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Title: Decoupling seasonal fluctuations in fluvial discharge from the tidal signature in ancient deltaic deposits: an example from the Neuquén Basin, Argentina

Running title: fluvial and tidal signals in sedimentation

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Abstract

Fluvial discharge fluctuations are a fundamental characteristic of almost all modern rivers and can produce distinctive deposits that are rarely described from ancient fluvial or mixed-energy successions. Large-scale outcrops from the Middle Jurassic Lajas Formation (Argentina) expose a well-constrained stratigraphic succession of marginal-marine deposits with a strong fluvial influence and well-known tidal indicators. The studied deposits show decimetre-scale interbedding of coarser- and finer-grained facies with mixed fluvial and tidal affinities. The alternation of these two types of beds forms non-cyclic successions that are interpreted to be the result of seasonal variation in river discharge, rather than regular and predictable changes in current velocity caused by tides. Seasonal bedding is present in bar deposits that form within or at the mouth of minor and major channels. Seasonal bedding is not preserved in channel thalweg deposits, where river flood processes were too powerful, or in floodplain, muddy interdistributary bay, prodelta and transgressive deposits, where the river signal was weak and sporadic. The identification of sedimentary facies characteristic of seasonal river discharge variations is important for accurate interpretation of ancient deltaic process regime.

Heterolithic deposits consisting of interlaminated and/or interbedded sandstone and mudstone include inclined heterolithic strata (IHS), flaser, wavy and lenticular bedding, and fluid mud-sand couplets (Reineck and Wunderlich 1968; Thomas et al. 1987; Ichaso and Dalrymple 2009; MacKay and Dalrymple 2011). These features are commonly identified in tidal depositional systems (Nio and Yang 1991; Dalrymple and Choi 2007; Geel and Donselaar 2007; Choi 2010; Dalrymple 2010; Davis 2012) and are often used to infer a tidal origin of ancient deposits. However, heterolithic deposits can also form in purely fluvial or mixed-energy settings due to temporal variations in river discharge at a seasonal or shorter time scale (Thomas et al. 1987) but in such settings they lack the ordered cyclicity of layer thickness and grain size that characterizes tidal sedimentation (Archer 1995; Kvale et al. 1995; Kvale 2012). River discharge fluctuations are a fundamental characteristic of almost all modern rivers (Milliman and Farnsworth 2011) and can also coexist with tidal processes in the deposits that accumulate in the lower reaches of rivers (e.g. Fraser River delta, Canada; Sisulak and Dashtgard 2012; Johnson and Dashtgard 2014), making it difficult to assess the relative importance of tidal and river currents.

In ancient successions tidal sedimentary structures (e.g. bundling, drapes, rhythmic lamination, bidirectional palaeocurrents, etc.), have received considerable attention (e.g. Visser 1980; Allen 1981; De Boer et al. 1989; Dalrymple et al. 1992; Willis 2005; Dalrymple and Choi 2007; Dalrymple et al. 2012; Plink-Björklund 2012; Legler et al. 2013) whereas facies associated with the seasonal variation of river discharge have received comparatively little emphasis (Bridge 2003; Rebata et al. 2006). The paucity of examples that describe river-generated seasonal bedding in the rock record may be hampered by the lack of a well-defined facies model. Discriminating between tidal and fluvial processes as the main control on deposition in the fluvial to marine transition zone (Dalrymple and Choi 2007) is crucial for improving and refining depositional models at the facies scale (Martinius et al. 2005; Nordahl et al. 2006), and for predicting the larger-scale geometry of sedimentary bodies (Reynolds 1999). Moreover, the recognition of fluvially generated seasonal deposits will improve palaeoclimatic and palaeogeographic reconstructions, particularly when other approaches (e.g. palaeobotanical, palaeontological) are not available or are non-diagnostic. The aims of this paper are: i) to establish recognition criteria to help distinguish between seasonal-discharge and tidal-process signals in the rock record and ii) to discuss how the tidal and seasonal signals are recorded in different facies, in order to help refine palaeoenvironmental reconstructions.

