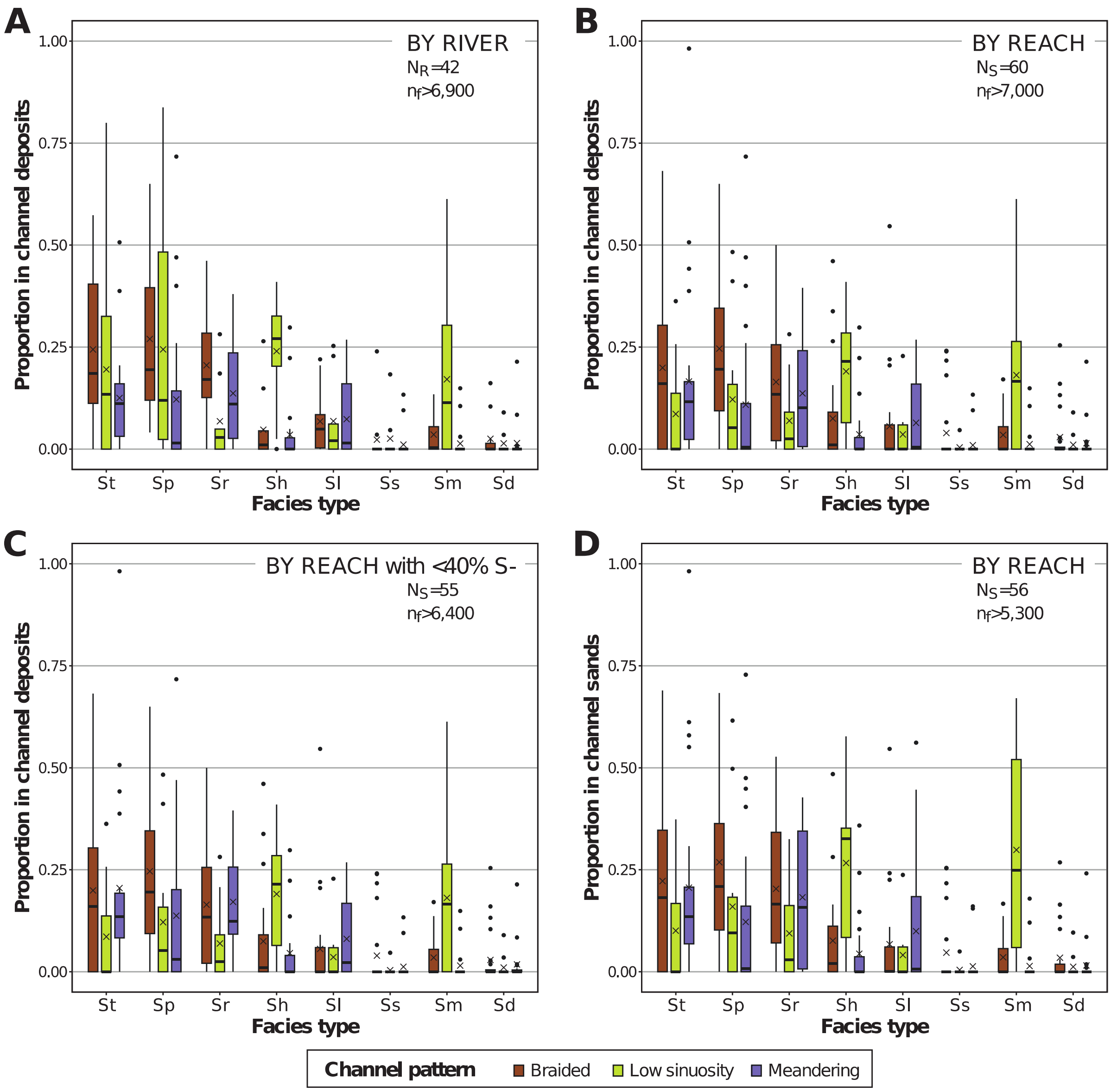

Figure 7. Distributions in sandy facies proportions of the channel deposits of fluvial systems classified by channel pattern. Distributions in facies proportions are presented by considering samples as being represented by: rivers (A), river reaches (B), reaches in which the relative proportion of sandy facies that are not classified on sedimentary structure is less than 40% (C), sandy deposits in river reaches (D). N_f = number of facies; N_R = number of rivers; N_S = number of reaches. See Table 1 for facies codes.

