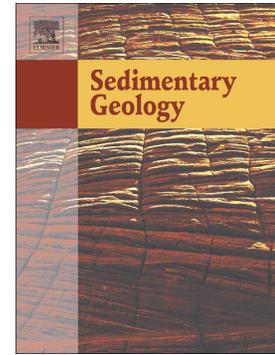


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The role of discharge variability in the formation and preservation of alluvial sediment bodies

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Abstract

Extant, planform-based facies models for alluvial deposits are not fully fit for purpose, because they over-emphasise plan form whereas there is little in the alluvial rock record that is distinctive of any particular planform, and because the planform of individual rivers vary in both time and space. Accordingly, existing facies models have limited predictive capability. In this paper, we explore the role of inter-annual peak discharge variability as a possible control on the character of the preserved alluvial record. Data from a suite of modern rivers, for which long-term gauging records are available, and for which there are published descriptions of subsurface sedimentary architecture, are analysed. The selected rivers are categorized according to their variance in peak discharge or the coefficient of variation (CVQ_p = standard deviation of the annual peak flood discharge over the mean annual peak flood discharge). This parameter ranges over the rivers studied between 0.18 and 1.22, allowing classification of rivers as having very low (< 0.20), low (0.20-0.40), moderate (0.40-0.60), high (0.60-0.90), or very high (> 0.90) annual peak discharge variance. Deposits of rivers with very low and low peak discharge variability are dominated by cross-bedding on various scales and preserve macroform bedding

structure, allowing the interpretation of bar construction processes. Rivers with moderate values preserve mostly cross-bedding, but records of macroform processes are in places muted and considerably modified by reworking. Rivers with high and very high values of annual peak discharge variability show a wide range of bedding structures commonly including critical and supercritical flow structures, abundant *in situ* trees and transported large, woody debris, and their deposits contain pedogenically modified mud partings and generally lack macroform structure. Such a facies assemblage is distinctively different from the conventional fluvial style recorded in published facies models but is widely developed both in modern and ancient alluvial deposits. This high-peak-variance style is also distinctive of rivers that are undergoing contraction in discharge over time because of the gradual annexation of the channel belt by the establishment of woody vegetation. We propose that discharge variability, both inter-annual peak variation and “flashiness” may be a more reliable basis for classifying the alluvial rock record than planform, and we provide some examples of three classes of alluvial sediment bodies (representing low, intermediate, and high/very high discharge variability) from the rock record that illustrate this point.

Keywords: rivers, fluvial facies models, peak discharge variance, alluvial architecture

1. Introduction

Facies models for alluvial systems and their deposits have advanced considerably since their first publication in the 1960s (Bernard et al., 1962; Doeglas, 1962; Allen, 1963a, 1964; Ore, 1964; Moody-Stuart, 1966). A diversity of fluvial styles and stratal stacking patterns is recognized, and the internal variability of fluvial systems and their deposits is broadly acknowledged. The major planform river types (straight, braided, meandering, anabranching) remain embedded in the perceptions of most geologists as the full range of possibilities, despite scepticism over the use of planform as a fundamental

classification criterion (Bridge, 1985, 1993, 2006; Bristow, 1996; Ethridge, 2011). Numerous objections to using planform as a basis for classifying alluvial rivers have been raised, including the observations that 1) numerous planform styles can coexist along discrete reaches of individual rivers, 2) many rivers display characteristics that are transitional between these planform styles, and 3) many rivers change planform at different flow stages. Another school of thought argues that anabranching/anastomosing patterns do not belong in the same classification as straight, braided, and meandering because the term describes channel belts rather than individual channels (Bridge, 2003, 2006; Ethridge, 2011).

Published facies models based on individual modern rivers have limited success in predicting the external geometry, internal structure, and lithology of alluvial sediment bodies preserved in the rock record (Ethridge, 2011), suggesting that factors not considered in these facies models exert strong control on alluvial sediment accumulation. This is important because facies models are used as predictors of the properties of alluvial sediment bodies, including those that host natural resources in the subsurface.

Climatic influences on fluvial systems have also featured prominently in the perceptions of those seeking to classify alluvial rivers. For many years, a distinction was drawn by those describing fluvial systems and deposits between systems in humid climates where there is an excess of water supply relative to evapotranspiration, and those in arid climates (so-called “dryland” rivers) where there is a deficit. More recently, fluvial systems in the seasonal or semiarid to subhumid tropics have been more fully documented, suggesting a spectrum of variability based on the balance between water discharge and evapotranspiration (Fielding et al., 2009, 2011). Many of the rivers in the last category display pronounced runoff seasonality, and pronounced inter-annual variability (Alexander et al., 1999; Fielding et al., 2011).

The role of inter-annual discharge variability in shaping fluvial sediment bodies has not been fully appreciated until very recently. Such variability, expressed as the “coefficient of variance” (standard deviation of annual peak discharge divided by the mean annual peak discharge) can be used as a measure of the inter-annual variability in the water discharge through a fluvial system, and is explored here as an influence on the sedimentology and stratigraphy of alluvium. We review the documented sedimentological characteristics of a set of modern rivers of varying planform, sediment load, and climatic setting, and relate this to the coefficient of variance in peak discharge calculated from historical gauge records. We find that the coefficient of variance for discharge covaries with the preserved stratigraphy and sedimentology of these rivers, suggesting that discharge variability plays an important role in the construction of alluvial sediment bodies modern and ancient.

2. A brief review of alluvial facies models

Facies models for fluvial systems first became available in the 1960s, with the work of Bernard et al. (1962) and Allen (1963a, 1964) on meandering rivers, and that of Doeglas (1962), Ore (1964), and Moody-Stuart (1966) on braided systems. The first generation of facies models were in the form of idealised vertical sequences that were said to be characteristic of particular planform styles. As research effort into the alluvium of modern rivers gained pace, it quickly became apparent that these simple vertical sequence models were of limited value (Collinson, 1978; Jackson, 1978). In the late 1970s and early 1980s, researchers began to recognise the value of documenting the second and third dimension in modern systems and in outcrops of ancient successions, epitomised by the work of Allen (1983) on the Devonian Brownstones of the Welsh Borderlands. Generic classifications for alluvial sediment bodies based on their geometry in three dimensions independent of any implied planform were first published at this time (Friend et al., 1979; Friend, 1983).

Allen (1983) also introduced the concept of “architectural elements”, or the constituent building blocks of alluvial sediment bodies, by which two- and three-dimensional exposures could be classified and interpreted. This concept was expanded upon, codified, and formalised by Miall (1985, 1988), and in an alternative scheme by Bridge (1993a). Both of these classifications made use of hierarchical arrays of bounding surfaces and constituent features at different scales, and they helped the interpretation of alluvial architecture. The distinction between small-scale bedforms (termed microforms and mesoforms) and larger features at the scale of bars and channel fills (macroforms) was well-established and became part of the rationale behind the concept of alluvial architecture.

Through the 1980s, analyses of well-exposed ancient alluvial successions were more sophisticated and detailed than those of modern systems because of the logistical difficulty of excavating deep into modern river bars and channel fills. This changed rapidly in the early 1990s with the application of Ground-Penetrating Radar (GPR) technology, which allowed high-resolution subsurface imagery of sand and gravel beds to be acquired quickly and easily. The technique was successfully applied to studies of modern rivers (e.g., Gawthorpe et al., 1993). Initially, small meandering (South Esk; Bridge et al., 1995, North Thompson; Leclerc and Hickin, 1997) and braided (Calamus; Bridge et al., 1998) systems were imaged, but in time a much broader variety of rivers was comprehensively investigated (e.g., Fielding et al., 1999; Best et al., 2003; Lunt et al., 2004; Sambrook Smith et al., 2006; Kostic and Aigner, 2007; Mumpy et al., 2007; Horn et al., 2012; Reesink et al., 2014; Okazaki et al., 2015). Some of these studies incorporated repeat surveys to quantify the effects of individual flow events (e.g., Fielding et al., 1999 on the Burdekin River, and Sambrook Smith et al., 2010 on the South Saskatchewan River). Others provided data from remotely sensed imagery and other records to assess change in fluvial form and deposits over historical timeframes (e.g., Joeckel and Henebry, 2008; Horn et al., 2012 on the Platte River).

A further leap in the understanding of fluvial facies and stratigraphy has been facilitated by the availability of increasingly sophisticated three-dimensional seismic reflection datasets from sedimentary basins. The ability to dissect seismic data volumes horizontally as well as vertically has allowed the mapping of fluvial geomorphology in the subsurface (“seismic geomorphology”), providing quantitative information on ancient fluvial channel styles and networks (e.g., Posamentier, 2001; Carter, 2003; Fitch et al., 2005; Nordfjord et al., 2005; Miall, 2006; Darmadi et al., 2007; Wood, 2007; Maynard et al., 2010; Reijenstein et al., 2011). Most recently, integration of multiple three-dimensional seismic datasets in northern Europe gave Klausen et al. (2014) novel insight into fluvial planform changes both spatially and temporally at the scale of an entire continental drainage basin.

Understanding of fluvial sedimentary process has also advanced significantly. Particularly important here is the increasing understanding of Froude-supercritical flows and the resulting bedforms and sedimentary structures (Alexander et al., 2001; Yagashita et al., 2004; Taki and Parker, 2005; Carling and Breakspear, 2007; Spinewine et al., 2009; Yokokawa et al., 2010; Cartigny et al., 2014). With the advent of more detailed diagnostic criteria for recognising Froude-supercritical flow structures in alluvial deposits has come the awareness that they are likely well-represented in the alluvial rock record (Fielding, 2006; Duller et al., 2008; Cartigny et al., 2014). A further area of progress has been in the understanding of flows with high particle concentrations, and the bed conditions that arise from such flows (Baas et al., 2011, 2016). The newly published bedform phase diagrams for mixtures of sand and mud offer realistic insight into natural flows in many modern rivers, particularly those prone to “flashy” (strongly peaked) discharge.

Recent reviews of fluvial facies models (Bridge, 2006; Ethridge, 2011) have concluded that extant models are not fully fit for purpose, and that seeking to diagnose ancient fluvial successions as the deposits of one of straight, braided, meandering, or anabranching planforms is futile. These authors, rather, advocate seeking to establish evidence for point bar, braid bar, and other bar construction

processes in ancient alluvial deposits, and to form an interpretation on this basis that is not fixated on one particular planform style. Recent research has also pointed towards alternative potential controls on alluvial deposit characteristics, among them the variability of discharge on different timescales. Nicholas et al. (2016) used physics-based modelling to establish relationships between morphology and dynamics in big rivers. They found that discharge variability and flood duration exerted a primary control on alluvial deposit characteristics, suggesting that fluvial geomorphology may not be a reliable guide to the alluvial stratigraphic record.

In this paper, we investigate the hypothesis that discharge variability is a first-order control on the nature of the alluvial sedimentary record. We do this by examining the sedimentology and stratigraphy of a suite of modern rivers documented in the literature and from our own experience, for which there also exists a long-term record of discharge from gauging stations. We examine linkages between the coefficient of variance of peak discharge and the sedimentary record for these systems (an aspect of discharge variability not examined by Nicholas et al., 2016), and we show an application of this approach to the examination of a thick alluvial succession in the Carboniferous of the Maritimes Basin Complex of Atlantic Canada.

3. A brief discussion of fluvial discharge variability

The discharge in all streams and rivers varies continuously, on periods of seconds to millennia. The steadiest rivers tend to be those that are groundwater-fed, and the least steady rivers are those in the arid and semi-arid tropics that are driven by precipitation variability. Discharge variability affects vegetation, geomorphology and sediment movement, resulting in sedimentary architectural patterns that are difficult to relate to single factors (such as river planform). Discharge statistics (e.g., mean discharge) and concepts such as “the 100-year flood” used for river management and flood prediction are not necessarily important for sedimentary architecture. Recent floods that are considered extreme

(in the eyes of local inhabitants, engineers or geomorphologists) may not leave diagnostic features in the deposits that will be preserved in the sedimentary record (Sambrook Smith et al., 2010), and the magnitude of most individual events may be unimportant in the rock record. Discharge changes on million-year time scales have impacts on large-scale formation architecture. Discharge changes and events on about a thousand-year time scale may impact avulsion occurrence and channel body stacking patterns. Discharge variability on time scales that controls individual channel body architecture is poorly researched, and deciding what discharge statistics may relate to sedimentary facies models is difficult.

Most rivers have seasonal variation in discharge, and the magnitude of this variation is dependent on geographic setting. High magnitude seasonal variation is particularly pronounced in many cold climate settings (e.g., Ob River in Siberia, Fig. 1B) and monsoonal settings (e.g., Brahmaputra/Jamuna River). Strong seasonal variation causes alternation of large and small discharges that commonly results in the large bedforms that grow in the high stage, becoming emergent as bars at low stage. Many of the classic braided rivers, such as the Brahmaputra, have strong seasonal discharge variations.

The magnitude of peak discharge is influenced strongly not only by meteorological event magnitude, but also by the rate of response of the system and runoff routing (how quickly precipitation over the catchment reaches a particular point on the river). For example, two runoff events with the same water volume but different routing cause different rate of change, peak discharge magnitude, and duration over any threshold (e.g., bank full) illustrated in Figure 1. Thus, the temporal variability in vegetation cover common in the semi-humid and arid tropics compounds the variability in the precipitation pattern to increase discharge variability more than in most (probably all) other climate settings.