Large-scale outcrops from the Middle Jurassic Lajas Fm. (Argentina) provide a well-constrained succession of marginal-marine deposits (Zavala 1996a, b; Brandsaeter et al. 2005; McIlroy et al. 2005; Kurcinka 2014; Gugliotta et al. 2015). These deposits contain well-known tidal indicators, and a strong fluvial influence, which are recorded in both heterolithic and sandstone-dominated deposits that are described in detail herein. Tide-dominated dunes and bars described in Zavala (1996a, b) and Martinius and Van den Berg (2011) are present in specific stratigraphic intervals but are not the focus of this paper.

Discharge fluctuations in modern rivers

Of the 1534 present-day rivers in the database of Milliman and Farnsworth (2011), almost 95% show variations in discharge through the year (Fig. 1). In most of the rivers in low- and mid-latitudes, discharge fluctuations reflect a direct response to precipitation, which may be driven by the monsoon (Purnachandra Rao et al. 2011), whereas rivers in high latitude and high elevation areas, exhibit discharge variations that are affected by the melting of snow and ice (Milliman and Farnsworth 2011; La Croix and Dashtgard 2014).

In systems with large catchment areas and relatively high runoff rates, the effects of individual rainfall events are dampened and only the longer-term, annual variation in runoff is recorded in the deposits (Allen and Chambers 1998). In systems with small catchment areas and/or relatively arid runoff conditions, flow generally responds to individual rainfall events and is not as obviously tied to the general climatic conditions (Gonzalez-Hidalgo et al. 2010; Gonzalez-Hidalgo et al. 2013), in which case there might be more than one river flood in a single year. In large rivers, the flood stage can last for weeks to months, whereas in small rivers the flood may be over in a few hours. The influence of individual precipitation events increases with a reduction of catchment size because the impact of peak events in small drainage basins reflects the erosive power of flash floods and the inability of small basins to absorb local precipitation (Gonzalez-Hidalgo et al. 2010; Gonzalez-Hidalgo et al. 2013). In flashy rivers, the discharge rises quickly, often by two to four orders of magnitude in a single day (Fielding and Alexander 1996). In perennial rivers, by contrast, the discharge rises from low flow to peak flood discharge more slowly and the difference between the two is commonly small (i.e. peak discharge is commonly only one order of magnitude larger than low flow). For example, in the Fraser River, during low flow the discharge rate is ca 1000 m^3 sec^{-1}, and increases up to 15200 m^3 sec^{-1} during high flow (La Croix and Dashtgard 2014), while in the Mississippi River, the minimum mean monthly water discharge is about 2900 m^3 sec^{-1}, whereas maximum mean monthly water discharge reaches 52000–55000 m^3 sec^{-1} (Mikhailov and Mikhailova 2010).

Recently, particular attention has been given to the interaction of seasonal discharge fluctuations and tidal processes in modern, fluvial-tidal, mixed-energy settings (van Maren and Hoekstra 2004; Dark and Allen 2005; van den Berg et al. 2007; Sisulak and Dashtgard 2012; Johnson and Dashtgard 2014). During the period of seasonal high river discharge, the effects of fluvial processes are extended seaward, reducing tidal and salinity effects and pushing the tidal and salt wedge limits seaward (Allen et al. 1980; Dalrymple and Choi 2007; van den Berg et al. 2007; Kravtsova et al. 2009; Dalrymple et al. 2012; Dashtgard et al. 2012), which also has implications for the location of the turbidity maximum and the distribution of mud in the system (Purnachandra Rao et al. 2011; La Croix and Dashtgard 2014).