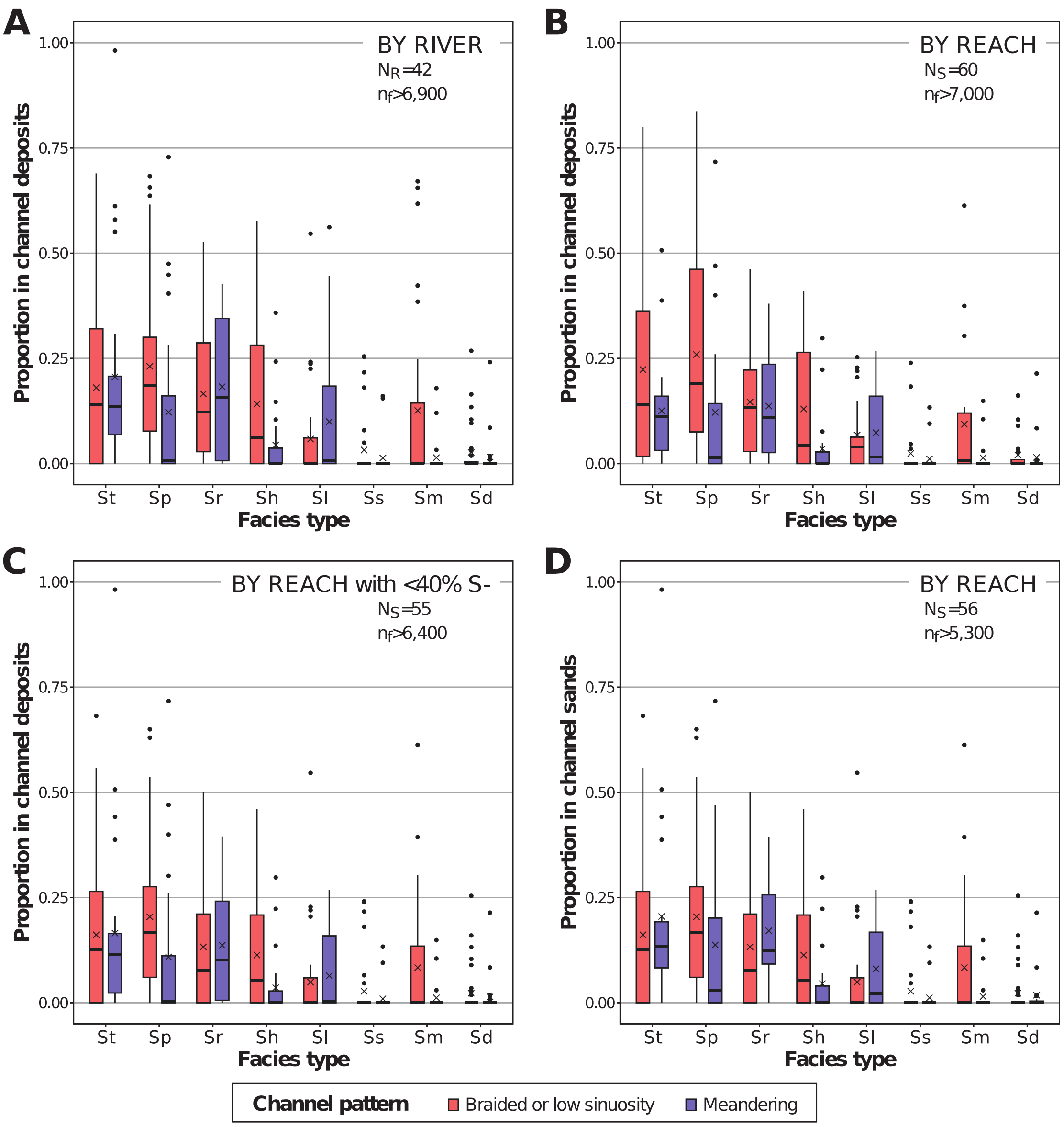

Figure 8. Distributions in sandy facies proportions of the channel deposits of meandering vs braided or low-sinuosity fluvial systems. Distributions in facies proportions are presented by considering samples as being represented by: rivers (A), river reaches (B), reaches in which the relative proportion of sandy facies that are not classified on sedimentary structure is less than 40% (C), sandy deposits in river reaches (D). N_f = number of facies; N_R = number of rivers; N_S = number of reaches. See Table 1 for facies codes.

The following observations are made:

- The median proportion of both trough and planar cross-stratified sands (St, Sp) is higher in the channel deposits of braided rivers (Fig. 7). More generally, the mean and median proportions of planar cross-stratified sands (Sp) are higher, by as much as 17% of total percentages (median), in the channel deposits of low-sinuosity (braided or single-thread) rivers compared to meandering rivers (Fig. 8). For all four types of samples, differences in the distributions of Sp proportions in high- and low-sinuosity (braided or single-thread) rivers are statistically significant at α of 0.1 based on Wilcoxon rank-sum tests (Table 3).
- The mean and median proportions of ripple cross-laminated sands (Sr) are lower in the channel deposits of single-thread low-sinuosity rivers (Fig. 7).
- The mean and median proportions of planar horizontally bedded sands (Sh) are higher in the channel deposits of low-sinuosity single-thread rivers, and smallest for meandering rivers

(Fig. 7). The difference in mean proportion of Sh is up to 10% of total percentages between high- and low-sinuosity rivers (Fig. 8), for which differences in the distributions are statistically significant at α of 0.1 based on Wilcoxon rank-sum tests across all four types of samples (Table 3).

- The mean and median proportions of massive sands (Sm) are highest in the channel deposits of low-sinuosity single-thread rivers, and smallest for meandering rivers (Fig. 7). The difference in mean proportion of Sm is up to 11% of total percentages between high- and low-sinuosity rivers (Fig. 8), for which differences in the distributions are statistically significant at α of 0.05 based on Wilcoxon rank-sum tests across all four types of samples (Table 3).

Table 3. P-values resulting from Wilcoxon rank-sum tests between distributions in sandy facies proportions of the channel deposits of meandering and braided or low-sinuosity fluvial systems. Distributions in facies proportions have been separately tested by considering samples as being represented by: (i) rivers (N=42), (ii) river reaches (N=60), (iii) reaches in which the relative proportion of sandy facies that are not classified on sedimentary structure is less than 40% (N=55), and (iv) sandy deposits in river reaches (N=56). P-values lower than 0.05 are highlighted in bold to indicate differences in facies proportions that are significant at that level. See Table 1 for facies codes.

Braided/low sinuosity vs meandering rivers	Facies							
	St	**Sp**	**Sr**	**Sh**	**Sl**	**Ss**	**Sm**	**Sd**
by river	0.224	**0.014**	0.880	**0.018**	0.787	0.397	**0.009**	0.429
by reach	0.914	**0.011**	0.754	**0.011**	0.475	0.338	**0.006**	0.746
by reach <40% S-	0.360	0.097	0.173	0.060	0.231	0.516	**0.021**	0.934
in sands	0.842	**0.009**	0.843	**0.007**	0.730	0.534	**0.012**	0.622

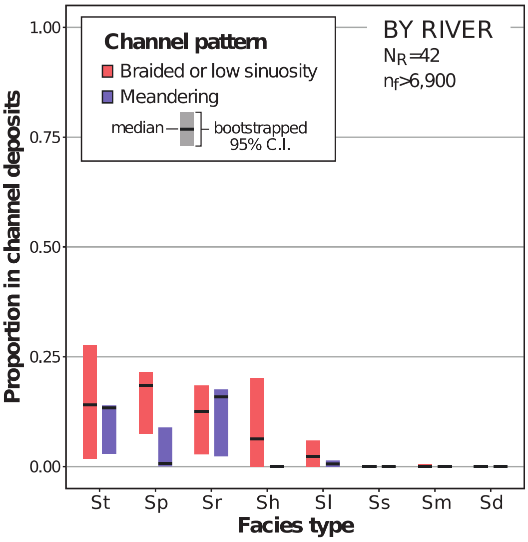

Figure 9. Median proportions of sandy facies in channel deposits of sandy rivers, for meandering vs braided or low-sinuosity fluvial systems, plotted with ninety-five-percent confidence intervals based on bootstrap with the bias-corrected and accelerated method (Efron & Tibshirani, 1986). Results based on 10,000 bootstrap resamples. See Table 1 for facies codes.

3.2 Facies proportions and basin climate

Distributions and statistics of the proportion of sandy facies are separately obtained for: (i) families of fluvial systems classified on the Thornthwaite moisture index (Thornthwaite, 1948) at the studied locations (Fig. 10), and (ii) families of rivers that either occur in dryland regions (i.e., with arid to dry subhumid climate) or in areas with moist to perhumid climates (Fig. 11). These data are again presented for samples consisting of the studied sand-bed rivers (Figs. 10A, 11A), their distinct reaches

(Figs. 10B, 11B), a selection thereof in which at least 60% of the sandy facies are classified according to their sedimentary structures (Figs. 10C, 11C), and as the relative proportion of sandy facies across all reaches (Figs. 10D, 11D). For all sandy facies types, Wilcoxon rank-sum tests are performed to test the significance of differences between their distributions in datasets of dryland and non-dryland (moist subhumid to perhumid) environments (Table 4). Ninety-five-percent confidence intervals of median facies proportions in dryland and non-dryland rivers are reported in Fig. 12.