The rate of change of discharge is important for sediment transport, sedimentary structure development and preservation of sedimentary features. The rates of change of stage, flow velocity and bed shear stress are particularly important for understanding many of the characteristics of the

sedimentary system and the resulting differences between the deposits of rivers in different climatic and geomorphic settings. Most of the research on sedimentary bedforms and interpretation of flow conditions from bedforms and sedimentary structures (e.g., using bedform stability diagrams; cf., Harms et al., 1975; Van Den Berg and Van Gelder, 1993; Carling, 1999; Baas and Best 2008) assumes that the bedforms are in equilibrium, or nearly in equilibrium, with the flow. For example, the size of dunes has been related to the flow depth assuming equilibrium conditions, but it takes time to reach equilibrium (Yalin, 1964; Allen, 1982a). Dunes (e.g., wavelength and height) only keep pace with changing river stage when the change is very slow; bedform hysteresis is the rule in most settings (Wilbers and Ten Brinke 2003). In slow-changing discharge, bedforms may maintain quasi-steady equilibrium with flow except for a little hysteresis, as is the case in the small, partly ground-water-fed Calamus River in Nebraska (Gabel 1993). The faster the rate of discharge change, the greater the hysteresis (cf., flume experiments reported by Martin and Jerolmack, 2013). Thus, in flashy systems, bedforms may never be in equilibrium with the flow. Not only does this mean that dune size and consequently cross-stratal set thickness may not fully represent flow conditions, but also that the bed roughness and consequently water stage and velocity relationships and consequently also suspended sediment transport may not be as anticipated.

In contrast to dunes, antidunes form and change very quickly in mobile sand or fine gravel and, because of the energetics of the flows in which they form, the bed responds quickly to change, and their wavelength will reach equilibrium very quickly. Antidunes form in mobile sediments under stationary water-surface waves when the Froude number, Fr , is equal to or greater than 1 ($Fr = U/(gh)^{0.5}$, where U is mean velocity, h is flow depth and g is acceleration due to gravity). Antidune wavelength is directly related to the wavelength, λ , of the stationary water-surface waves and that is controlled directly by the mean flow velocity, U , and mean flow depth, h_m (Kennedy, 1963). For waves where the crest-parallel length is long compared to the wavelength, $U = \sqrt{(g\lambda/2\pi)}$ and $h_m = \lambda/2\pi$. Antidunes are occasionally observed on riverbeds (e.g., Alexander and Fielding, 1997) but the bed surface is easily reworked by

subsequent flows so that the long-term preservation of the bed topography is likely to be relatively uncommon. In contrast, the sedimentary structures resulting from antidune growth and movement are likely to be more commonly preserved but are still rarely identified (e.g., Duller et al., 2008; Carling et al., 2009; Froude et al., 2017). A range of sedimentary structures, including lenses and inclined stratification have been attributed to antidune growth and change, and their size may be indicative of flow conditions (e.g., Foley, 1977; Alexander et al., 2001, Fielding, 2006; Cartigny et al., 2014; Froude et al., 2017).

Although antidunes reach equilibrium with respect to flow conditions very quickly, the preservation of the bedforms and the structures requires them not to be reworked as discharge changes. In settings where there is large seasonal variation but slow rates of change, although such features may form frequently, the probability of their preservation is very low. This may explain why historically it was thought that antidunes and related structures were unimportant for sedimentary geology. In contrast, in settings where discharge declines rapidly and where there is a big difference in magnitude of low and high discharge, preservation potential of such features is much higher.

Bedform stability diagrams omit unit bars (cf. Reesink and Bridge 2011) mainly because they are too big to examine in equilibrium conditions in flume channels, and this together with their variability and the relative paucity of research on them in modern rivers means that they are largely ignored in interpreting fluvial deposits.

Inter-annual variability is an important control on the preservation of channel belt architecture. If there is little inter-annual variability, sedimentary structures formed by any big event will tend to be reworked by subsequent years' events, and this is the main explanation why in most settings flood events that seem exceptional to a human observer are unlikely to preserve diagnostic facies. The higher the inter-

annual variability, the greater the chance of preserving event-deposits. In addition to this, if the large infrequent events are sufficiently powerful, there will be a tendency to produce outsized flood-stage channels such that the “normal” flow appears as a misfit stream within the larger channel. This will change the nature of the preserved channel belt deposits. Thus, understanding inter-annual variability is important for channel-belt facies architecture. One measure of inter-annual variability is the variance in peak discharge or the coefficient of variation $CVQ_p = \text{standard deviation of the peak flood discharge over the mean peak flood discharge}$. The coefficient of variation is also known as relative standard deviation. Many rivers have very large seasonal variation, but relatively small inter-annual variability. This pattern is particularly marked in large, cold climate rivers such as the Ob, Russia, and Mackenzie, Canada, and wet-tropical systems such as the Jamuna. At the other extreme are rivers with very high inter-annual variability in arid and semi-arid settings.

Using modern discharge data to understand fluvial architecture

Most rivers are not gauged or have not been gauged for long enough to generate a data set that is useful for analyzing inter-annual variability. At most gauged sites, the accuracy of the estimate of discharge may decrease at high stage, such that the biggest floods are often not reliably measured or are only estimated. Added to this is the problem that most gauged rivers have undergone some amount of river management which may have also changed over the period of gauging records. Even in rivers with little or no active river management, there has inevitably been land use change and consequent likely changes in routing over the gauging period. The consequence of this is that recent discharge data can only be related directly to the active sedimentary processes in the river and young deposits, and any comparison with preserved ancient deposits must be made with considerable care. To illustrate this

point, data for the Niobrara and Burdekin Rivers both pre- and post-regulation are illustrated in Table 1, plotting in different peak discharge variance fields.

For the purposes of this paper, we sought discharge data from rivers for which sediments had been described, and from gauging stations as near to the sediment study sites as possible where there was an adequate period of data (twenty years or so as a minimum). In some cases, e.g., Wabash and Niobrara Rivers, it was possible to obtain data pre-regulation and disregard later data. In a few cases (notably the Burdekin), comparison of peak discharge before and after dam construction demonstrated that the dams had little impact on the peak discharge distribution (even though it had a significant impact on low-stage flow).

An alternative approach would be to attempt to analyze maximum discharge frequency and magnitude via a distributed large-scale hydrological model, using as input data, time series of meteorological data. Climate variables from regional climate models that use boundary conditions from Global Climate Models could also be used, but over broad regions to produce output resolution sufficient to consider river discharge, as Adam et al. (2014) attempted for consideration of floods in the upper Paraná river basin. There are many problems associated with these approaches related to resolution, defining the relationships between runoff and precipitation (e.g., Osborne et al. 2015) and the large number of parameters that need to be defined and feedbacks established in addition to the practical limitations of computational times and difficulty in ground truthing any results. The reliability of this approach for estimating maximum discharge magnitudes with sufficient resolution to be useful for understanding sediment deposit patterns is yet to be adequately proven.

Sediment yield and flux

The timing of precipitation relative to vegetation growth is important both for discharge patterns and for the character and volume of sediment transported relative to discharge magnitude. It also has implications for the weathering of source areas and of sediment in the transport system. In addition, it impacts the amount and types of organic matter in the sediment load. A critical difference is that between areas that have predominantly erratic seasonal rainfall (dry areas impacted by tropical cyclones and unreliable monsoons) and seasonal tropical areas with reliable monsoon systems (with precipitation over longer periods but still with very strong seasonality and inter-annual variability).

At continental scales, sediment yield from catchments varies with tectonic activity, topography, vegetation cover and annual runoff (e.g., Vanmaercke et al., 2014). Unfortunately, resolving the relative importance of individual variables in controlling sediment yield is difficult, not least because of the interrelationship between the factors (e.g., rainfall on vegetation cover). Syvitski and Milliman (2007) detected no meaningful correlation between rainfall measures and river sediment load at a global scale, but suggest that average temperature has a greater impact on sediment yield. Vanmaercke et al. (2014) found that variables that express the intra-annual variability in rainfall and runoff did not show significant correlations with sediment yield in data from African catchments. This may be attributed to the large uncertainties associated with the data and the factors used by these authors to indicate seasonal fluctuations. Runoff has a relatively limited impact on average sediment yield at regional or global scales (e.g., Aalto et al., 2006; Syvitski and Milliman, 2007; Vanmaercke et al., 2014).

4. Sedimentology vs. discharge variance of rivers

In the following section, the sedimentology of a set of rivers is summarized, in the context of the peak annual discharge variance calculated for those rivers. The dataset, which is not comprehensive, is defined by those rivers for which long-term discharge records could be readily accessed, and for which

sedimentological information is also available. The dataset is divided into five classes, based on their annual peak discharge variance (Table 1). Representative aerial images of these systems are provided in Figure 2, and representative stratigraphic cross-sections derived from GPR data are shown in Figure 3.

Rivers with low peak discharge variance

Well-known rivers that experience low annual peak discharge variance (< 0.4) include the Ob (Fig. 2A), Mississippi, Jamuna (Fig. 2B), South Esk, Mackenzie, and Fraser Rivers (Table 1). These rivers represent a wide range of drainage basin size, discharge range, and climate. Despite some having very great seasonal variation, they all have very low or low inter-annual discharge variability. Within the limitations imposed by the availability of data, these rivers also share some common sedimentary characteristics.

The Mississippi, Mackenzie, and Jamuna Rivers are the largest of the rivers in this group. Unfortunately, little is known about the channel deposits of the Mackenzie River (Hill et al., 2001). The modern Mississippi, which drains a significant proportion of the USA, is a meandering river over much of its length, with classical examples of meandering fluvial landforms (e.g., Fisk, 1944; Saucier, 1994).

Macroform features are dominated by large-scale point bars defining channels with strongly asymmetric cross-sections (Fisk, 1944; Saucier, 1974) that preserve evidence for systematic migration over time via expansion, translation, and rotation of bends. Its bed is covered principally in subaqueous dunes of various sizes, and large compound bedforms up to several metres in height (Jordan and Pryor, 1992; Harbor, 1998; Nittrouer et al., 2008, 2011, 2012). These compound bedforms (“compound dunes” of Harbor, 1998; “lobe sheets” of Jordan and Pryor, 1992) are unit bars (cf., Smith, 1974), and are the principal building blocks of point bars. Jordan and Pryor (1992, their Figure 9) inferred that in cross-section, point bars are composed of large-scale epsilon cross-sets (cf., Allen, 1963b), the height of which approximates to channel depth. This implies preservation in the Mississippi alluvial record of macroform bedding structure, although it is not clear how this interpretation was derived.

Core of channel fill sediments (Jordan and Pryor, 1992) indicates a dominance of small- to medium-scale (< 1 m thick) cross-sets preserved within recent alluvium with subordinate flat-laminated and ripple cross-laminated sand. Jordan and Pryor (1992, their Figs. 17, 18) suggest that unit bars preserve larger-scale cross-sets up to 3 m thick. Thus, the available database suggests that the modern alluvium of the Mississippi River is dominated by mesoscale cross-bedding, with some larger cross-beds recording the fronts of unit bars, and channel-scale epsilon cross-bedding resulting from growth and migration of point bars. None of the studies carried out to date on the lower Mississippi River have identified deposits of exceptional flows, rather, the available evidence points towards regular overprinting of depositional patterns in response to annual flow events.

The Jamuna River (Figs. 2B, 3A) is a large, sand-bed river that rises in the Himalayan mountain chain and drains to the Bay of Bengal. Its discharge is strongly controlled by summer monsoonal rainfall, which produces seasonal peak flows (Thorne et al., 1993). At low-stage, much of the river is braided, while at high flow stage the river becomes a single, continuous, straight channel system (Bridge, 1993b; Thorne et al., 1993). Processes of sediment accumulation on bars were initially studied from surface exposures and trenches (Coleman, 1969; Bristow, 1987, 1993), and more comprehensive studies of both river bed sedimentation patterns and bar accretion processes were conducted with geophysical techniques (Best and Ashworth, 1997; Ashworth et al., 2000; Best et al., 2003) (Fig. 3A).

Bathymetrical profiling of the Jamuna River shows the presence of dunes of various sizes on the channel floor, and by a variety of accretion processes constructing bank-attached and mid-channel (braid) bars over periods of years to tens of years (Bristow, 1987, 1993; Thorne et al., 1993; Ashworth et al., 2000; Best et al., 2003, McLelland et al., 2009). Ground-penetrating radar surveys and coring shows that bars are composed principally of cross-bedded sands at scales ranging from small-scale to sets several metres thick (the latter reflecting bar margin slipface progradation; Best et al., 2003). If the large bar studied by Best et al. (2003, and see McLelland et al., 1999) is representative, then the sedimentology of the

Jamuna River is dominated by cross-bedded sands on with sets of various scales, with macroform cross-bedding representing a variety of bar accretion processes. The internal structure of the studied bar furthermore is a complex mosaic of partial remnants of numerous phases of bar-building activity, suggesting that single events are not solely responsible for constructing large geomorphic features in this river (Fig. 3A).