Geological background

The Neuquén Basin is an important hydrocarbon-producing sedimentary basin (Zambrano and Yrigoyen 1995) located in central-western Argentina and extending into east-central Chile, between 32° S and 40° S latitude (Fig. 2A). It covers more than 137,000 km^2 (Urien and Zambrano 1994) extending up to 700 km in a north-south direction and up to 400 km from west to east. The basin originated as a volcanic rift in the Triassic and evolved into a post-rift back-arc basin during the Jurassic. It is bounded on its north-eastern, eastern and southern margins by wide cratonic areas, which were the main source areas for the basin-fill sediment during the Jurassic (Uliana and Legarreta 1993), and by a magmatic arc on the active margin of the Gondwanan–South American Plate to the west (Howell et al. 2005). The Lajas Formation was deposited diachronously as a series of N and NW prograding wedges during the late Middle Jurassic (Fig. 3) and comprises more than 500 m of sandstone-, heterolithic- and mudstone-dominated deposits that accumulated in a variety of marginal-marine settings. The deltaic nature of most of the Lajas Fm. has been recognized in several studies (Spalletti 1995; Zavala 1996a, b; McIlroy et al. 2005) and for the last two decades has been interpreted as a tide-dominated system (McIlroy et al. 1999; Brandsaeter et al. 2005; McIlroy et al. 2005; Morgans-Bell and McIlroy 2005). More recently, however, the degree of tidal influence preserved in the delta plain to delta front deposits of the Lajas Fm. has been questioned (Kurcinka 2014; Gugliotta et al. 2015).

During the Middle Jurassic, South America was located in a similar orientation and latitude to the present-day configuration (Iglesia Llanos et al. 2006; Iglesia Llanos 2012) and was part of the west margin of the Gondwanan continent. The palaeoclimate of the study area has been interpreted by several palynological studies as warm and mainly arid, but with variable humidity (Quattrocchio et al. 2001; Martinez et al. 2002; Garcia et al. 2006; Stukins et al. 2013).

Methods and dataset

The stratigraphy of the Lajas Fm. has been investigated along 2 main cliff exposures near the village of Los Molles (Fig. 2B). Cliff-line A is SSW-NNE oriented and provides continuous exposure for about 8 km, whereas cliff-line B is oriented E-W and extends for approximately 10 km. Both cliff-lines are oriented at an oblique angle to the regional palaeoflow, which is broadly toward the NW (Zavala and González 2001; McIlroy et al. 2005). Numerous canyon exposures provide three-dimensional constraint on the stratigraphic architecture at the small to intermediate scale. This paper describes deposits from intervals through the entire 500 m-thick Lajas Fm. in a proximal to distal sense (from purely fluvial channels to the prodelta) and across depositional strike (from distributary channel axes to the flanking interdistributary bay deposits). Data collection included detailed measured stratigraphic sections, integrated with annotated photopanels, in order to document the stratal architecture, correlation of the main stratigraphic surfaces, and lateral and vertical facies variations. Photopanel correlations were verified by physical tracing (walking out) of contacts. More than 70 GPS located sections were logged at 1:50 and 1:25 scale. Facies and facies associations were interpreted in terms of depositional processes and environments based on grain size, sorting, stratal geometries, sedimentary structures and the presence and character of body and trace fossils.

Facies associations

In this section, we describe the deposits and interpret the major depositional environments based on facies, process sedimentology and stratigraphic context. Detailed description of the nature of the interbedding is provided in the next section. Facies are grouped into eight facies associations (FA 1 to FA 8). Bioturbation intensity is generally low but highly variable, and is described in terms of Bioturbation Index (BI) from 0 to 6 (Taylor and Goldring 1993; MacEachern et al. 2010).

FA 1: Fluvial and distributary channel deposits

Description: FA 1 consists mainly of moderately to well-sorted sandstone, up to very coarse-grained, with sparse granules and subordinate heterolithic and mudstone deposits. Units of FA 1 are up 12 m thick and laterally extensive for several hundred metres to over one kilometre. They are erosionally based, lenticular and show fining- and thinning-upward trends (Fig. 4A). FA 1 deposits are either structureless or show unidirectional, N or NW (seaward-directed), trough and planar-tabular cross-stratification, but also includes units of interbedded inclined coarser- and finer-grained sandstone and heterolithic beds (Fig. 4A, B, C). Beds are up to 0.4 m thick and laterally extensive for tens of metres. Depositional dip of the inclined master bedding is commonly perpendicular to the orientation of the cross-stratification. Some of the cross-stratification shows randomly-distributed carbonaceous drapes, but cyclical carbonaceous drapes are present in places. The cross-stratified facies is typically unidirectional and seaward-oriented and shows distribution of drapes composed of carbonaceous debris, commonly associated with plant debris and mica. Drapes are found in groups of 2-5 that are separated by a few millimetres to centimetres of sandstone whereas groups of drapes show spacing of several decimetres (Fig, 5A). This facies can show cyclical patterns in the distribution of drapes and height reached by the drapes on the foresets (Fig.