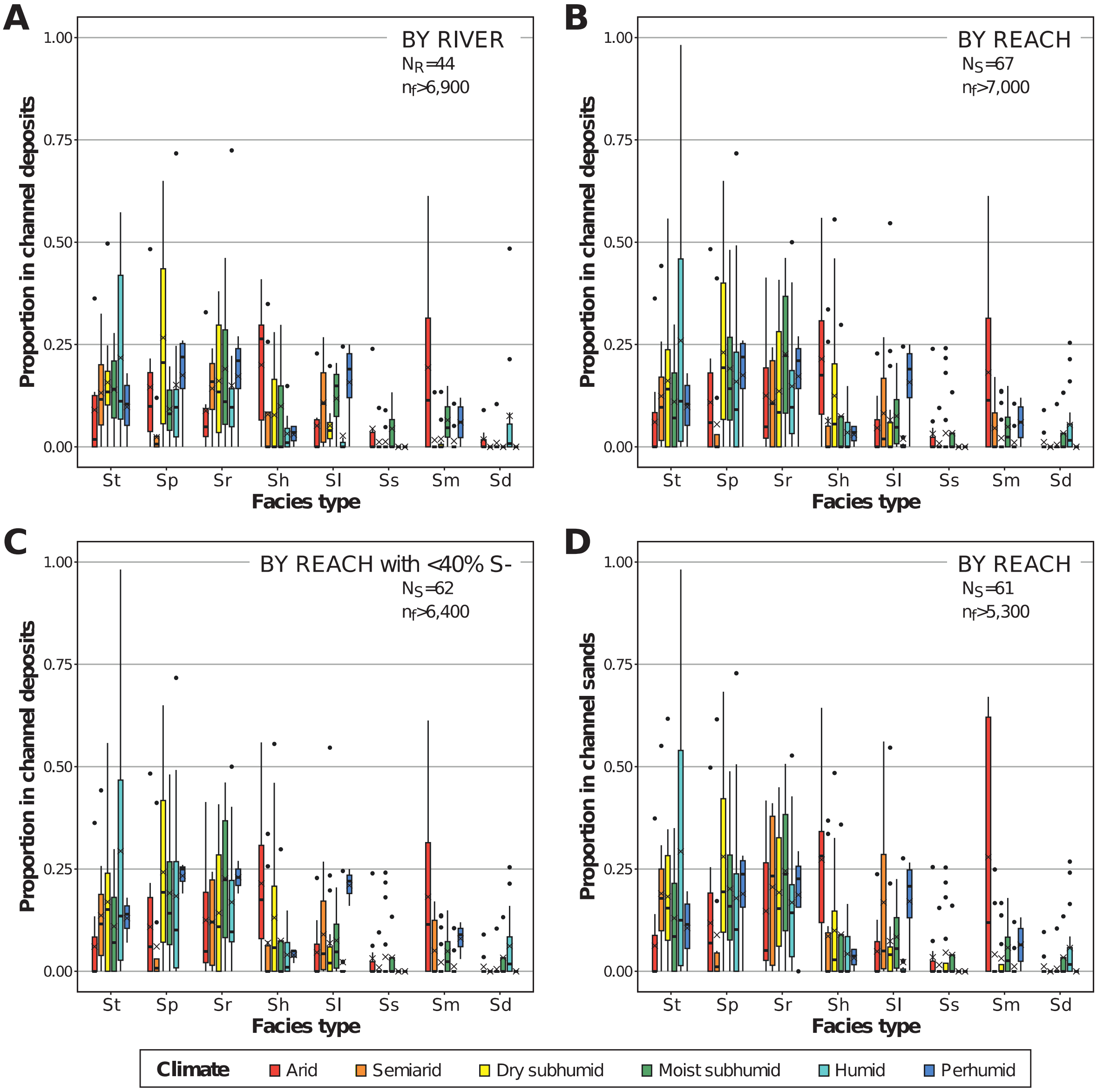

Figure 10. Distributions in sandy facies proportions of the channel deposits of fluvial systems classified on Thornthwaite climate types at the studied locations. Distributions in facies proportions are presented by considering samples as being represented by: rivers (A), river reaches (B), reaches in which the relative proportion of sandy facies that are not classified on sedimentary structure is less than 40% (C), sandy deposits in river reaches (D). N_f = number of facies; N_R = number of rivers; N_S = number of reaches. See Table 1 for facies codes.