The much smaller, meandering South Esk River of central Scotland preserves a record of both macroscale and mesoscale alluvial features (Bridge et al., 1995). Here, inclined point bar accretion surfaces are well visualized in GPR data and ground truthed by core, in addition to the mesoform bedding structures (principally small- to medium-scale cross-bedding) that dominate the alluvial clinothems (Fig. 3B). The systematic expansion and downstream translation of a meander is documented from the preserved accretion patterns that record gradual development of the point bar (Bridge et al., 1995).

In summary, the available evidence suggests that the alluvium of rivers with low peak discharge variance is a composite mosaic of deposits accumulated over long time intervals, with little if any preservation of bigger flood event deposits, but rather a fragmented record of the history of many events. In nearly all cases, a coherent macroscale architecture is recorded in subsurface imagery.

Rivers with moderate peak discharge variance

Representatives of the group of rivers with intermediate values of discharge variance (0.4-0.6) for which there is detailed sedimentological data include the Calamus and Wabash Rivers of central USA, the South Saskatchewan River of western Canada (Fig. 2C), and the Congaree River of eastern USA (Table 1). These rivers span a range of climatic context and drainage basin size, but are all from the same continent.

One such intensively studied sandy braided river is the South Saskatchewan River in western Canada. This river is now highly regulated and so its modern discharge pattern cannot be considered as representative of the natural system. However, peak discharge is probably the least altered component of the discharge pattern. The early sedimentological analysis and facies model of Cant (1978a, b) and Cant and Walker (1978) for this river was reassessed with the aid of subsurface imaging technologies by Sambrook Smith et al. (2006, 2010), Ashworth et al. (2011), Reesink and Bridge (2011), Parker et al. (2013) and Lunt et al. (2013). These authors found that the volumetric abundance of high-angle cross-bedding (reflecting migration of bar margins) had been over-estimated in the Cant and Walker (1978) model. They furthermore found that the subsurface structure of compound braid bars in the South Saskatchewan River is dominated by a record of small dunes and unit bars (Figs. 2C, 3C). Sambrook Smith et al. (2010) found that a bankfull flow event on the South Saskatchewan River in 2005 left no discernible imprint on the sedimentary record of the river, leading them to suggest that its stratigraphy is a composite record of events of varying magnitudes. The event was estimated to be a 1 in 40 year flood, so perhaps not particularly large in the context of the history of the channel belt, but that the deposits of this event were indistinguishable from the deposits of previous events is consistent with the pattern observed in other rivers with only moderate annual peak discharge variability.

Another, much smaller river of similar character is the Calamus River of Nebraska, central USA (Bridge et al., 1986, 1998; Bridge and Gabel, 1992; Gabel, 1993). The study site has a grazed catchment and is unregulated so that the relationship between the discharge data and recently deposited architecture is probably robust. The catchment is in the Nebraska Sandhills; aeolian dunes that are now inactive but were intermittently active through the Holocene (Miao et al., 2007) and the sediment is consequently dominantly sand. Subsurface GPR data tied to core data (Bridge et al., 1998) indicate a subsurface stratal architecture similar to that described from the South Saskatchewan River, with little evidence of preservation of individual large event deposits (Fig. 3D).

Two meandering rivers that have been extensively studied also fall into this category. These are the Wabash River of central USA (Jackson, 1975, 1976a, b) and the Congaree River of the southeast USA (Levey, 1978). The trenching and borings undertaken by Jackson (1976a, b) indicate a dominance of cross-bedding produced by dunes of various sizes in the Wabash River, while macroform (bar scale) features and their resulting deposits were also identified. No subsurface imagery has yet been acquired on the Wabash, however, making it difficult to determine the extent to which a macroform structure is recorded within the alluvium.

A surface investigation of the Congaree River in southeast USA was conducted by Levey (1978). A series of sand and gravel point bars were studied and found to be superimposed by smaller “transverse bars” (in effect, unit bars). The surface and near-surface stratigraphy was found to be dominated by cross-strata, and thus Levey (1978) argued that the subsurface stratigraphy is also dominated by cross-bedding.

Rivers with high peak discharge variance

Rivers with high peak discharge variance (0.6-0.9) for which there are sedimentological data include the Eel River of northern California, and the sandy, braided Niobrara, Platte (Fig. 2D), and Loup Rivers (Fig. 2E) of Nebraska, central USA.

The sand bed, braided Niobrara River has been studied using GPR to provide subsurface imagery of its alluvium to < 5 m depth (Bristow et al., 1999; Ethridge et al., 1999; Skelly et al., 2003). Skelly et al. (2003) found evidence for preservation of both low-flow deposits and some high-flow deposits, including records of both macroform (bars, channel fills) and mesoform (dunes) features. GPR profiles and vibracores indicate preservation of Froude-transcritical stratification as a substantial constituent of the alluvial record. Reworking of high-flow deposits at lower stages nonetheless produced a succession with abundant internal erosion surfaces and a fragmentary record of channel and bar accretion processes

(Skelly et al., 2003, their Fig. 15). Skelly et al. (2003) further noted (p. 267) that the preserved alluvial architecture reflects in large part rare or extreme flow events.

Early sedimentological studies of the Platte River by Smith (1970, 1971a, b, 1972), Blodgett and Stanley (1980), and Crowley (1983) focused on the surface and near-surface record, and informed the generalized facies model for sandy braided streams of Miall (1977, 1978). These models emphasized stacks of cross-bedded sand as the principal characteristic of the Platte's alluvial record. Nonetheless, no substantial information on the subsurface character of the deposit was available at that time, apart from shallow trenches excavated to the water table. More recently, Horn et al. (2012a, b) used a combination of surface investigation, drilling, and GPR to acquire a more three-dimensional understanding of the Platte River alluvial record. They found a strongly fragmented subsurface stratigraphy characterized by numerous erosion surfaces, and a plethora of bedding structures collectively similar to that documented by Skelly et al. (2003) from the Niobrara River (Fig. 3E). An aspect of the sedimentology of the Platte and other rivers of moderate and high peak discharge variability not evident in rivers of low discharge variance is the abundance of riparian woodland within the active channel belt, often at elevations that are close to the thalweg. Groves of trees can form "vegetated islands" some of which can be stable over periods of tens of years (Joeckel and Henebry, 2008; Horn et al., 2012a, b; Joeckel et al., 2015). Due to the presence of riparian woodland, major flow events on the Platte and other such rivers produce a variety of phenomena caused by interactions among flow, particulate sediment and vegetative debris (Joeckel et al., 2015) including obstacle structures, sediment shadows, accumulations of large woody debris (log jams), and sand accumulations baffled by non-woody vegetation. Furthermore, because of the greater abundance of trees on the river bed, greater volumes of large woody debris are generated during flow events, leading to more common log jam deposits.

The role of large flood events in shaping channel morphometry and alluvial record is also evident from published studies of the Eel River of northern California. This small catchment is characterized by

strongly peaked runoff that has a significant inter-annual variability (Brown and Ritter, 1971; Sloan et al., 2001). Although sedimentological data from the subsurface are as yet lacking, it is clear from surface morphology and cutbanks that frequent reworking of river deposits occurs during major flow events. The crudely stratified alluvium illustrated by Sloan et al. (2001, their Fig. 8) also preserves upright, *in situ* tree trunks, similar to the Platte and Niobrara Rivers.

The Loup River of central Nebraska, USA (Fig. 2E), drains a small catchment in a temperate, continental interior climate zone. It is a sand bed river with a low base flow that carries very little mud or gravel, because its principal source is the Nebraska Sandhills; aeolian dunes that are now inactive but were intermittently active through the Holocene (Miao et al., 2007). Inter-annual variability in peak discharge means that the Loup River is also classified in the category of high peak discharge variance. It preserves a record of *in situ* tree growth on bars similar to that of the Platte River. Alternate and braid bars are well-developed on the Loup and its tributaries, and abundant unit bars are present on the surfaces of these features and adjacent channel beds. In addition to small dunes and abundant ripples, plane beds are abundantly developed on bar surfaces and in channels. GPR data indicate that the subsurface architecture preserves numerous scour fills, some cross-beds, and much flat to low-angle discordant bedding that may be a record of Froude-critical or supercritical flow at high stage (Fig. 3F). Common point diffractions in GPR data suggest the presence of buried logs and/or *in situ* tree stumps within the alluvial record (Fig. 3F).

Rivers with very high peak discharge variance

Rivers recording very high levels of peak discharge variance (> 0.9) and that have been studied sedimentologically include the Burdekin (Fig. 2F) and Fitzroy Rivers of tropical northeast Australia, and the Bijou Creek of the subhumid, continental western USA. The first two of these drain large catchments in the seasonal tropics and show both highly flashy discharge regimes and major inter-annual variability.

Rivers in hot semiarid and subhumid climates have runoff that is both strongly seasonal and very variable from year to year (Fig. 1B). In areas where evaporation generally exceeds precipitation, small volumes of precipitation (e.g., light rain) may produce little or no runoff. In contrast, moderate or more intense rain tends to produce rapid runoff with a short response time, leading to highly peaked discharge hydrographs. The rapid response and peaked discharge is particularly pronounced when rain falls on dry land with sparse vegetation following a prolonged drought. An important difference between these regions and other climatic settings is that sediment supply rate, like water runoff, is highly variable both in magnitude and rate of change, and may not be in phase with changes in discharge. This type of flow regime is likely to produce sediment waves (unit bars) more commonly than in other types of systems.

The Burdekin River has been studied intensively for over twenty years (Fielding and Alexander, 1996; Alexander and Fielding, 1997; Alexander et al., 1999a, b, 2001b; Fielding et al., 1997, 1999; Nakayama et al., 2002; Amos et al., 2004), leading to the formulation of a facies model for rivers in seasonal tropical and subtropical settings (Fielding et al., 2009; 2011). These rivers are characterized by a low base flow (zero to tens of $\text{m}^3 \text{s}^{-1}$), relatively infrequent bank full events (1 in >10 years; compared to 1 in 1-2 years in low variability rivers) and occasional (one in every 20-40 years compared to one in hundreds of years in low variability rivers) high stage flow events that rise precipitately to $> 30,000 \text{ m}^3 \text{ s}^{-1}$, peak briefly, and then decline almost as rapidly. The short duration of events and rapid rates of change in discharge mean that the channel is unable to maintain equilibrium with flow conditions. One consequence of the rapid fall in discharge is that high stage bedforms and their resulting sedimentary structures are readily preserved, unmodified during falling stage (cf., Jones, 1977). The relative size of the high flow events together with the volume of sediment remobilized and deposited in individual events contributes to the abundant evidence of big events in the deposits. Because base level flow is so much lower than bank-full flow, and because bank-full and greater size flows are relatively infrequent, woody vegetation can

establish on the river bed. The short duration (hours to a few days) of flow events results in short periods of submergence, so that if trees are not buried or broken off, they may survive peak flows. Some trees have adopted strategies to survive occasional inundation by fast-flowing water and damage from coarse sediment and other debris, and bars form around linear, flow-parallel groves of trees that can significantly affect in-channel sediment accretion patterns (Fielding et al., 1997). Thus, large *in situ* woody vegetation is common within channel deposits.

The sedimentary deposits of a part of the Bijou Creek in eastern Colorado, U.S.A., were studied by McKee et al. (1967) following an overbank flash flood in 1965. Trenching of the mainly medium-grained sand deposits revealed a dominance of flat and low-angle lamination, which McKee et al. (1967) attributed to upper flow regime deposition. Deposits preserved a minor component of high-angle cross-bedding, ripple cross-lamination, and soft-sediment deformation. McKee et al.'s (1967) field photographs show stratification that probably includes examples of upper plane bed, antidune and possibly chute-and-pool stratification (cf., Alexander et al., 2001a). Abundant vegetational and other large debris was also noted, attesting to strong, deep flow during the peak of the event (depths of up to 6.5 m and velocities of up to 7 m s^{-1} were estimated).

The Burdekin River, Bijou Creek, and other rivers like them (e.g., Fitzroy: Amos et al., 2008; Croke et al., 2011) are characterized by an abundance of sedimentary structures indicative of Froude-critical and supercritical flow, preservation of abundant remains of both *in situ* and arborescent vegetation and transported vegetational debris (and particularly large woody debris), pedogenically-modified mud partings within the channel deposit, abrupt lateral facies changes, and a paucity of macroform structure in the subsurface alluvial record (Fig. 3G). Repeat GPR surveys across the same transect in the Burdekin (Fielding et al., 1999) indicate that during major flow events, the entire alluvial record of the river may be substantially reworked. This is a significantly different fluvial style to that portrayed in conventional fluvial facies models.

5. Discussion

The depositional record of fluvial discharge variability

The categorization of sedimentological and stratigraphic characteristics of rivers according to the coefficient of variance for annual peak discharge, detailed above, identifies clear distinctions between the two end-members (low vs. very high variance), with intermediate cases displaying some characteristics of both end-members. Examples of the architectural styles, based on studies of the rivers used in this review, are provided in Figure 3, and discussed below.