5B), as also described by Martinius and Gowland (2011). This facies lacks the features typical of the dominant current, slack water and subordinate tidal current, such as cyclically distributed reactivation surfaces, opposite directed ripples, and single and double mud drapes (Visser 1980). Pieces of silicified wood up to 1 m long are present and are typically oriented in the direction of the palaeoflow. Trace-fossil content is generally low (BI 0-1) and consists mainly of *Planolites.*

Interpretation: FA 1 is interpreted as fluvial and distributary channel deposits. The structureless and trough- and planar-tabular cross-stratified sandstones are interpreted as channel-axis deposits, whereas the inclined, interbedded coarser- and finer-grained sandstones indicate lateral accretion and are interpreted as bank-attached side bars and point bars. The interbedded finer- and coarser-grained beds are interpreted to reflect fluctuations in current speed as a result of changes in river discharge. The presence of unidirectional, seaward-oriented palaeocurrents in cross-stratification indicate fluvial dominance; minor tidal influence is indicated by the presence of cyclical carbonaceous drapes (Martinius and Gowland 2011), whereas the non-cyclical carbonaceous drapes are not considered to have been generated by tides, but instead to reflect non-periodic fluctuations of the river currents. The cyclically-distributed carbonaceous drapes are interpreted to reflect acceleration and deceleration (tidal modulation or tidal backwater effect) of fluvial currents, formed in the fluvial-dominated part of the fluvial to marine transition zone (Dalrymple and Choi 2007; Martinius and Gowland 2011; Dashtgard et al. 2012).

FA 2: Floodplain and crevasse-splay deposits

Description: FA 2 consists of poorly sorted, structureless or weakly laminated mudstones ranging from dark grey (with abundant detrital plant matter), to green, blue, purple and red (scarce plant matter). This FA forms tabular units up to several tens of metres thick, laterally extensive for several kilometres, and intimately associated with FA 1. A minor facies within FA2 consists of tabular, structureless sandstone beds, a few tens of centimetres thick that form units up to 1 m thick and extend laterally for tens to hundreds of metres. Large pieces of silicified wood up to 8 m long are present along with root traces. The trace-fossil content consists of root traces that generally are abundant in mudstones (BI 6), but absent in the sandstone beds (BI 0).

Interpretation: The tabular, laterally extensive mudstone units of FA 2 are interpreted as largely subaerial floodplain deposits. The variations in colour and amount of organic matter are interpreted to reflect different states of oxidation, which are probably linked to the level of the water table and, in general, the distance from the coastline (Retallack 2008; Varela et al. 2012). The dark, organic-rich floodplain deposits may have formed in distal positions and under conditions of poor drainage, whereas the green-blue and purple-red deposits may represent relatively more proximal, inland positions with moderate to well-drained floodplain conditions. The lenticular and tabular sandstone units are interpreted as the deposits of crevasse splays.

FA 3: Minor distributary channel deposits

Description**:** FA 3 consists of erosionally based, lenticular, fining- and thinning-upward units up to 1.5 m thick that are laterally extensive for a few tens of metres (Fig. 4D). FA 3 usually erosionally overlies FA 2 and FA 4 deposits and is laterally associated with FA 1. FA 3 is commonly heterolithic with local high mudstone content. Sandstones range from very fine-grained to coarse-grained and are poorly to well sorted. These deposits can show dm-scale interbedding of inclined, thinning-upward, coarser- and finer-grained beds. Beds are structureless or show unidirectional trough and planar-tabular cross-stratification and ripple cross-lamination or subordinate bidirectional ripples and non-cyclical rhythmites with mudstone and carbonaceous drapes. Carbonaceous drapes can also show cyclical patterns. Palaeocurrents show a wide range of directions, but are mainly toward the N and NW; they are generally unidirectional within a single unit. Subordinate palaeocurrents are broadly toward the S (landward). Dipping of the inclined master bedding is commonly perpendicular to the cross-stratification. In some parts of FA 3, however, the coarser- and finer-grained couplets are not well-developed and structureless sandstones or flaser, wavy and lenticular bedding with rare bidirectional current ripples are present. Trace-fossil content is generally low (BI 0-1) and consists mainly of *Planolites* and *Dactyloidites.*