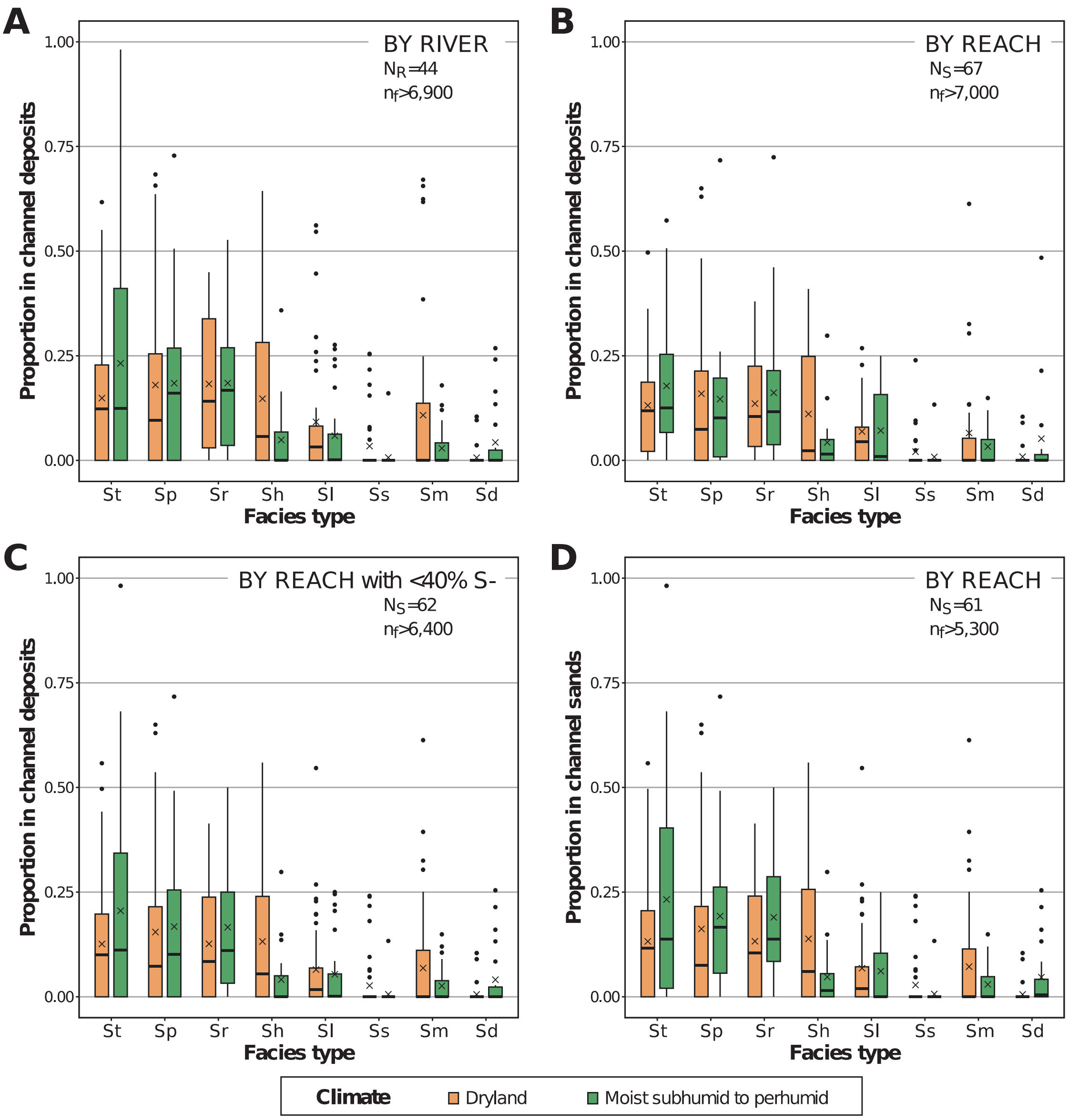

Figure 11. Distributions in sandy facies proportions of the channel deposits of dryland vs non-dryland fluvial systems. Distributions in facies proportions are presented by considering samples as being represented by: rivers (A), river reaches (B), reaches in which the relative proportion of sandy facies that are not classified on sedimentary structure is less than 40% (C), sandy deposits in river reaches (D). N_f = number of facies; N_R = number of rivers; N_S = number of reaches. See Table 1 for facies codes.

The following observations are made:

- The mean proportion of trough cross-stratified sands (St) appears to be higher in the channel deposits of rivers flowing in humid regions (Fig. 10), and generally lower for dryland rivers (Fig. 11); however, differences in the distributions of St proportion between dryland and non-dryland rivers are not statistically significant (Table 4).
- The mean proportions of planar cross-stratified (Sp) and ripple cross-laminated (Sr) sands are comparable between dryland rivers and rivers occurring in more humid areas (Fig. 11; Table 4), as differences across these two classes of systems are not statistically significant.
- The average cumulative proportion of trough- or planar cross-stratified sands (St, Sp) or ripple cross-laminated sands (Sr) is lower in the channel deposits of dryland river reaches (41%), compared to those of rivers in wetter climates (54%), although the difference is not

statistically significant at the 0.1 level (two-sample t-test: T = -1.67, d.f. = 43, p-value = 0.103).

- The mean and median proportions of planar horizontally bedded sands (Sh) and massive sands (Sm) are higher in the channel deposits of rivers in arid climates (Fig. 10). The difference in mean proportion of Sh and Sm are up to 10% and 8%, respectively, of total percentages between rivers of drylands and wetter environments (Fig. 11); for both facies types, differences in the distributions are statistically significant at α of 0.05 based on Wilcoxon rank-sum tests applied to the channel deposits of the river reaches and to their sand fractions (Table 4).
- The largest values in mean and median absolute proportion of low-angle cross-stratified sands (Sl) are seen in the channel deposits of rivers from perhumid climates, and particularly in reaches of the Squamish River (Fig. 5). The difference in distributions in proportions of Sl between dryland and non-dryland rivers (Fig. 11) are not statistically significant (Table 4).
- Scour-fill sands (Ss) appear to be marginally more common in the channel deposits of dryland rivers (Fig. 11); however, differences in the distributions of Ss proportion between dryland and non-dryland rivers are not statistically significant (Table 4).
- The mean proportion of sands with soft-sediment deformation (Sd), which is mostly expressed as convoluted bedding, is lower in the channel deposits of dryland rivers, by 4% of all channel deposits (Fig. 11); differences in the distributions of Sd proportion between dryland and non-dryland river reaches are statistically significant at α of 0.05 based on Wilcoxon rank-sum tests (Table 4).

Table 4. P-values resulting from Wilcoxon rank-sum tests between distributions in sandy facies proportions of the channel deposits of fluvial systems located in drylands and in moist to wet climate zones. Distributions in facies proportions have been separately tested by considering samples as being represented by: (i) rivers (N=44), (ii) river reaches (N=67), (iii) reaches in which the relative proportion of sandy facies that are not classified on sedimentary structure is less than 40% (N=62), and (iv) sandy deposits in river reaches (N=61). P-values lower than 0.05 are highlighted in bold to indicate differences in facies proportions that are significant at that level. See Table 1 for facies codes.

Rivers in dryland vs wetter climates	**Facies**							
	St	**Sp**	**Sr**	**Sh**	**Sl**	**Ss**	**Sm**	**Sd**
by river	0.631	0.571	0.905	0.430	0.678	0.800	0.877	0.051
by reach	0.370	0.636	0.295	**0.038**	0.791	0.114	0.574	**0.001**
by reach <40% S-	0.225	0.347	0.148	0.061	0.789	0.142	0.692	**0.000**
in sands	0.471	0.740	0.915	**0.027**	0.398	0.074	0.472	**0.011**

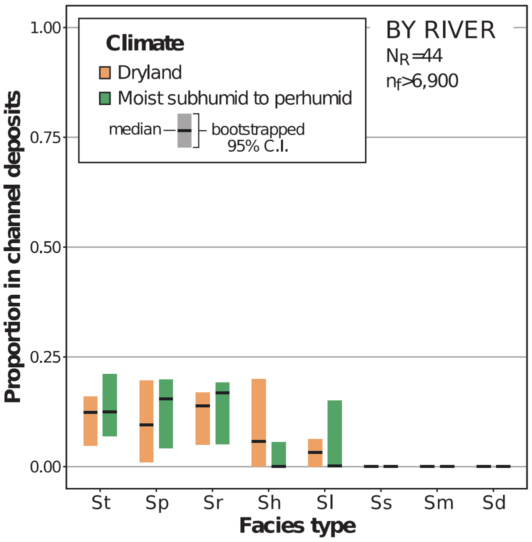

Figure 12. Median proportions of sandy facies in channel deposits of sandy rivers, for dryland vs non-dryland fluvial systems, plotted with ninety-five-percent confidence intervals based on bootstrap with the bias-corrected and accelerated method (Efron & Tibshirani, 1986). Results based on 10,000 bootstrap resamples. See Table 1 for facies codes.

3.3 Facies proportions and discharge regime

Distributions and statistics of the proportion of sandy facies are separately obtained for families of fluvial systems classified on discharge regime as either temporary (i.e., ephemeral or intermittent) or perennial (Fig. 13); these data are again presented for samples consisting of the studied sand-bed rivers (Fig. 13A), their distinct reaches (Fig. 13B), a selection thereof in which at least 60% of the sandy facies are classified according to their sedimentary structures (Fig. 13C), and as the relative proportion of sandy facies across all reaches (Fig. 13D). For all sandy facies types, Wilcoxon rank-sum tests are performed to test the significance of differences between their distributions in the two families of river systems (Table 5). Ninety-five-percent confidence intervals of median facies proportions in perennial and temporary rivers are reported in Fig. 14.