The alluvial records of rivers with very low to low peak discharge variance tend to be dominated by cross-bedding on various scales. Cross-sets are typically superimposed on clearly preserved macroform bedding structures (channel forms, bar accretion surfaces). The example GPR profile from the braided Jamuna River (Fig. 3A) is one of many from the work of Ashworth et al. (2000) and Best et al. (2003), which show macroform bedding structure indicative of bar construction and modification over time. Cross-sections observed in shallow excavations from bar tops and edges (e.g., Best et al., 2003, their Fig. 8) corroborate this impression. The very small, meandering South Esk River in Scotland (Fig. 3B) shows exquisitely preserved macroform structure related to meander bend expansion and translation over tens to hundreds of years, with both large-scale point bar bedding and smaller, unit bar forms recognisable in the GPR data (Bridge et al., 1995). Data from the much larger Mississippi River near Hickman, Kentucky (Jordan and Pryor, 1992) indicate a similar architecture, with more complex mesoform stratification preserved in this much thicker deposit. In all three of these examples mud partings and some evidence of *in situ* vegetation may be present in upper bank and upper bar deposits, but both are uncommon or absent in lower parts of channel deposits.

The examples of rivers with moderate peak discharge variability; the South Saskatchewan River of Canada (Fig. 3C) and the Calamus River of Nebraska (Fig. 3D), both have architectural features consistent

with braiding (consistent with their planform at the study sites), and preserve both macroform and mesoform structure allowing interpretation of bar formation and modification over time. However, Sambrook Smith et al. (2010) and Lunt et al. (2013) also reported evidence for significant erosional truncation and modification of both unit bars and larger barforms within the subsurface architecture of the South Saskatchewan River, such that the diagnosis of formative bar morphology from stratigraphic data is challenging. In the Calamus River, *in situ* vegetation is present on banks and more mature braid bars, rooting down into bar deposits, but not growing on the river bed. Mud partings are rare in the Calamus River deposits.

The alluvial records of rivers with high and very high peak discharge variance preserve a plethora of bedding structures but generally a paucity of macroform bedding structures such that the geometry of bars and bar growth history is difficult to interpret from the deposits, and plan form at time of deposition is often unrecognizable. The deposits tend to include sedimentary structures resulting from both subcritical and supercritical flow, with a distinctive component of Froude-transcritical bedding structures (plane beds, antidunes, etc.) in many cases. They also preserve records of *in situ* plant growth on the river bed (rather than just on banks and bar tops as may occur in rivers with lower variance), abundant mud partings throughout the channel depth (often pedogenically modified) with abrupt lateral facies changes, and a general paucity of macroform bedding structures in the subsurface. Architecture in rivers of high peak discharge variance is illustrated by the Platte (Fig. 3E) and Loup Rivers (Fig. 3F) both of Nebraska, USA. Both of these have complex and highly fragmented subsurface architecture below active, modern river bars, and both show point diffractions in GPR data that are likely to result from buried trees or large woody debris (given that there are no boulders in either river, this might be the most likely alternative interpretation). A characteristic of both of these rivers is the transient to semi-permanent establishment of wooded bars or “islands” (Fig. 2D, E), providing the raw

material for both *in situ* burial of tree stumps and extensive accumulation of large woody debris within the alluvial record (Joeckel and Henebry, 2008; Horn et al., 2012a; Joeckel et al., 2015).

The extreme end of the spectrum, very high peak discharge variability, is exemplified by the Burdekin River (Fig. 3G), a system draining a predominantly subhumid to semiarid tropical region of northeastern Australia that experiences extremely variable discharge from year to year (Alexander et al., 1999a). Indeed, data and observations from this river informed a facies model recently proposed for such distinctive rivers (Fielding et al., 2009, 2011). GPR data from the Burdekin River (Fielding et al., 1999) indicate local preservation of unit bars but little other recognisable macroform structure (Fig. 3G). They also show a subsurface record that is a complex arrangement of a broad array of bedding structures, including abundant critical and supercritical flow structures. Abundant point diffractions in GPR data illustrate the frequent preservation of *in situ* tree trunks and branches and transported large, woody debris in the alluvial record with evidence of growth not only on banks and bar tops but also near the deepest parts of the contemporary channel.

Discharge variability - A new basis for alluvial facies models?

Given that channel planform is an imperfect basis for alluvial facies models, and that many modern rivers do not all preserve a coherent record of macroform architecture which might facilitate an understanding of bar construction processes, there is a clear need for an alternative basis for classifying and so understanding alluvial stratigraphic records. We propose that discharge variability might constitute a robust basis on which to classify alluvial systems, their deposits, and ancient counterparts.

Rivers with very low and low peak discharge variability result in alluvial architectures that are typical of “classical” alluvial facies models, in showing a dominance of cross-bedding at various scales, with lesser flat to planar lamination, and common internal erosion surfaces and architectural patterns that clearly record bar and bank evolution. We suggest that such architectures reflect discharge regimes in which

peak flows of relatively consistent magnitude allow construction of a record of bar formation and other alluvial processes. There may be seasonal variability in discharge, but the constancy in peak discharge ensures that the processes of bar formation and modification are dependably recorded in the alluvial stratigraphy.

Rivers with moderate discharge variability show records that are more difficult to interpret in terms of bar formation and other such depositional processes, because the inter-annual variability in discharge causes frequent superimposition of records of widely varying flows. Sambrook Smith et al. (2010) were unable to detect any clear record of a documented high flow event in the South Saskatchewan River, because the deposits of that flow event were indistinguishable from those of older events. Such records are, nonetheless, still dominated by cross-bedding with at least some preservation of macroform structure.

Rivers with high and very high discharge variability show a distinctively different architectural style, in which macroform structure is infrequently or uncommonly preserved, a wide range of bedding structures is abundantly preserved as a complex mosaic (including structures indicative of supercritical flows), and *in situ* trees are abundantly preserved within the channel deposits with the bases of trunks lower than bank level and lots of transported large woody debris (Alexander et al., 1999b). Facies variability in three dimensions is characteristic, and pedogenically modified mud partings are commonly preserved within alluvium, even near the base of channel bodies. This style is quite different from what sedimentologists have traditionally associated with the deposits of rivers, but we believe it is not uncommon. The abundance of woody vegetation (both *in situ* and transported), and the presence of pedogenically modified mud layers within the channel body, reflect intervals of several successive years with low peak annual flow which can occur in rivers with high and very high peak discharge variability. Periods of ten or more years between big events allow for tree growth on the channel bed. The opportunistic tree species that typically grow on alluvial bars show rapid rates of growth (cf., Fielding et

al., 1997), allowing establishment of transient groves of trees on active bars in such circumstances. This process may allow semi-permanent vegetated islands to form (cf., Joeckel and Henebry, 2008), thereby annexing parts of the alluvial channel belt and contributing to channel migration. *In situ* tree growth on channel bed surfaces facilitates bar growth (Fielding et al., 1997) and forms a distinctive suite of sedimentary structures formed as flow is diverted and modified around the obstacles represented by extant vegetation (Fielding et al., 1997, Nakayama et al., 2002; Joeckel et al., 2015).

The establishment of vegetational communities on alluvial surfaces becomes even more pronounced in circumstances where fluvial discharge through a system declines over time, such as in the modern Platte River (Joeckel and Henebry, 2008; Horn et al., 2012b). Figure 4A shows a portion of the Platte River near Lexington, Nebraska, USA, in which the formerly larger channel belt has contracted to a single main channel and a series of narrow anabranches. Areas of dense tree growth are interpreted as the sites of vegetated islands which once were part of the active channel belt. The contrast between the subsurface architecture of the extant river and that of abandoned river reaches, as imaged by GPR (Horn et al., 2012a), allows formulation of a cross-sectional model for alluvial record of such a river forced by gradual contraction of the system (Fig. 4B).

In summary, we submit that the spectrum of variation recorded by the modern fluvial records shown in Figure 3 constitute the basis for an alternative classification of facies models for fluvial systems, based on the variability of peak discharge.

Ancient Examples

In this section, we provide some examples of sediment bodies from the rock record that we believe are representative of the three classes (low, intermediate, and high/very high discharge variance; Figs. 5-7). The examples are based on the preserved set of facies characteristics, and represent the specific outcrop shown. Since the preservation of woody vegetational debris is an important element of this classification, we add the caveat that it may be more difficult to diagnose fluvial style in pre-Devonian systems where there is no record of woody, higher land plants. We acknowledge that a given formation may preserve examples of more than one style, and that the classes have somewhat arbitrary boundaries. Nonetheless, we submit that the differences among the three classes are distinctive and reproducible. A summary of the vertical sequence characteristics of the three groups, is shown in Figure 8, and examples from a single succession (Pennsylvanian of Atlantic Canada (Allen et al., 2013, 2014; Fielding et al., 2011) are shown in Figure 9.

Low discharge variance alluvial deposits

The alluvial channel sediment bodies that make up this class are those that are generally viewed as “archetypal” channel bodies, that is, coarse-grained sediment bodies internally dominated by cross-bedding on various scales with ripple cross-lamination, and with subordinate flat and low-angle lamination. Numerous examples are recorded in the literature, and a selection from our experience are shown in Figure 5. These are erosionally-based bodies, in many cases with significant internal erosion surfaces, dominated by sand and gravel-sized sediment. All are dominated internally by cross-bedding, both of mesoform and macroform scale. Channel bodies are composed of a combination of both complete and erosionally truncated channel fills. Common macroforms include those formed by lateral and downstream accretion as well as nested channel fills. Examples include Pleistocene incised valley deposits from SE Nebraska, Jurassic deposits from eastern Australia (the Walloon Coal Measures; Yago and Fielding, 2015), Permian rocks from north Queensland, Australia (Betts Creek Beds; Fig. 8; Allen and

Fielding, 2007a, b), and Pennsylvanian incised valley deposits from SE Nebraska (Indian Cave Sandstone; Fischbein et al., 2009).

Intermediate discharge variance alluvial deposits.

Alluvial channel deposits that represent this class of intermediate discharge variance are those that contain abundant cross-bedding, but a greater variety of styles of cross-bedding (including humpback cross-bedding and other forms transitional to upper plane bed stratification), together with a record of critical and supercritical flow in the form of low-angle discordant stratification, antidunal, and even chute-pool or cyclic step stratification. They are somewhat similar to the “archetypal” channel body styles, but show some departures from the norms and may have been noted as unusual in some way by those who described them (Fig. 6). A plausible example is given by exposures of the Middle Permian Colinlea Sandstone in the Springsure Shelf area of central Queensland, Australia (Fielding, 2006) (Fig. 6A, B), which in addition to various cross-bedding morphologies preserves draping, undulatory stratification that includes backsets, possible examples of chute-pool stratification. A second example is provided by Namurian (mid-Carboniferous) coastal alluvial channel deposits from County Clare, western Ireland (Pulham, 1989), which show a variety of cross-bedding, abundant flat and low-angle discordant stratification, and large, undular bedding structures with local preservation of antidunal form sets on bed tops (Fig. 6C). Further examples are given by the Pennsylvanian Boss Point (upper part) and South Bar Formations of Nova Scotia, Canada (Rust and Gibling, 1989; Browne and Plint, 1994; Gibling et al., 2010; Fielding et al., 2011; Allen et al., 2013, 2014; Rygel et al., 2015) (Figs. 6D, 8). The prominent role of vegetation in shaping these alluvial deposits was documented by Gibling et al. (2010) and Ielpi et al. (2014). This latter example is significant also because the Cumberland Basin section is part of a long-term transition from a fluvial style characteristic of low discharge variance (lower Boss Point Formation) through to a style characteristic of high discharge variance (Little River Formation, lower Joggins

Formation), before reverting to a more intermediate style higher in the Joggins Formation (Fielding et al., 2011).

High and very high discharge variance alluvial bodies

Alluvial channel bodies that represent the class of high to very high discharge variance include those described previously from the semiarid to subhumid tropics and subtropics (Fielding et al., 2009, 2011), and an array of bodies from a broader range of climates and paleoclimates (Fig. 7). Again, this group comprises erosionally-based bodies, commonly composed of a composite of channel fill elements. These alluvial channel bodies preserve a suite of sedimentary structures in which cross-bedding may be a subordinate or absent constituent, and which includes abundant structures formed under critical to supercritical flow conditions (flat and low-angle discordant stratification, undular and convex-upward stratification, low-angle backset bedding, interpreted as the record of plane bed, antidune, chute-pool and cyclic step conditions). Macroform features are conspicuously absent from many of these channel bodies, and may be only locally developed. Where preserved, macroforms are typically cryptic and not easily recognized (for example in the Pennsylvanian Port Hood Formation of Atlantic Canada; Keighley and Pickerill, 1996). Another significant feature of these deposits is the preservation of abundant, large woody debris and in situ tree fossils within channel bodies, and the physical sedimentary structures formed due to flow interference around channel floor vegetation (Vegetation-Induced Sedimentary Structures, or VISS of Rygel et al., 2004; see also Ielpi et al., 2015). Abrupt lateral and vertical facies and lithological changes are typical, as is the frequent preservation of laterally discontinuous, pedogenically-modified mudrock partings. It is important to note that these facies transitions to mudrock occur within the channel fill.