Interpretation: FA 3 is interpreted as minor distributary channel deposits, eroding into the subaerial delta plain (FA 2) and linked to the main distributive system (FA 1). FA 3 is distinct from FA 1 as the channels are considerably smaller (~1 m thick versus 4-12 m thick) and consist of more heterolithic deposits or less well-sorted, muddy sandstones. The alternating, inclined finer- and coarser-grained beds are interpreted as laterally accreting bars with a prevalence of unidirectional, seaward-oriented bedforms; sedimentation was, therefore, fluvially dominated. However, the presence of cyclic rhythmites with mudstone drapes and bidirectional ripples suggests that the fluvial signal may be locally and temporally overprinted by tidal reworking. Carbonaceous drapes might result either from random fluctuations in the strength of the river current or tidal modulation of the fluvial current.

FA 4: Crevasse mouth bar deposits

Description: Typically, FA 4 consists of coarsening- and thickening-upward heterolithic units, up to 2 m thick (Fig. 6A), that are laterally extensive for tens to hundreds of metres. FA

4 gradually passes vertically and laterally into FA 7 and is incised by FA 1 and FA 3. Internally, units of FA 4 comprise alternations of medium-/coarse-grained and fine-grained beds that can be traced from only a few metres up to a few tens of metres. The beds are inclined and dip at up to 15-20 degrees, but commonly at lower angles (5-8 degrees). In the upper parts of FA 4, the coarser-grained beds are thicker and amalgamated, and the finer-grained intervening deposits may be missing such that the interbedding is not as clearly distinguishable as it is in the lower part of the unit (Fig. 6A). Coarser-grained beds are structureless or show unidirectional cross-stratification and ripple-cross-lamination. Finer-grained beds show internal mm-scale rhythmites with mudstone drapes and rare bidirectional ripples (Fig. 6B, C). The dips of the master bedding and cross-bedding show a wide range of directions, but both show a general prevalence toward the NW to NE (seaward-directed). The trace-fossil abundance is highly variable (BI 0-5).

Interpretation: FA 4 is interpreted as the deposits of mouth bars of crevasse delta systems. The common orientation of the inclined master bedding and cross-bedding indicate forward accretion. The alternating finer- and coarser- beds are interpreted to reflect fluctuations of river discharge, that together with the prevalence of unidirectional, seaward-directed palaeocurrents indicate river dominance. In the finer-grained beds, a tidal origin can be argued because of the presence of bidirectional ripples, mudstone drapes and a brackish water trace fossil assemblage. The poor sorting is attributed to the presence of high turbidity and entrainment of mud during deposition. The association with FA 1, FA 3 and FA 7 and the poor sorting suggest that FA 4 formed in interdistributary-bays of lower-delta-plain settings (Gugliotta et al. 2015).

FA 5: Terminal distributary channel deposits

Description: FA 5 consists of fine- to medium-grained, moderately to well-sorted, lenticular, erosionally-based sandstones up to 3 m thick that are laterally extensive up to a few tens of metres. FA 5 is usually structureless or trough-cross-stratified and is erosive into FA 6. Cross-stratification can show cyclically-distributed carbonaceous drapes. Palaeocurrents are commonly unidirectional to the N and NW (seaward-oriented), although rare S- (landward-) directed palaeocurrents were recorded. Trace-fossil abundance and biodiversity are generally low (BI 0-1), although rare examples show BI levels up to 5.

Interpretation: FA 5 is interpreted as terminal distributary channel deposits because of their relatively small size and intimate association with mouth bar deposits (FA 6). The predominantly unidirectional, seaward-oriented palaeocurrents suggest river dominance, consistent with the setting in which terminal distributary channels form (Olariu and Bhattacharya 2006). The rare landward-directed palaeocurrents and cyclically-distributed carbonaceous drapes suggest subordinate tidal influence at times.