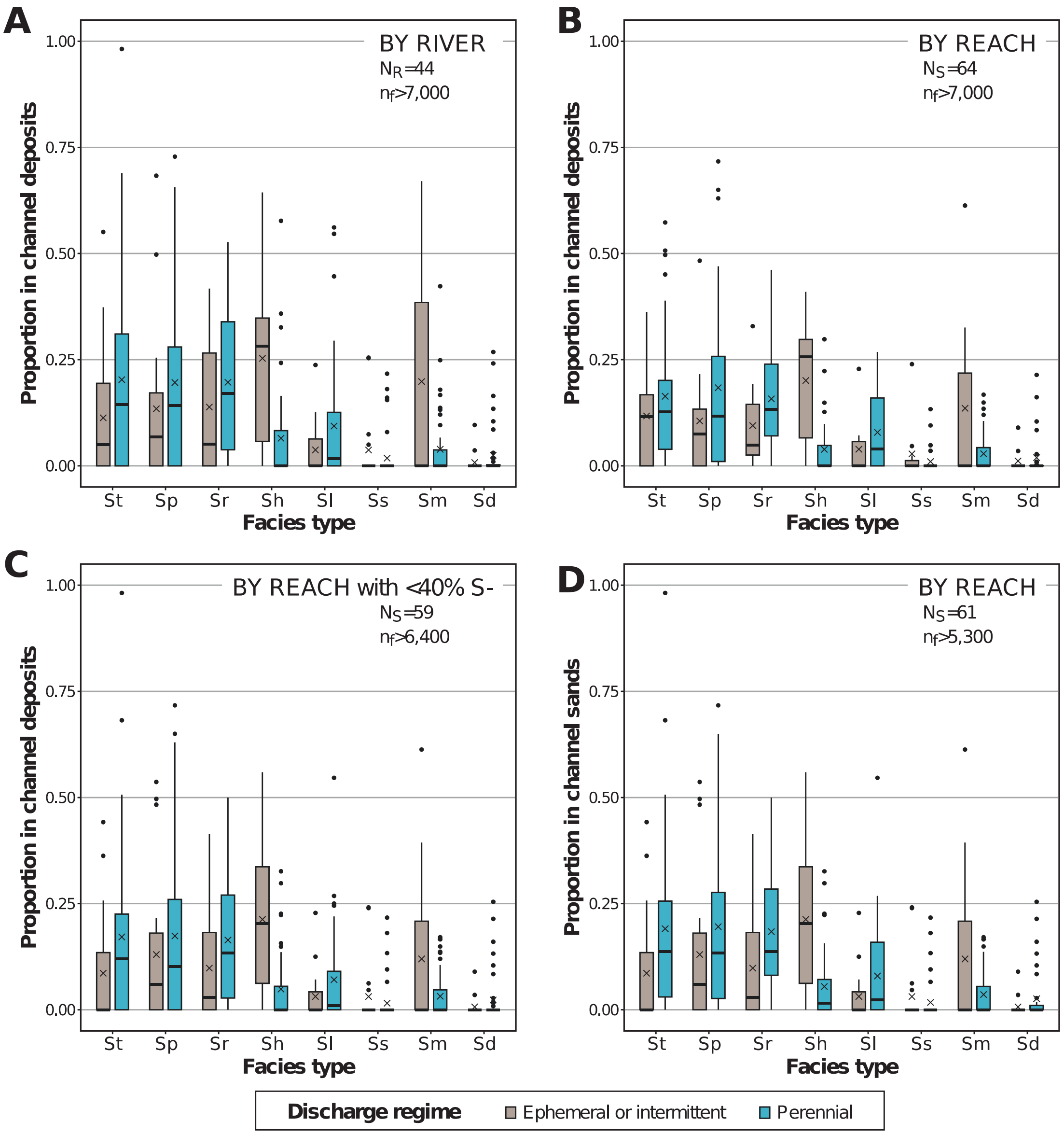

Figure 13. Distributions in sandy facies proportions of the channel deposits of fluvial systems classified on discharge regime. Distributions in facies proportions are presented by considering samples as being represented by: rivers (A), river reaches (B), reaches in which the relative proportion of sandy facies that are not classified on sedimentary structure is less than 40% (C), sandy deposits in river reaches (D). N_f = number of facies; N_R = number of rivers; N_S = number of reaches. See Table 1 for facies codes.

The following observations are made:

- The mean and median proportions of trough and planar cross-stratified sands (St, Sp) and ripple cross-laminated sands (Sr) are higher in the channel deposits of perennial rivers, across all four sample types (Fig. 13). Differences in the distributions of absolute facies proportions between perennial and temporary river reaches are statistically significant at α of 0.05 for St and at α of 0.1 for Sr, based on Wilcoxon rank-sum tests (Table 5).
- The average cumulative proportion of trough- or planar cross-stratified sands (St, Sp) or ripple cross-laminated sands (Sr) is higher in the channel deposits of perennial reaches (51%), compared to those of ephemeral or intermittent rivers (31%), to a statistically significant level (two-sample t-test: $T = -2.69$, d.f. = 44, p-value = 0.010).
- The mean and median proportion of planar horizontally bedded sands (Sh) is higher, by as much as 28% of the absolute percentages (median), in the channel deposits of ephemeral or

intermittent rivers (Fig. 13). For all four types of samples, differences in the distributions of Sh proportions in perennial and temporary rivers are statistically significant at α of 0.005 (Table 5).

- The mean and median proportions of low-angle cross-stratified sands (Sl) are higher by up to 6% of the absolute percentages (mean), in the channel deposits of perennial rivers (Fig. 13). Differences in the distributions for classes of discharge regime are only statistically significant, at α of 0.1, in reaches where at least 60% of the sandy facies are classified on sedimentary structure (Table 5).
- Scour-fill sands (Ss) appear to be marginally more frequent in the channel deposits of ephemeral or intermittent rivers (Fig. 13); however, differences in the distributions of Ss proportion between classes of discharge regime are not statistically significant (Table 5).
- The mean proportion of massive sands (Sm) is higher in the channel deposits of ephemeral or intermittent rivers, by up to 16% of all channel deposits (Fig. 13); however, differences in the distributions of Sm proportion between perennial and temporary river reaches are statistically significant at α of 0.05 only when relative proportions of sandy facies are considered (Table 5).

Table 5. P-values resulting from Wilcoxon rank-sum tests between distributions in sandy facies proportions of the channel deposits of perennial and ephemeral or intermittent fluvial systems. Distributions in facies proportions have been separately tested by considering samples as being represented by: (i) rivers (N=44), (ii) river reaches (N=64), (iii) reaches in which the relative proportion of sandy facies that are not classified on sedimentary structure is less than 40% (N=59), and (iv) sandy deposits in river reaches (N=61). P-values lower than 0.05 are highlighted in bold to indicate differences in facies proportions that are significant at that level. See Table 1 for facies codes.