Prominent among ancient examples of flashy discharge systems are some Pennsylvanian formations of the Maritimes Basin Complex, Nova Scotia (notably Little River Formation and lower Joggins Formation

at Joggins, along with some others; Fielding et al., 2011; Figs. 7A-C, 8). These formations preserve all of the characteristics mentioned above, and show good examples of *in situ* fossil vegetation encased within channel sediment bodies. Other examples from the rock record where similar features have been found include parts of the Permian Wilton Formation of the southern Sydney Basin, Australia (Fig. 7D), and parts of the Newcastle Coal Measures of the northern Sydney Basin (Fig. 7E). The presence of *in situ* tree fossils was documented previously by Fielding and Alexander (2001) and attributed to sediment accumulation under the influence of a strongly seasonal discharge regime.

An interval from the uppermost Boss Point Formation through the Little River Formation, into the lowermost Joggins Formation of the Cumberland Basin, Nova Scotia, records a progressive change in alluvial style from low to intermediate discharge variance bodies in the upper Boss Point Formation, high discharge variance alluvial bodies in the Little River and lowermost Joggins Formations, and intermediate to low discharge variance alluvial bodies in the remainder of the Joggins Formation (Fig. 9). These changes are interpreted to coincide with a complete cycle of palaeotropical climate change from humid to strongly seasonal and subhumid or semiarid to again relatively humid, wherein the paleoclimate signal can be recognized using the suite of sedimentary features characteristic of each of the various discharge styles, independent of accommodation controls (tectonics and relative sea-level change, Fielding et al. 2011; Allen et al. 2013).

6. Conclusions and future outlook

Existing facies models for alluvial deposits, which are predicated on fluvial planform, are not fully fit for purpose, because there is little in the alluvial rock record that is distinctive of any particular planform, and because individual rivers vary in planform in both time and space. Accordingly, existing facies models have limited predictive capability. This paper discusses the role of inter-annual peak discharge

variability as a control on alluvial architecture. A dataset from a suite of modern rivers, for which both a long-term gauging record is available and for which subsurface data on the alluvial record has been published from ground-penetrating radar and other methods, has been assembled and evaluated. The rivers are categorized according to their variance in peak discharge or the coefficient of variation (CVQ_p = standard deviation of the peak flood discharge over the mean peak flood discharge).

Deposits of rivers with very low (< 0.20) and low (0.20-0.40) discharge variability are dominated by cross-bedding on various scales and contain macroform bedding structure, allowing the interpretation of bar construction history. Rivers with moderate values (0.40-0.60) preserve mostly cross-bedding, but records of macroform processes are in places muted and considerably modified by later reworking. Rivers with high (0.60-0.90) and very high (> 0.90) annual peak discharge variability show a wide range of bedding structures including common critical and supercritical flow structures, a general lack of macroform structure, abundant *in situ* trees and transported large, woody debris, and pedogenically modified mud partings low in the channel body. Such a facies assemblage is distinctively different from the conventional fluvial style recorded in published facies models, but is widely developed both in modern and ancient alluvial deposits. This style is also distinctive of rivers that are undergoing contraction in discharge over time because of the gradual annexation of the channel belt by the establishment of woody vegetation.

While the broad classes of very low/low, moderate, and high/very high discharge variability are somewhat arbitrarily defined, and the distinctions between facies classes are therefore somewhat gradational, it is nonetheless possible to distinguish them on the basis of the preserved facies assemblage and sediment body characteristics. There are numerous well-documented ancient alluvial record examples of all three classes. Accordingly, we conclude that discharge variability may be a more reliable basis for classifying the alluvial rock record than planform. A new generation of facies models for the deposits of alluvial rivers is needed, and this analysis suggests that a focus on flow patterns and their

variability over time may yield fruitful outcomes. A critical re-examination of a broader suite of modern rivers, and of well-exposed ancient alluvial deposits, may yield important insights in this regard. Another profitable direction for future work may be to model process variability, both numerically and in scaled flume experiments, in order to assess under controlled conditions, the effects of different discharge regimes.

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List of Figures and Tables

Figure 1. Discharge patterns for rivers. (A) Unit hydrographs for two different responses to the same volume of runoff. (B) Ten years of discharge data from the rivers Ob (dark blue) and Burdekin (orange) showing different patterns of variability in high and low latitude climatic zones, respectively. These graphs are constructed from daily maximum discharge data 1968-1978 recorded on the Ob River at Belogor'e (Latitude and Longitude 61.07, 68.6. Drainage area 2690000 km²) and the Burdekin River at Clare (Latitude and Longitude -19.75, 147.24 Drainage area 129876 km²). Ob River data available from <http://www.r-arcticnet.sr.unh.edu/ObservedAndNaturalizedDischarge-Website/>. Burdekin river data data supplied by the Queensland Department of Natural Resources and Mines.

Figure 2. Satellite imagery of selected rivers discussed in this paper, arranged in order of increasing peak discharge variability to facilitate comparison (all images courtesy of Google Earth). In each image, flow direction is indicated by an arrow, and the scale is shown. (A) Ob River of west Siberia, looking downstream obliquely, at Batovo (foreground, right bank). The main channel at this location is 800 m wide. (B) Jamuna River of Bangladesh, looking downstream obliquely, at Dangdhadra (left bank). The

channel belt is 11-13 km wide at this point. (C) Oblique view of the South Saskatchewan River of Canada, flow left to right, near Outlook, Saskatchewan. Channel is 750 m wide. (D) Vertical view of the lower Platte River of the USA, near Plattsmouth, Nebraska, USA. Flow is left to right, and the channel is 500-600 m wide. (E) Oblique view of the Loup River of the USA near Fullerton, Nebraska, USA. Flow is from left to right, and the channel belt is 850 m wide. (F) Vertical view of the Burdekin River of north Queensland, Australia at Big Bend. Flow is from left to right, and the channel varies from 250 – 700 m wide.

Figure 3. Line drawings of alluvial architecture in the subsurface of selected modern rivers, interpreted from ground-penetrating radar data. (A) Jamuna River of Bangladesh (redrawn from Best et al., 2003), (B) South Esk River of central Scotland (redrawn from Bridge et al., 1995), (C) South Saskatchewan River of Canada (redrawn from Lunt et al., 2013), (D) Calamus River of central USA (redrawn from Bridge et al., 1998), (E) Platte River of central USA (from Horn et al., 2012), (F) Loup River of central USA (Fielding, unpublished data), (G) Burdekin River of north Queensland, Australia (from Fielding et al., 1999). The drawings are arranged to illustrate architectural changes associated with the spectrum of peak discharge variability, from very low (A) to very high (G). See text for discussion.

Figure 4. Consequences of declining discharge over time in the Platte River of central USA. (A) Satellite image (courtesy of Google Earth) of the Platte River near Lexington, Nebraska, showing the contraction of the Platte to a single main channel that displays elements of braiding, and two-three narrow, functional anabranches. Note areas of dark colour that are interpreted as former vegetated islands within the active channel belt that were annexed from the zone of flow during channel belt contraction. Flow is from left to right, and the channel belt is 1500 m wide in total. The alluvium of the modern Platte River contains abundant large woody debris and remains of *in situ* trees. (B) A simple cartoon model to show the stratigraphic consequences of flow contraction in the Platte River, based on GPR data from extant and older Holocene deposits presented by Horn et al. (2012a). In Stage 1, flow is considerable,

and macroform sedimentary structure is formed and preserved in deep channels and large bars. As flow contracts (Stage 2), so the discharge variability increases, and alluvial surfaces available for colonization by trees multiply. Macroform structure becomes progressively reworked, and mesoform structure becomes more common. With continuing contraction in flow (Stage 3), the intervals between major flows become lengthier, allowing establishment of semi-permanent vegetated islands that are then annexed from the active channel belt. Macroform structure has by this stage been completely reworked into mesoform features. Thus, the alluvial record becomes progressively more dominated by small-scale features over time and more influenced by both *in situ* and transported vegetation.

Figure 5. Illustrations of alluvial channel bodies from the rock record representative of low discharge variance. (A) Line drawing with interpretation of a large cliff face exposing part of the Middle-Upper Permian Betts Creek Beds in the northern Galilee Basin, Queensland, Australia. The cliff comprises a series of sheet-like fluvial sandstone bodies internally composed of various architectural elements. Facies that make up in-channel elements are predominantly cross-bedded sandstone. Architectural elements: NC – Nested Channel Fills, CF – Channel Fill, CS – Crevasse Splay, OF – Overbank Fines. SB – Sequence Boundary. See Allen and Fielding (2007b) for further details. (B) Outcrop view of the cliff shown in part A). Height of cliff is 30 m. (C) Close-up view of part of the uppermost Pennsylvanian Indian Cave Sandstone in SE Nebraska, USA, an incised valley fill the lower part of which is a coastal fluvial sandstone internally dominated by cross-bedding. See Fischbein et al. (2009) for further details. (D) View of an excavation near Fairbury, Nebraska, USA, showing a 20 m vertical section through a Pleistocene incised valley fill composed almost entirely of cross-bedded sand and gravel. (E) View of part of the Middle to Upper Permian Bainmedart Coal Measures in the Prince Charles Mountains of East Antarctica. Cliff is about 30 m high, and exposes several fluvial channel bodies each composed predominantly of cross-bedded sandstone.

Figure 6. Illustrations of alluvial channel bodies from the rock record representative of moderate discharge variance. (A) Line drawing of bedding structure in part of a Middle Permian channel sandstone body in the Colinlea Sandstone of central Queensland, Australia (modified from Fielding, 2006). Note the abundance of Froude-transcritical sedimentary structures in addition to cross-bedding. Abbreviations: SB – Sandy Bedforms, UFR – Upper Flow Regime architectural elements. Box outlines the location of part B). (B) Close-up view of part of the outcrop shown in A). Marker pen for scale. Note the low-angle discordant bedding that locally defines backset cross-bedding, interpreted as possible chute-and-pool stratification. (C) View of the upper part of an lower Pennsylvanian coastal fluvial channel body at Cleedagh Bridge, County Clare, Ireland, showing large bed waves preserved as a form set, and interpreted as the product of large antidunes. (D) Cliff exposure (30 m high) of the lower Pennsylvanian South Bar Formation north of Sydney, Nova Scotia, Canada. The cliff is composed of amalgamated channel fills predominantly composed of flat- and low-angle-stratified sandstone (see Gibling et al., 2010 for further details).

Figure 7. Illustrations of alluvial channel bodies from the rock record representative of high and very high discharge variance. (A) Line drawing and graphic log of an exposure of Pennsylvanian fluvial strata near Morien, Nova Scotia, Canada, showing characteristics of the high discharge variance fluvial style (from Fielding et al., 2009). (B) Outcrop view of a part of the fluvial channel body shown in part A). Hammer 0.28 m for scale. (C) Part of a fluvial channel body in the Pennsylvanian Little River Formation near Joggins, Nova Scotia, Canada, showing preservation of a small fossil tree rooted *in situ*, inclined in the down-palaeoflow direction (left to right, as indicated by cross-bedding) and with upstream-trailing roots. These characteristics suggest the tree grew in the low-stage channel bed and was subjected to frequent inundation by flowing water. (D) An *in situ* tree fossil preserved within an Upper Permian channel sandstone body in the Wilton Formation of the Illawarra Coal Measures near Wollongong, New South Wales, Australia. This exposure shows abundant evidence of *in situ* tree growth within the

channel bed, suggesting a strongly seasonal climatic regime where water availability was spatially and temporally restricted. (E) An upright, *in situ* tree fossil preserved within coarse-grained and pebbly channel deposits of the Upper Permian Newcastle Coal Measures near Newcastle, New South Wales, Australia. The tree fossil is rooted within an underlying overbank siltstone deposit, but clearly extends some distance up into the overlying sandstone, indicating that it lived in the active channel.

Figure 8. Suite of three schematic graphic logs summarising the sedimentological characteristics that define (A) low, (B) intermediate, and (C) high and very high peak discharge variance alluvial channel bodies. Diagram is based on intervals within the thick, stratigraphically complete Pennsylvanian succession of the Maritimes Basin Complex of Atlantic Canada.

Figure 9. Graphic log of a measured section through the upper Boss Point Formation, the entire Little River Formation, and the lower Joggins Formation at Lower Cove, Nova Scotia. Log illustrates several upward changes in fluvial style from low discharge variance alluvial sand bodies to intermediate discharge variance sand bodies within the upper Boss Point Formation, to high discharge variance sand bodies that characterise the Little River and lower Joggins Formation, then back to intermediate and low discharge variance sand bodies in the upper Joggins Formation.

Table 1. Classifying rivers by peak discharge variability (see text for more details). Abbreviations: UK – United Kingdom, QLD – Queensland (Australia), BC – British Columbia, NWT – NorthWest Territories, SK – Saskatchewan (Canada), CA – California, CO – Colorado, IL – Illinois, MS – Mississippi, NE – Nebraska, SC – South Carolina (USA).