FA 6: Mouth bar deposits

Description: FA 6 consists of coarsening- and thickening-upward units (Fig. 7A), up to 12 m thick, that form bodies several kilometres in lateral extent. FA 6 gradually passes downward and laterally into FA 7 and is erosionally incised by FA 1 and FA 5. FA 6 is composed of decimetre-scale interbedded fine-/medium-grained and very fine-/fine-grained sandstone (Fig. 7B, C, D, E). Beds are up to 0.4 m thick, dip at up to 15 degrees and show internal unidirectional, trough and planar-tabular cross-bedding and ripple-cross lamination oriented toward the N and NW, with subordinate, bidirectional ripples and rhythmites with mudstone drapes. The inclination of master bedding and cross-bedding are both seaward-directed and parallel to each other. In the upper part of FA 6, the coarser-grained beds are thicker and amalgamated (Fig. 7B), and the finer-grained intervening deposits may be missing. Trace-fossil abundance is highly variable (BI 0-6), but the diversity is generally low.

Interpretation: FA 6 is interpreted as mouth-bar deposits that formed in a delta-front area. The parallel orientation of the inclined beds and the cross-bedding indicates forward accretion. The alternating finer and coarser beds are interpreted to reflect fluctuations in river discharge that, together with the unidirectional, seaward-oriented palaeocurrents, indicate river dominance, although heterolithic deposits with rhythmically-distributed mudstone drapes and bidirectional ripples suggest subordinate tidal influence. FA 6 differs from FA 4 in size and in grain sorting. The mouth-bar deposits of FA 6 are interpreted to be distal features of major distributary channels (FA 1), and therefore had more time for sediment to move downstream to become overall finer. In contrast, the crevasse delta mouth bars have a coarser grain size that reflects their more proximal position in the system. The higher mud content in FA 4 reflects the overall lower-energy setting and higher turbidity present in interdistributary bays relative to mouth bars in an exposed frontal location (Gugliotta et al. 2015).

FA 7: Interdistributary-bay and prodelta mudstones

Description: FA 7 consists of blue to grey mudstones lacking any internal structures, with sandstone and coarse siltstone layers from a few millimetres to 0.1 m thick. Units are tabular, up to several tens of m thick and extend up to several kilometres laterally. FA 7 is gradationally overlain by FA 4 or FA 6 and is associated with FA 8. Trace-fossil abundance is generally high (BI 5-6).

Interpretation: FA 7 is interpreted as interdistributary-bay and prodelta deposits rather than open-shelf offshore mudstones because of the lateral association with FA 4 and FA 6, and the lack of open-marine indicators such as a pelagic fauna (e.g. ammonites, belemnites) or carbonates. FA 7 formed mainly from suspension fallout away from the main distributary channels and in the distal part of the delta system. Thin sandstone and coarse siltstone beds are interpreted as episodic depositional events marking large river floods. The lack of lamination is probably due to complete or almost complete bioturbation (BI 5-6), which suggests the presence of relatively more persistent brackish-water to fully marine conditions, with long periods of slow to negligible deposition.

FA 8: Transgressive and abandonment deposits

Description: FA 8 consists of a variety of siliciclastic and carbonate deposits that usually cap coarsening-upward units of FA 6, but can also overlie all of the other facies associations. These units are commonly laterally extensive, being traceable for distances of up to several kilometres, although they can also extend for only a few tens of metres in other cases. Siliciclastic deposits consist of sandstone beds up to 0.4 m thick that contain hummocky cross-stratification or dune-scale bedforms up to 1.5 m high. Carbonate deposits consist of shell-beds containing corals, oysters, echinoderms, *Trigonia*, brachiopods and other undifferentiated shells. Shells are usually well preserved and consist of articulated and disarticulated valves. Beds composed of broken shells are rare. Shell beds overlying delta plain deposits (FA 2, FA 3, FA 4 and FA 7) are commonly composed exclusively of oysters whereas those overlying delta front deposits (FA 5, FA 6, FA 7) contain a more diverse range of shells.