Ephemeral/intermittent vs perennial rivers	**Facies**							
	St	**Sp**	**Sr**	**Sh**	**Sl**	**Ss**	**Sm**	**Sd**
by river	0.387	0.280	0.157	**0.002**	0.190	0.394	0.112	0.758
by reach	**0.044**	0.331	0.070	**0.000**	0.147	0.307	0.102	0.217
by reach <40% S-	**0.015**	0.130	**0.017**	**0.000**	0.091	0.407	0.167	0.152
in sands	0.106	0.224	0.205	**0.000**	0.226	0.241	**0.042**	0.271

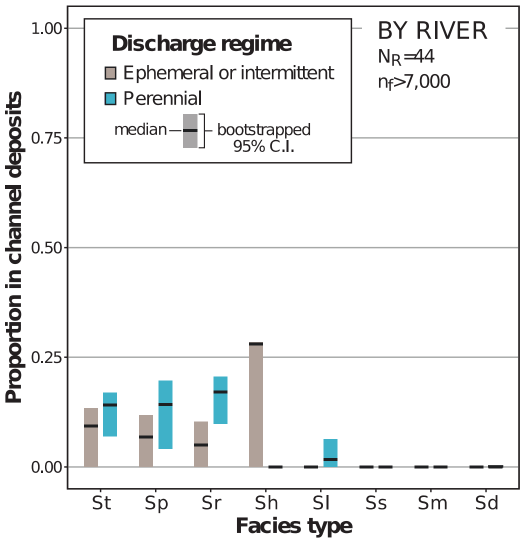

Figure 14. Median proportions of sandy facies in channel deposits of sandy rivers, for perennial vs temporary fluvial systems, plotted with ninety-five-percent confidence intervals based on bootstrap with the bias-corrected and accelerated method (Efron & Tibshirani, 1986). Results based on 10,000 bootstrap resamples. See Table 1 for facies codes.

For selected sandy facies types, relationships are also investigated between their proportion among sands in channel deposits and the discharge peakedness (sensu Leier et al., 2005) of their respective reaches (Fig. 15). Additionally, for certain facies, proportions are assessed against the size of the catchment areas of each reach, in consideration of how drainage areas of different sizes are expected to respond to flood waves and modulate water discharge. The following observations are made:

- A weak positive relationship is seen between the relative proportion of planar horizontally bedded sands (Sh) among all sandy facies and the measure of discharge peakedness (Pearson's correlation coefficient $r = 0.281$; p-value = 0.147; Fig. 15A).
- No correlation exists between the proportion of low-angle cross-stratified sands (Sl) and discharge peakedness ($r = 0.089$; p-value = 0.653; Fig. 15A).
- When Sh and Sl facies are considered jointly, a modest positive relationship is seen between the cumulative proportion of these facies and discharge peakedness (Pearson's correlation coefficient $r = 0.320$; p-value = 0.097; Fig. 15B), whereas a modest negative relationship is seen between their proportion and the size of the catchment of the reaches in which they occur ($r = -0.346$; p-value = 0.007). When Sh, Sl, Ss (scour-fill sands) and Sm (massive sands) facies are considered jointly, a modest positive relationship is seen between their cumulative proportion and discharge peakedness ($r = 0.393$; p-value = 0.038; Fig. 15B); again, a weak negative relationship is seen between their proportion and the size of catchments ($r = -0.365$; p-value = 0.004).
- A weak negative relationship is seen between the proportion of ripple cross-laminated sands (Sr) and discharge peakedness (Pearson's correlation coefficient $r = -0.266$; p-value = 0.171; Fig. 15C).
- When trough and planar cross-stratified sands are considered jointly, no correlation is seen between their cumulative proportion and discharge peakedness ($r = 0.014$; p-value = 0.942; Fig. 15A).
- A very weak negative correlation is seen between the cumulative proportion of sands with soft-sediment deformation and discharge peakedness ($r = -0.152$; p-value = 0.450).
- For the studied reaches, the average discharge peakedness of braided rivers is higher than that of meandering rivers (3.1 vs 2.2); this difference is statistically significant at the 0.05 level (two sample t-test: $t = 2.29$, $df = 24$, p-value = 0.031).

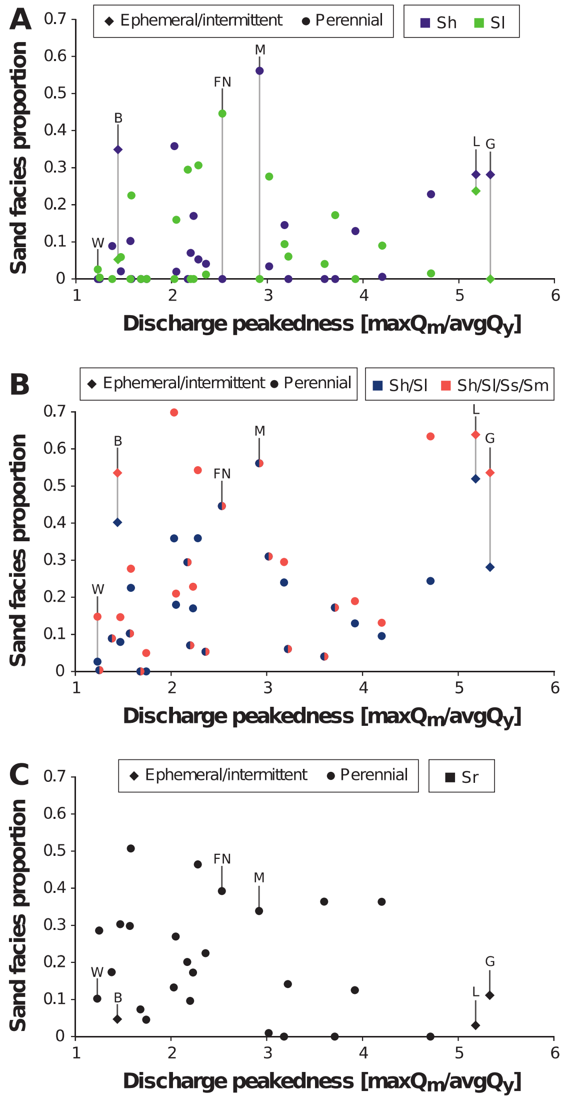

Figure 15. Cross-plot of proportion of facies types in the channel deposits of the studied reaches against a measure of river seasonality and discharge peakedness, provided by the ratio between the average monthly water discharge for the month when the river carries the largest flow and the mean annual discharge (cf., Leier et al. 2005). Data on 28 river reaches that are located in proximity of gauging stations. Selected rivers are labelled to provide context. (A) Proportions of facies Sh and Sl against discharge peakedness. (B) Cumulative proportions of facies Sh and Sl, and of facies Sh, Sl, Ss and Sm, against discharge peakedness. Half-and-half spots denote reaches for which the two proportions are the same. (C) Proportions of facies Sr against discharge peakedness. W = Wabash; B = Bijou Creek; FN = Fort Nelson; M = Muskwa; L = Luni; G = Gash. See Table 1 for facies codes.