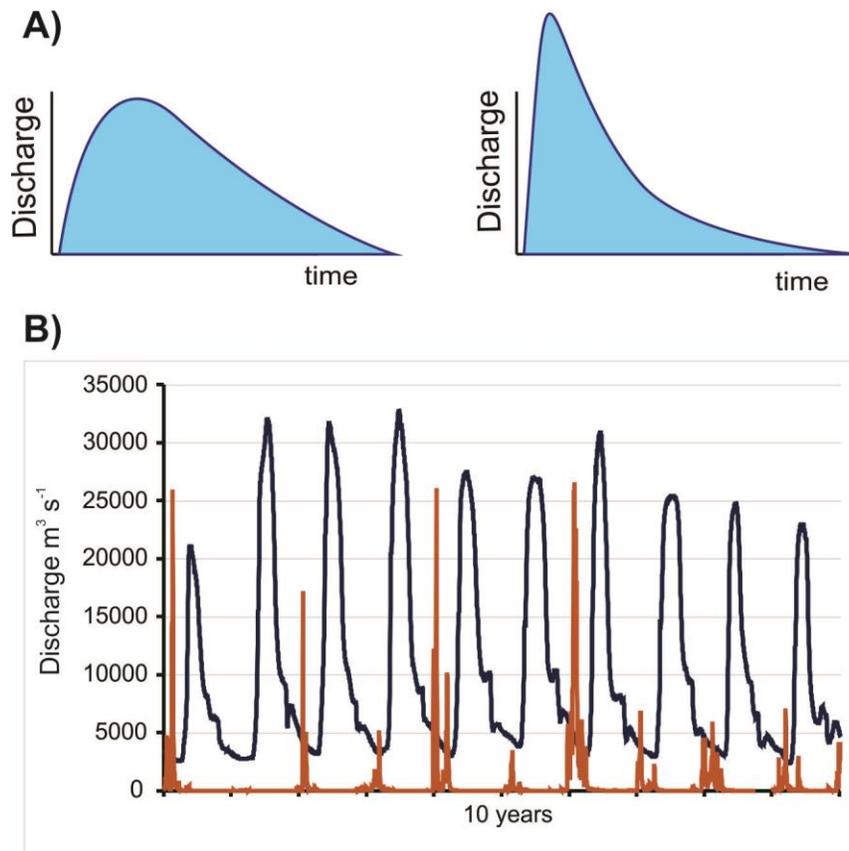


Figure 1

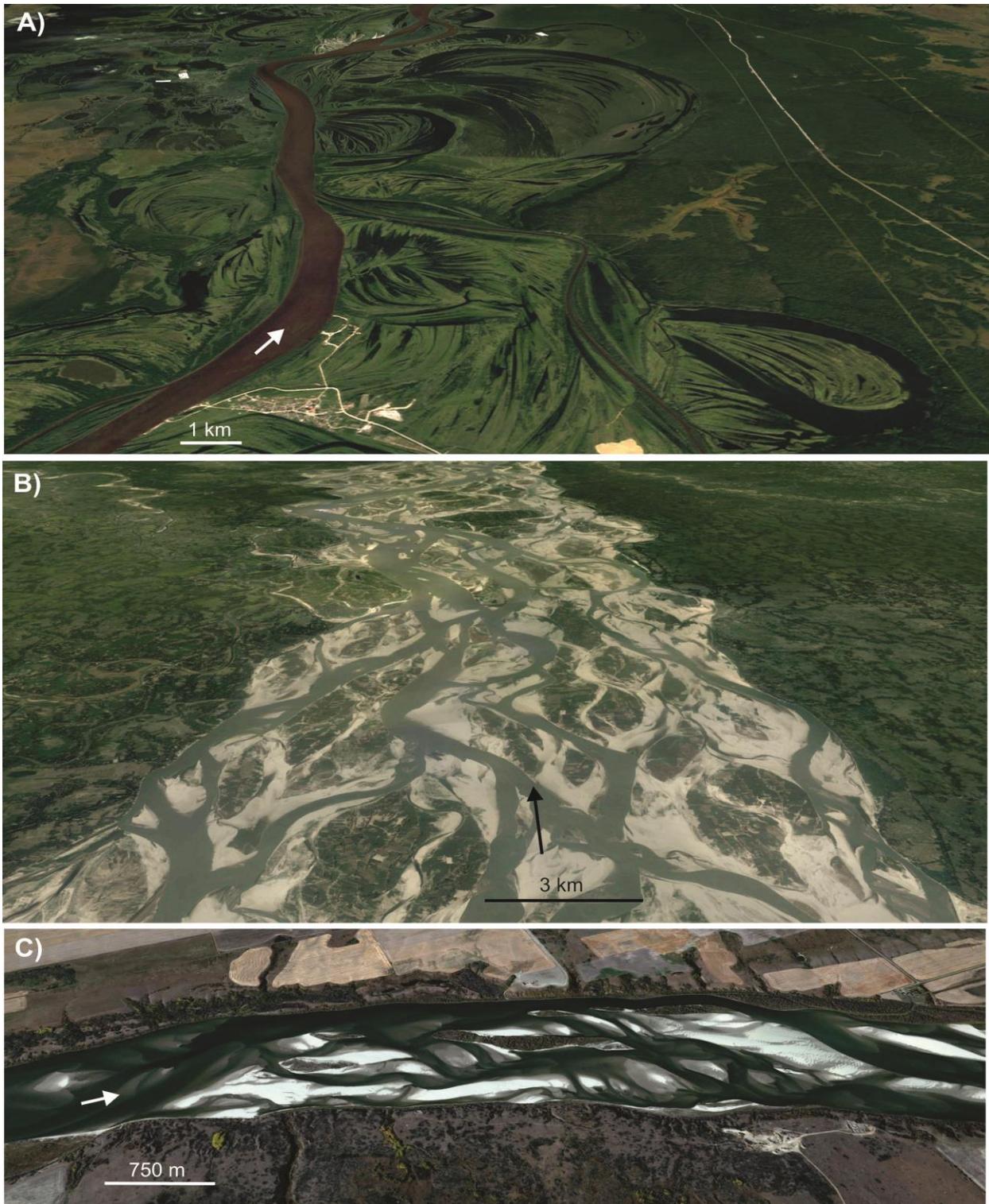


Figure 2A-C

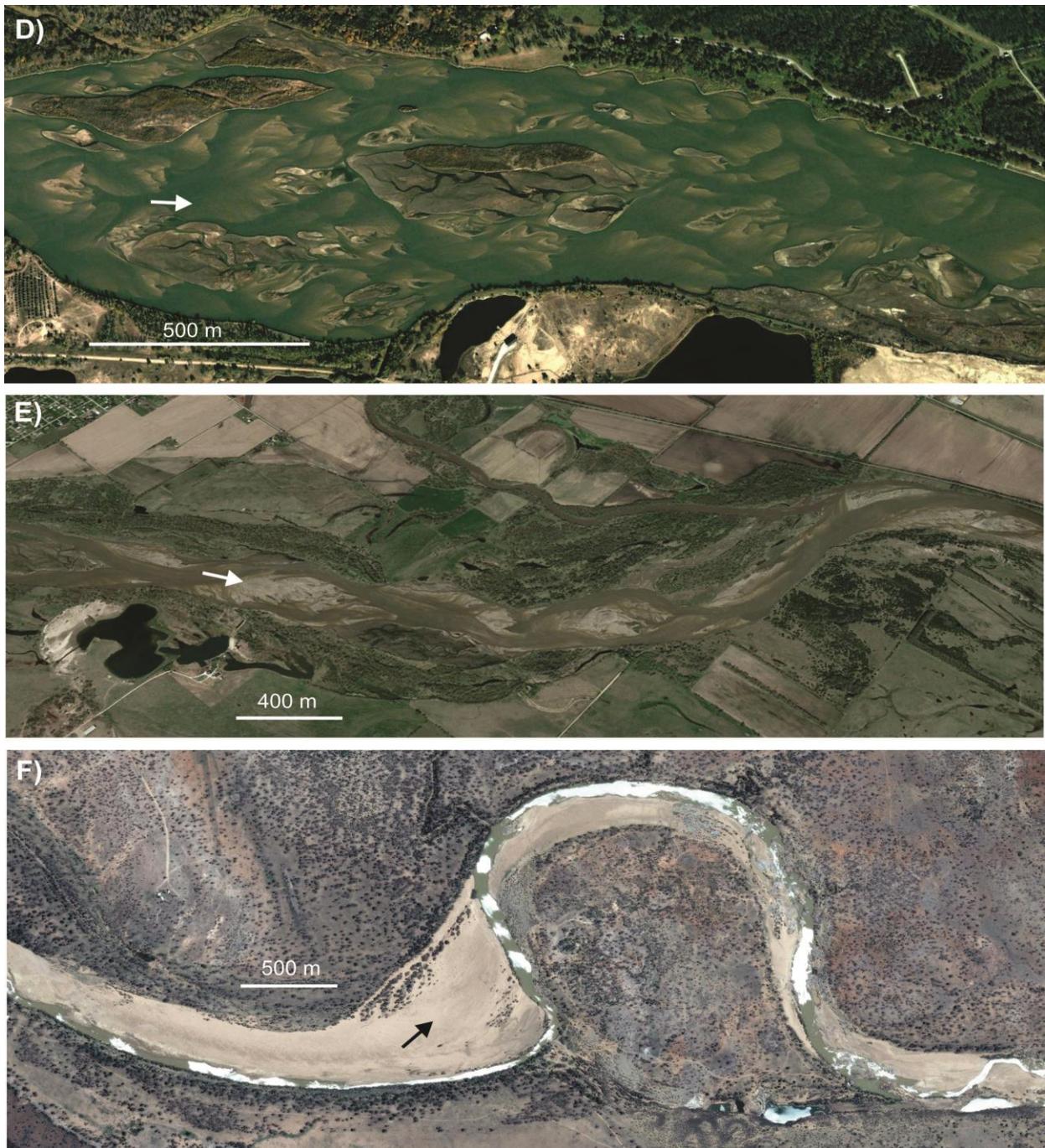


Figure 2D-F

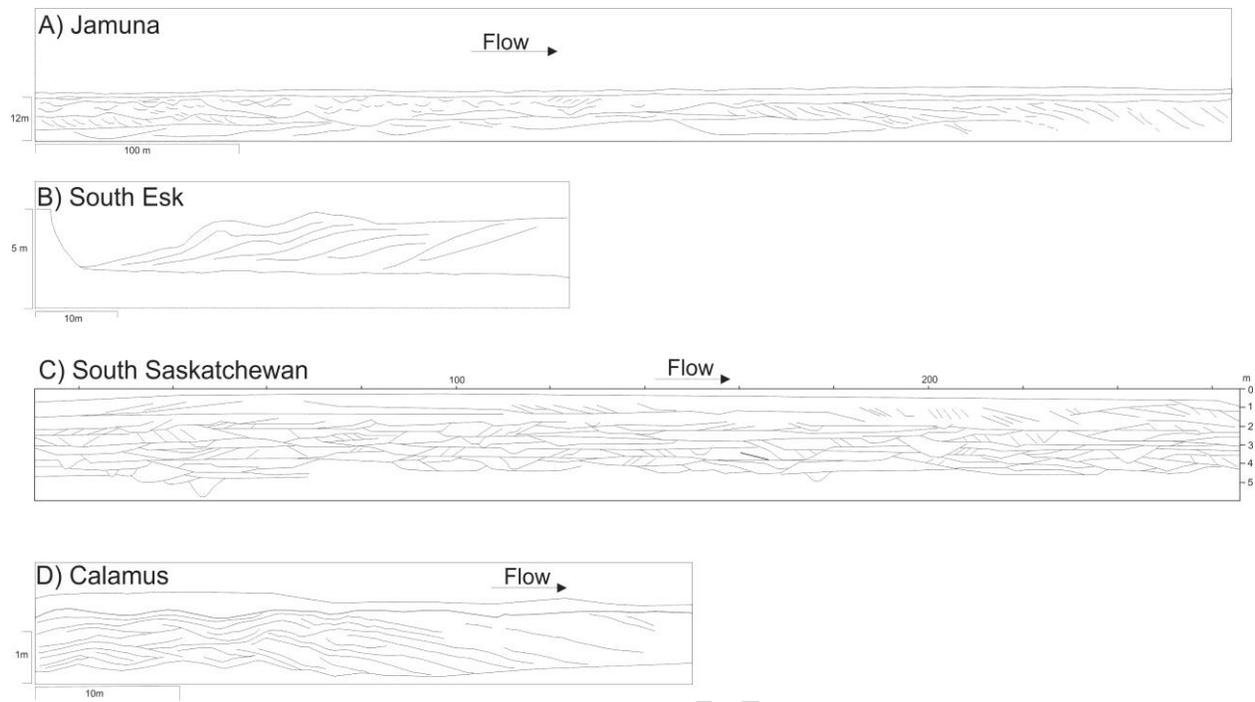


Figure 3A-D

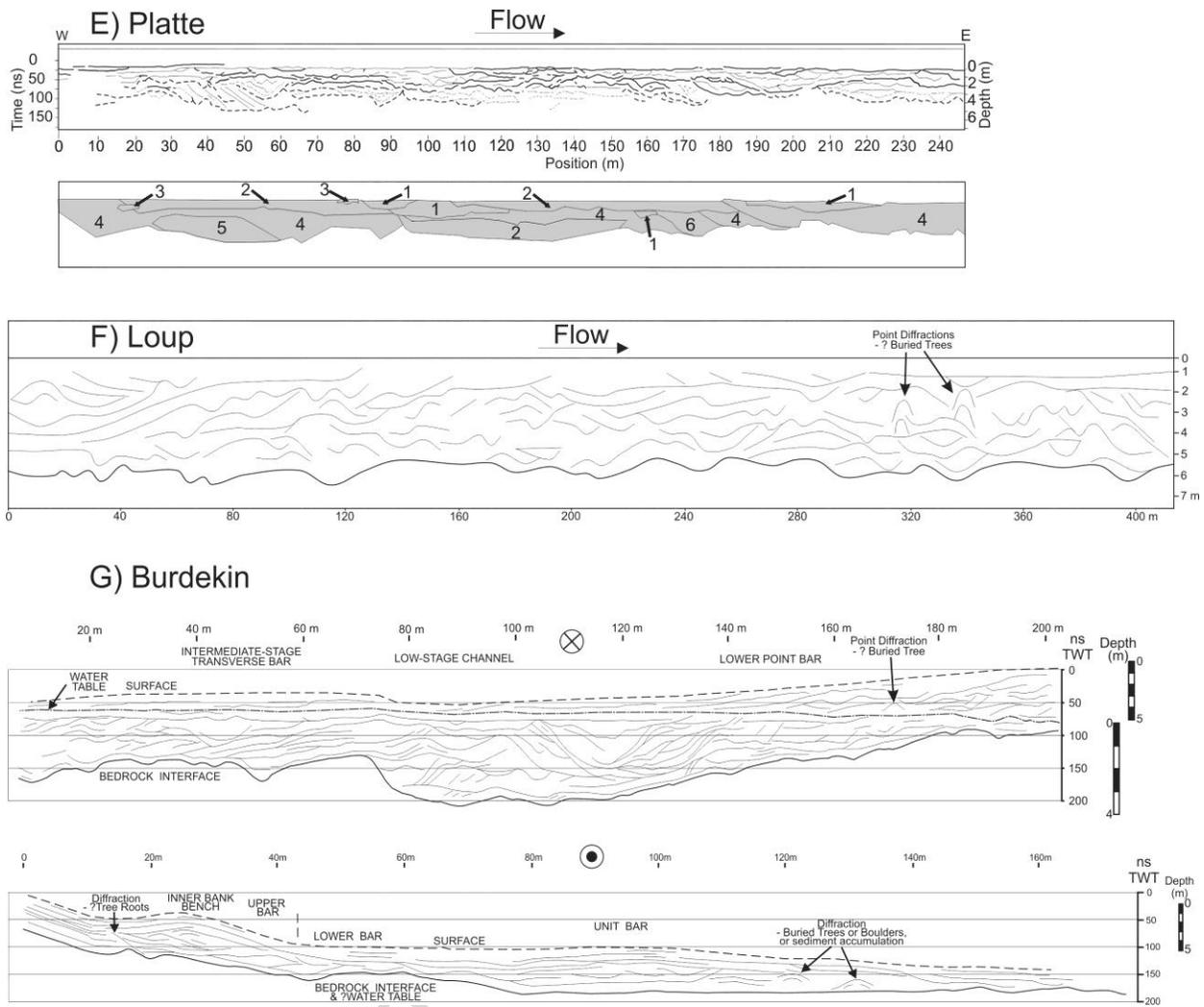


Figure 3E-H

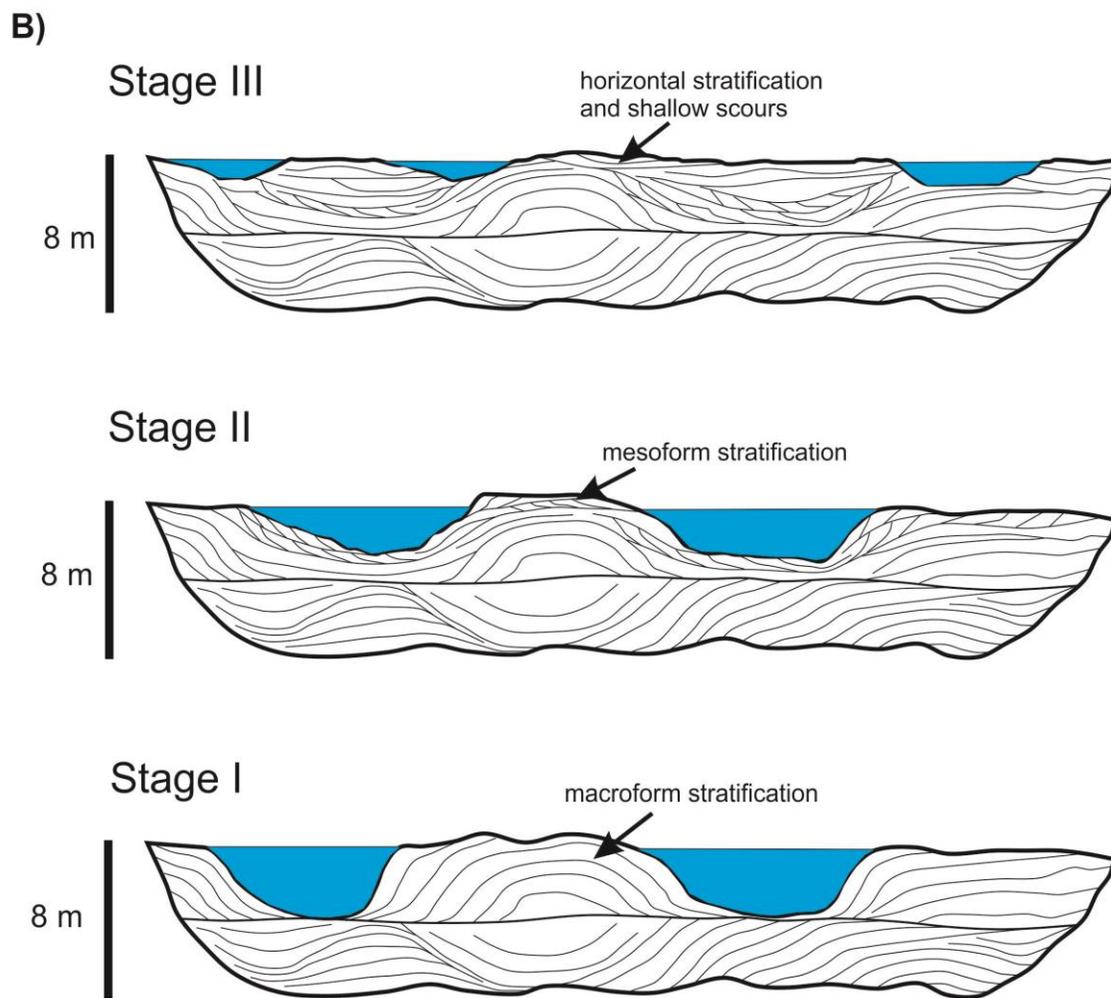


Figure 4

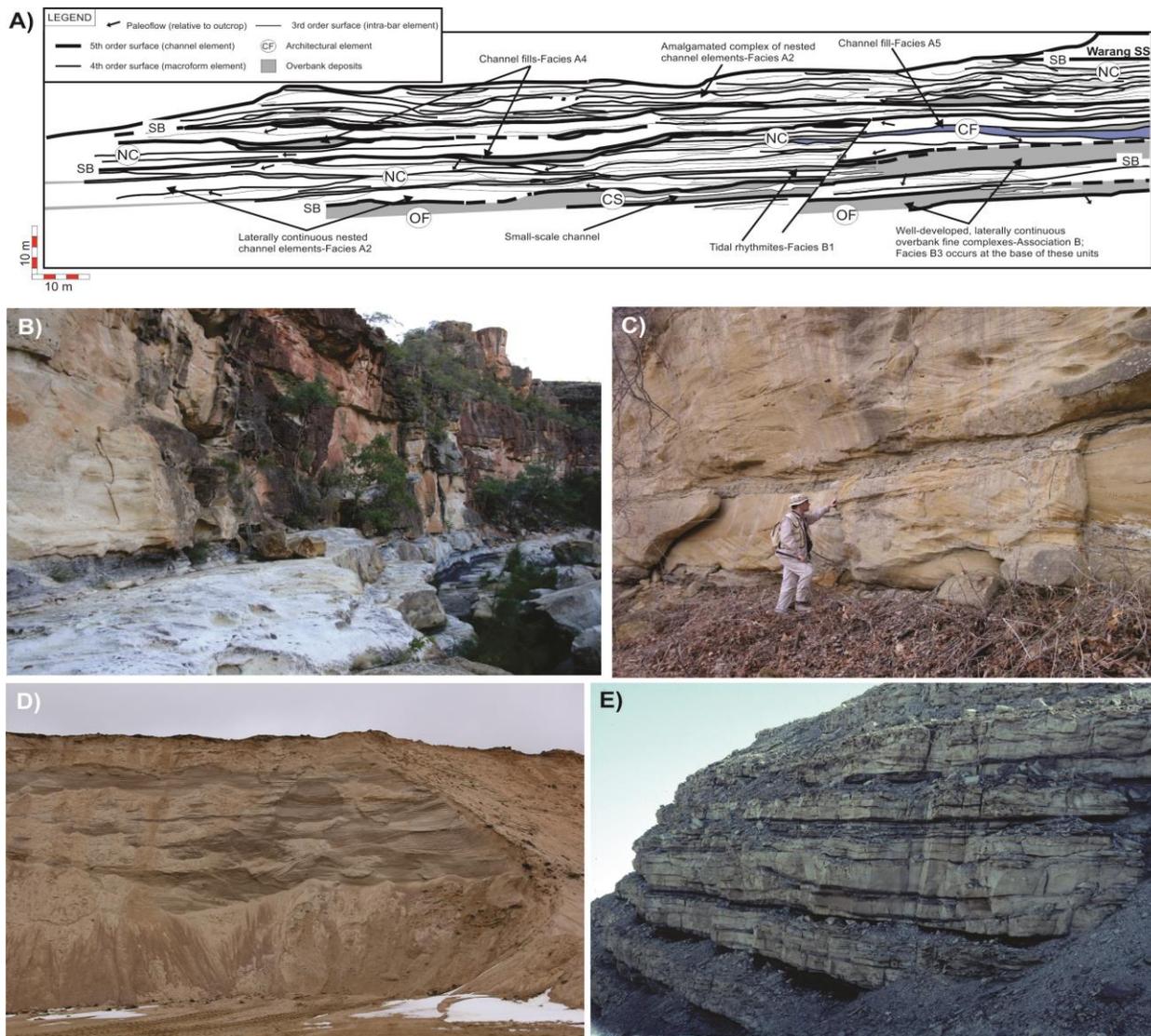


Figure 5

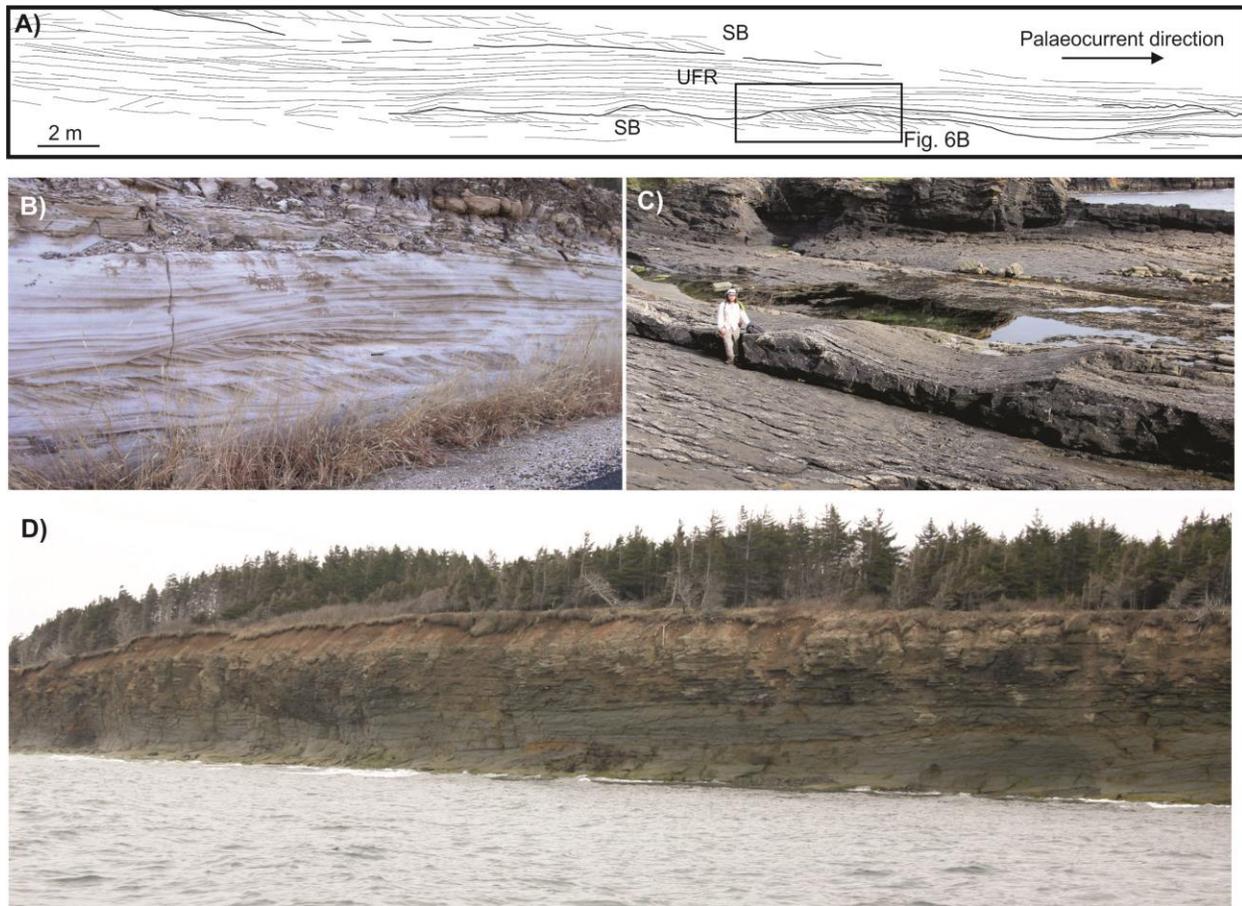


Figure 6

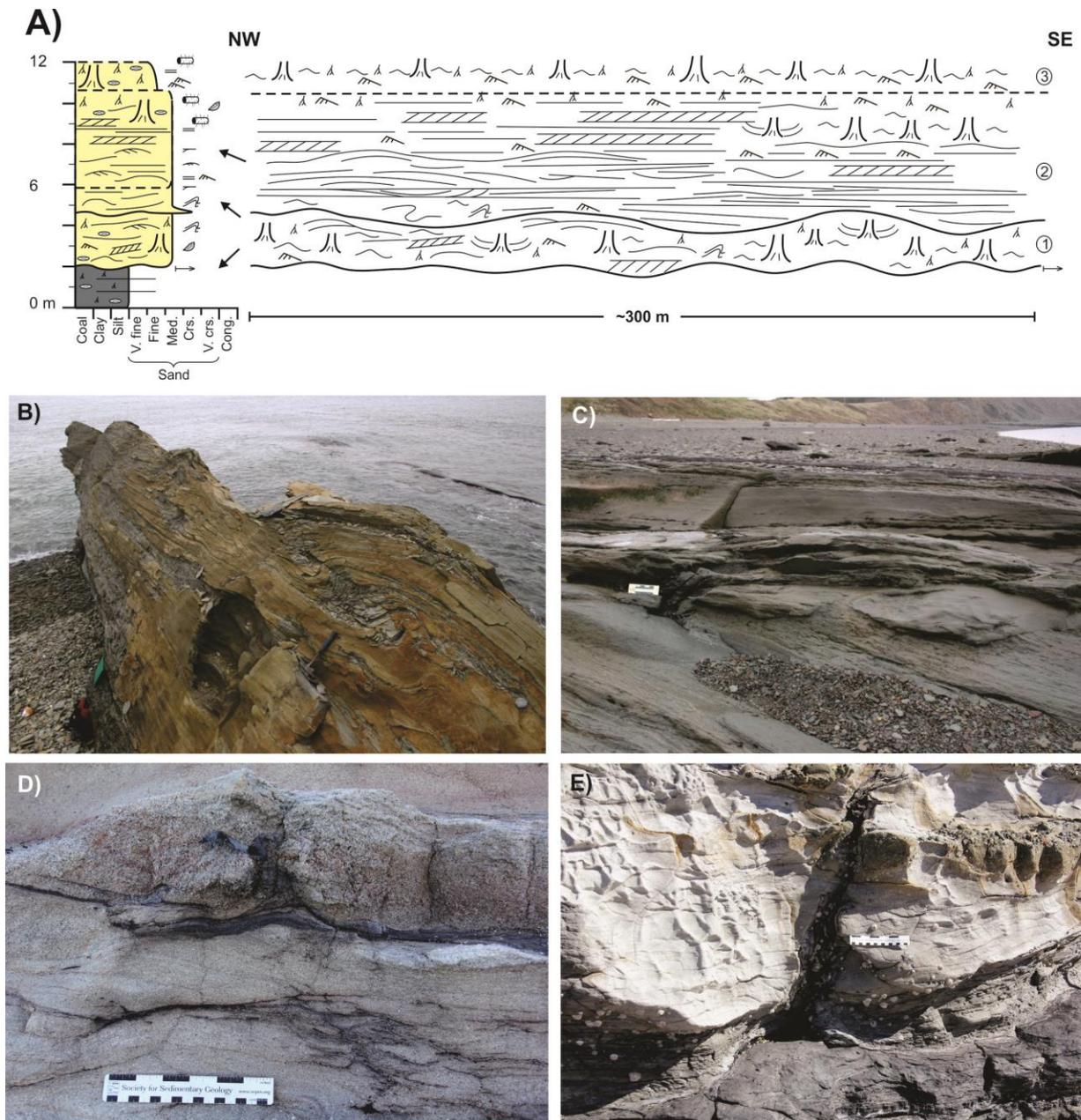
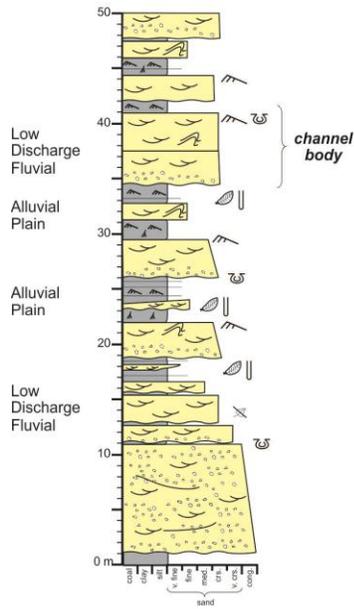
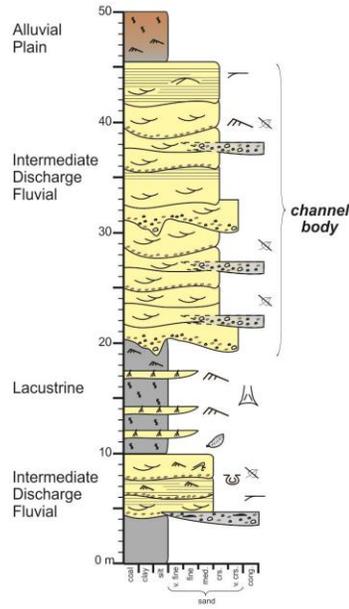


Figure 7

A. Low Discharge Variance



B. Intermediate Discharge Variance



C. High to Very High Discharge Variance

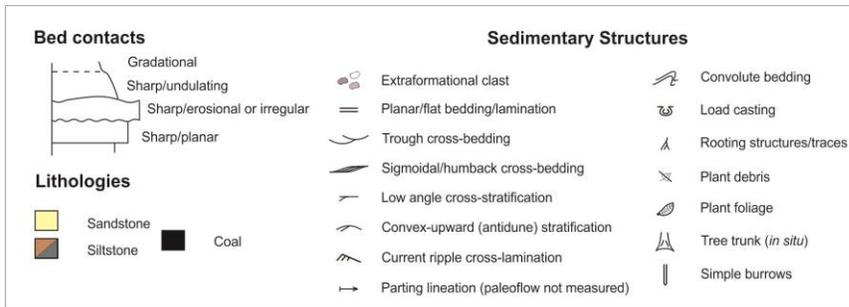
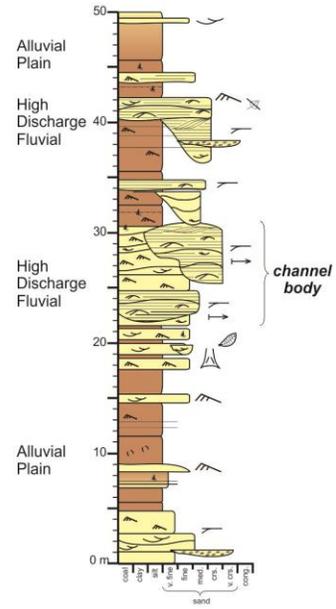


Figure 8

Table 1. Classifying rivers by peak discharge variability

River site	Mean annual peak discharge ($\text{m}^3 \text{s}^{-1}$)	Standard deviation of annual peak discharge	Coefficient of annual peak discharge variation	Length of record (years)	Drainage basin area above gauge (km^2)	Data source	Key related publication (see also references cited in text on the case studies)
Very low peak discharge variability			<0.20				
Fraser River near Marguerite, BC, Canada	4694	875	0.19	48	114000	a.	Rice et al. (2009) Rennie and Church (2010)
Mackenzie River at Fort Simpson, NWT, Canada	17372	3262	0.19	70	1300000	a.	Hill et al. (2001), Vesakoski, et al. (2017)
Ob at Belogor'e, Siberia	27502	4943	0.18	59	486000	b.	Meade et al. (2001), Yang et al. (2004)
Jamuna at Bahadurabad, Bangladesh	66070	13096	0.20	56	636130	c.	Bristow (1987, 1993), Bristow et al. (2000), Ashworth et al. (2000), Skelly et al. (2003), McLelland et al. (2009)
Low peak discharge variability			0.20-0.40				
Fraser at Shelley gauge, BC, Canada	3312	693	0.21	62	32400	a.	
Ob at Kolpashevo, Siberia	13540	3464	0.26	73	2690000	b.	
Mississippi at Vicksburg, MS, USA	39204	8747	0.22	103	2964241	d.	Fisk (1944). Harbor (1998) Jordan and Pryor (1992),

Niobrara below Box Butte Reservoir, NE, USA (regulated)	5.9	1.9	0.32	46	3781	d.	Nittrouer et al. (2008, 2011, 2012)
South Esk at Gala Bridge, United Kingdom	72.9	21.3	0.29	18	130	e	Bridge and Jarvis (1982), Bridge et al. 1995
Mid peak discharge variability			0.40-0.60				
Calamus near Harrop, NE, USA	17	7	0.40	20	1795	d.	Bridge and Gabel (1992), Gabel (1993), Bridge et al. (1998)
Calamus near Burwell, NE, USA	19	8	0.42	54	2577	d.	Leclair and Bridge (2001)
South Saskatchewan near Outlook, SK, Canada	1460	766	0.53	20	158600	a.	(Cant 1978 a, b), Cant and Walker (1978) Ashmore and Day, 1988 Sambrook Smith et al. (2010), Parker et al. (2013)
Wabash at Mt Carmel, IL, (pre regulation) USA	4094	2131	0.52	86	74164	d.	Jackson (1975, 1976a, b)
Upper Congaree at Columbia, SC, USA	2478	1652	0.67	123	20331	d.	Levey (1978), Levey et al. (1980)
high peak discharge variability			0.60-0.90				
Eel River at van Arsdale Dam, CA, USA	461	376	0.81	106	904	d.	Brown and Ritter

							(1971)
Eel River at BL Scott Dam, CA, USA	408	349	0.85	93	751	d.	
Eel, nr Dos Rios, CA, USA	764	576	0.75	30	1368	d.	Sloan et al. (2001)
Niobrara at Agate, NE, USA (pre regulation)	2.8	1.1	0.61	34	2419	d.	Ethridge et al. (1999), Bristow et al. (1999), Skelly et al. (2003)
Platte near Overton, NE, USA	245	202	0.82	99	145816	d.	Miall (1977); Smith (1970, 1971), Horn et al. (2012 a, b)