4 DISCUSSION

4.1 Interpretation of facies and of variations in their frequency across river types

Considering the dominance of point bars and braid bars in meandering and braided rivers respectively, and of alternate bars or featureless beds in low-sinuosity rivers (Church, 2006, and references therein), the current analysis could ideally provide insight into the degree of association between types of macroforms and lower-scale bedforms as a form of self-organization in sand-bed rivers. However, the sampling of channel deposits undertaken in the original studies considered is not systematic with respect to channel sub-environment and sample size, and therefore care must be exercised in any comparison. By adopting the climatic classification of Thornthwaite, emphasis is placed on the balance between precipitation and potential evapotranspiration, which act as controls, either directly or through multiple levels of intermediate variables (e.g., vegetation density and type, alteration and weathering, groundwater table, runoff-generation mechanisms), on river discharge, sediment calibre and supply rate, and bank stability, which ultimately control in-channel processes. Employing such a narrow range of classes (six, from arid to perhumid) is preferable, as it enables meaningful statistical comparisons despite the relatively limited number of case studies. However, in this way, no consideration is given to the effects of other important factors, such as seasonality (e.g., monsoonal variations in discharge) or thermal regime (e.g., meltwater discharge, permafrost). Also, climatic factors are solely considered in terms of moisture budget at the study sites, even though climates in the respective watersheds likely exert a stronger control on river hydrology and might differ significantly, especially for large river basins. Yet, this type of analysis might shed light on the relative frequency of different in-channel processes in different climatic regions, and of whether a distinctive facies signature can be truly seen for dryland river systems. Similarly, the chosen differentiation of rivers into perennial and temporary classes allows testing the role of streamflow discharge regime as the main control on in-channel processes and bedforms. The continuum of discharge variability is also taken into account, by quantifying river seasonality against the mean annual discharge, as proposed by Leier et al. (2005). However, both discharge flashiness and interannual variability, which are significant factors for rivers in drylands (Osterkamp and Friedman, 2000), are ignored; this is particularly highlighted by the fact that Bijou Creek, a stream that has experienced infrequent major floods in response to extreme rainfall (Javier et al., 2007), is characterized by a strikingly low value of estimated discharge peakedness (Fig. 15).

Cross-stratification generated by migrating sinuous and straight-crested dunes is often reported as the most common sedimentary structure in the deposits of braided rivers (Reesink et al., 2014, and references therein). Cross-stratification of equivalent scale can also be related to unit bars, and in particular to transverse bars that undergo leeside accretion (e.g., Sambrook Smith et al., 2006; Reesink and Bridge, 2011): unit bars that evolve in a manner that would produce cross-stratified sets of this type, albeit also seen in meandering channels (e.g., Levey, 1977, Reesink, 2019), are usually considered as characteristic bedforms of braided rivers. Although these views appear to be in accord with the data presented here, it must be noted that the overlap in distributions of abundance across families of channel pattern is remarkable, highlighting how any such observation on facies organization of channel deposits has very limited diagnostic value for rock-record interpretations of river planforms. It can also be noted that the expected contrasting stream power of braided and meandering rivers (Leopold and Wolman, 1957; Ferguson, 1987; van den Berg, 1995) is not strongly reflected in the difference in frequency of cross-laminated and cross-stratified sands; in particular only modest differences in descriptive statistics of the proportions of ripple cross-laminated sands are seen across the two types. The increased cumulative proportion of trough and planar cross-stratified sands in braided channel belts can be interpreted as reflecting a higher fraction (or at least more frequent sampling; Table 2) of deposits recording the infill of channels traversed by dunes and undergoing thalweg shoaling (cf., Fig. 4), relative to bar-accretion deposits. The observation that the cumulative proportions of trough and planar cross-stratified sands and cross-laminated sands are higher on average in the channel deposits of perennial rivers and in those of rivers from moist to wet climates, compared to those of ephemeral and dryland rivers (by 20% and 13% of all channel deposits, respectively), supports the notion that sand accumulation under subcritical flow conditions occurs and is preserved more frequently in sand-bed rivers of the former types (Plink-Björklund, 2015; Fielding et al., 2018). However, based on discharge-peakedness analysis, river seasonality does not appear to be an equally good predictor of the abundance of lower-flow-regime sands, contrary to what might be expected (cf., Plink-Björklund, 2015).

The vast majority of the studied low-sinuosity rivers occur in arid to semiarid regions and are characterized by ephemeral discharge (Fig. 3). This aligns with the understanding that limited macroform development is a typical feature of rivers that are subject to highly variable water discharge (Tooth, 2000; Billi, 2007; Plink-Björklund, 2015; Fielding et al., 2018), even though braided rivers are thought to be most common, and meandering rivers not uncommon, in dryland settings favourable to these conditions (Tooth, 2000; Billi et al., 2018). The significantly larger values of mean and median proportions of planar horizontally bedded sands seen in channel sediments of low-sinuosity rivers can thus be explained by the fact that these rivers are prone to floods with flashy