Platte near Duncan, NE, USA	349	228	0.65	105	153586	d.	Blodgett and Stanley (1980), Crowley (1983) Joeckel and Henebry (2008)
Burdekin at Clare, QLD, Australia	7857	6893	0.88	40	129876	f.	
Very high peak discharge variability			>0.90				
Bijou Creek near Ft Morgan, CO, USA	5.9	5.4	0.92	11	3581	d.	McKee et al. (1967)
Burdekin at Charters Towers, QLD, Australia	5852	7135	1.22	26	35 000	f.	Fielding and Alexander (1996), Alexander et al. (1999a), Fielding et al. (1999)
Burdekin at Sellheim, QLD, Australia	7194	6634	0.92	65	36400	f.	Alexander and Fielding (1997)
Burdekin at Clare, QLD,	6813	6820	1.00	20	129876	f.	Amos et al.

Australia (since Burdekin Falls Dam built)						(2004)
Fitzroy at the Gap, QLD, Australia	3341	3401	1.01	53	135757	f. Croke et al. (2011)

Rivers listed in this table are ones on which sedimentological studies have been published. Gauging stations were selected on basis of nearest proximity to the sedimentological study site(s) were record was of sufficient quality and duration. Data for some rivers is given for more than one gauging station or for more than one time period. These are discussed in the in the text.

- Database for Canadian rivers is published by Environment and Climate Change Canada the Government of Canada (<https://wateroffice.ec.gc.ca/>)
- r-arcticnet.sr.unh.edu/ObservedAndNaturalizedDischarge-Website/
- Data taken from Mostafizur Rahman (2015) and originally from Bangladesh Water Development Board.
- USA data from USGS database <http://waterdata.usgs.gov/nwis>
- British river data from the from the National River Flow Archive
- Data from the Burdekin and Fitzroy Rivers were approved by the Department of Environment Management, QLD.