hydrographs, conducive to deposition under conditions of upper-stage plane beds (Picard and High, 1973; Reid and Frostick, 1987). Channel deposits of the same low-sinuosity reaches are also characterized, on average, by markedly larger proportions of sands that appear massive. The origin of massive sands can be either primary or post-depositional, and in some cases the massive appearance might be due to laminations being faint or non-visible (cf., Hamblin, 1965). In the studied reaches, some of the massive sandy beds are interpreted as the direct product of depositional processes (e.g., Ringrose et al., 2018; Carling and Leclair, 2019). Massive sands of primary origin can result from the rapid dumping of sand from suspension, and are often interpreted as deposited by hyperconcentrated flows, or more rarely by mass flows (cf., Scott, 1988; Maizel, 1993; Svendsen et al., 2003). Occasionally, massive sands represent, or are associated with, the deposits of upper flow-regime bedforms (Alexander et al., 2001; Cartigny et al., 2014; Froude et al., 2017). Deposition of massive sands can take place during floods, possibly under waning-flow conditions (Knight and Evans, 2017) or as a result of liquefaction due to bank collapse (Martin and Turner, 1998; cf., van den Berg et al., 2017). The importance of bank failure as a potential trigger to the deposition of massive sands, and of bank strength as a controlling factor on their proportion, is likely limited for the studied examples, as it would be in apparent contrast with the more frequent occurrence of massive sands in: (i) low-sinuosity rivers, as these likely have relatively more stable planforms; and (ii) in dryland systems, as these likely experience reduced soil-moisture conditions, albeit also having sparser vegetation cover. In some of the examples, the massive structure of channel sands is inferred to be due to bioturbation, taking place on exposed river beds during prolonged dry intervals (e.g., Sridhar et al., 2013; Ghandour et al., 2016). Differences in the proportions of massive and horizontally bedded sands seen across rivers in dryland and wetter climates and across rivers in ephemeral to intermittent and perennial rivers mirror differences seen between low-sinuosity rivers and rivers with meandering and braided planform styles. This reflects the expected dominance of upper-flow-regime conditions in the channel deposits of dryland ephemeral river systems (Picard and High, 1973; Miall, 1996). It is notable, however, that analogous differences in facies statistics across the same families of rivers are not seen for distributions in the proportion of either scour-fill sands or low-angle cross-stratified sands (Figs. 7, 10 and 11), which are thought to record deposition under high-energy conditions, especially by migrating bedforms within – or at the transition to – the upper flow-regime, or as plane-bed deposits over inclined surfaces (Miall, 1996; Alexander et al., 2001; Fielding, 2006; Cartigny et al., 2014). Nonetheless, the observed relationships between the proportions of facies that may have been deposited by supercritical flows (horizontally bedded, low-angle cross-stratified, massive, and scour-fill sands) and both discharge peakedness (cf., Fig. 15B) and catchment size suggest that variability in water discharge might leave a recognizable record in the facies architecture of channel deposits. However, this also suggests that a relatively similar facies signature might be left by discharge variability whether be it due to seasonality or linked to the size of drainage areas; the latter factor likely reflects how smaller and steeper river basins are typically characterized by stronger differences between high-magnitude floods and baseflow (cf., Smith, 1992; Robinson and Sivapalan, 1997; Sømme et al., 2009), in part as an effect of the relative size of catchments and convective storms, and possibly because of relationships between catchment gradient and size with runoff and transmission loss (Nassif and Wilson, 1975; Pilgrim, 1983; Fox et al., 1997).
The increased proportion of sands with soft-sediment deformation in the channel deposits of rivers with more perennial discharge and from wetter climates (Figs. 10 and 11) might reflect the relative frequency and extent to which channel-belt sediments are in water-saturated conditions across these environments. There is no evidence to suggest that soft-sediment deformation is more commonly recorded in the channel deposits of ephemeral rivers that experience flashy discharge (cf., Rana et al., 2016). Similarly, data across the spectrum of discharge peakedness indicate that seasonality in water discharge does not appear to control the frequency of soft-sediment deformation in the manner suggested by Plink-Björklund (2015).

4.2 Implications for environmental interpretations

The relative dominance of lithofacies in the facies associations of fluvial systems is still being proposed as a type of observation on which to ground interpretations of environmental setting (Plink-Björklund, 2015; Fielding et al., 2018; Horn et al., 2018). Recognition of a diagnostic value in the lithofacies characteristics of fluvial-channel deposits is potentially important, as it is commonly the main aspect of facies architecture that can be considered in the interpretation of one-dimensional subsurface datasets consisting of cores and/or image logs. The presented analysis offers a systematic assessment of the ability to infer the environmental context of fluvial successions based on the record of the dominance of processes and bedforms provided by channel facies, and gives a measure of the uncertainty in any such interpretation.

In the characterization of hydrocarbon reservoirs, it is still very common to attempt the categorization of stratigraphic intervals of fluvial successions on the basis of the inferred channel pattern of the formative rivers. From an applied standpoint, there is merit in attempting predictions of planform styles because of their relationships with net volumes, static connectivity and petrophysical heterogeneity (Martin, 1993; Shepherd, 2009; Colombera et al., 2017b). Even though it has long been argued that any such inference is fundamentally uncertain, and in some cases not meaningful given the intrinsic temporal and spatial variability of river planforms (Jackson, 1977; Miall, 1985; Bridge, 1993a; Ethridge, 2011; Hartley et al., 2015; Fielding et al., 2018), interpretations are still being made in these terms, in particular by non-specialists. The uncertainty in the interpretation of facies associations is especially significant in data-poor situations, for example where insight from three-dimensional reflection-seismic data (e.g., recognition of bars and channel fills, quantification of channel-belt ‘rugosity’ sensu Payenberg et al., 2014) is limited or not available, and where accretion geometries cannot be established from cores or image logs. In these situations, the proposed quantitative facies models can act as useful references, by highlighting and helping communicate the uncertainty that is related to facies variability in fluvial channel deposits, and which would be translated to any conceptual models of the subsurface.

The ability to make inferences of discharge variability is also potentially important for subsurface studies, because it allows attempts at predicting the larger-scale architectural configuration of alluvial strata and of the types of sedimentary heterogeneities that may occur within sandbodies (cf., Plink-Björklund, 2015; Nicholas et al., 2016; Esposito et al., 2018; Fielding et al., 2018). Likewise, in outcrop studies of the rock record, the relative frequency of facies with sedimentary structures relating to bedforms and processes that are typically produced under lower and upper flow-regimes are often taken as indicators of water-discharge seasonality and flashiness and as evidence for environmental change, though usually in combination with other independent geological proxies, such as larger-scale sedimentary architectures or pedogenic features (Fielding, 2006; Plink-Björklund, 2015; Sakai et al., 2016; Colombera et al., 2017a; Gall et al., 2017; Fielding et al., 2018; Soares et al., 2018; Bataille et al., 2019). Data from the studied river reaches support the view that discharge regime is a primary control on the facies organization of fluvial channel deposits, as differences and trends are seen statistically. However, overlaps in distributions of facies proportions are still important, suggesting that caution is advisable when making interpretations of the environmental significance of the facies arrangements of channel bodies.

5 CONCLUSIONS

A meta-analysis has been undertaken of several published datasets of the facies organization of modern and recent channel deposits, from rivers distributed globally and considered with respect to their planform style, climatic setting, and discharge characteristics.

Bearing in mind the limitations of a study of this type, the results of this work have implications for the value of lithofacies data for rock-record interpretations, which can be summarized as follows.

- The proposed synthesis on the proportion of facies in modern rivers (Fig. 5) represents a collection of example facies arrangements in fluvial-channel deposits that, with consideration of the type of sub-environment being sampled in each (Table 2), can be referred to for the identification of possible actualistic analogues to ancient subsurface or outcropping successions.
- Quantitative facies models (Figs. 7-13) are presented that account for variability of facies proportions in the channel deposits of sand-bed river systems of different types. These serve

as templates for sedimentological interpretations that provide a measure of uncertainty to conceptual models of the subsurface that are based on limited core data.

- A test is made of relationships between the relative proportion of channel lithofacies and parameters that represent controlling factors and covariates, for sand-bed rivers. The effect of discharge characteristics on the facies record of upper and lower flow-regime conditions and possible relationships between channel pattern and bedform frequency are observed statistically, but seem to have modest predictive value because of inherent variability in facies properties within fluvial systems of some type.

Care needs to be taken when considering the prevalence of facies types in fluvial channel deposits as a possible indicator of depositional-system type.

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