Interpretation: Both carbonate and siliciclastic deposits in FA 8 are interpreted as brackish to fully marine facies that sharply overlie, and are in turn overlain by, shallower-water deposits (such as interdistributary bay, mouth bar or prodelta facies). Shells can be preserved *in situ* (articulated) or have been subjected to minor transport and reworking (disarticulated valves). The carbonate shell beds are interpreted as lags accumulated during times of low siliciclastic input that allowed a benthic invertebrate fauna to thrive (Fuersich and Oschmann 1993). Shell-beds composed of broken shells are interpreted as storm deposits. The dunes composed of reworked sand, are known to be common on transgressive surfaces (Correggiari et al. 1996), whereas hummocky cross-stratification implies a general deepening of water and an increase in wave fetch. FA 8 is interpreted as marine sediments associated with regional flooding surfaces or local abandonment of the deltaic lobes.

Fluctuation of fluvial discharge and tidal signals

Interbedding: description

The coarser-grained beds described in FA 1, FA 3, FA 4 and FA 6 show a high degree of variability in their detailed characteristics, but also share many affinities (Fig. 8). Typically, the coarser-grained beds have erosional bases, can contain mudstone clasts and are structureless or show seaward-directed, unidirectional trough or planar-tabular dune-scale cross-stratification and current-ripple cross-lamination. Locally, these beds contain cyclical carbonaceous drapes on dune foresets, but these are not common. The trace-fossil content is absent or extremely low (BI 0-1) and generally of low diversity. Contacts are gradational with the overlying finer-grained sandstones and siltstones that may contain mudstone or carbonaceous and/or mica drapes, forming mm-scale cyclical rhythmites. These rhythmites rarely show cyclical patterns and can be associated with bidirectional ripples. A more abundant and diverse suite of trace fossils (e.g. *Palaeophycus*, *Ophiomorpha, Dactyloidites, Thalassinoides, Planolites*) is present compared to coarser-grained beds and is associated with an increase in the size of burrows. The intensity of bioturbation can be either low (BI 2-3) or can obliterate all sedimentary structures (BI 5-6; Fig. 7D, E). Some examples show the trace fossils extending downwards into the underlying coarser beds. Alternatively, the finer-grained intervening bed may show high concentrations of carbonaceous matter (Fig. 4B).

Interbedding: interpretation

The sandstone beds with erosional bases and unidirectional, offshore-directed palaeocurrents are interpreted as the deposits of river floods, which formed under strongly or entirely fluvial conditions. The rare rhythmic carbonaceous drapes may be the result of a tidal modulation of the river flow (Martinius and Gowland 2011), which would nevertheless imply a dominance of river currents as such tidal modulation of unidirectional river flow is inferred to occur in the inner part of the fluvial to marine transition zone (Dalrymple and Choi 2007; Dashtgard et al. 2012). The intervening, finer-grained beds with bidirectional ripples, cyclical rhythmites, and increased bioturbation levels are interpreted as interflood deposits formed during low river stage and under short-term dominance of tidal processes and brackish to fully marine conditions. Cyclical patterns are similar to those described in tidal deposits (De Boer et al. 1989). Rare top-down burrows in the coarser beds originated from the interflood beds, suggesting a stronger marine influence during low river stage. The abundance of carbonaceous material in the interflood deposits is interpreted as a sign of low river energy, because of the hydraulically light nature of the fine-grained “tea leaves” that comprise the organic detritus.

Additional indicators of river discharge fluctuations

The sedimentary facies described above provide process-based indications that significant variations in river discharge are recorded in the deposits. Other features can be used to support this interpretation although these features alone are insufficient to prove the impact that river discharge fluctuations had on sedimentation. In general, the trace fossils in the

Lajas Fm. show low numbers of infaunal populations, which suggest a stressed environment (MacEachern et al. 2010). This is possibly the result of low and variable salinity and inconstant discharge, although it has been previously associated with temperature stress (McIlroy et al. 2005). Also, the ichnotaxa *Dactyloidites* is common in many of these deposits, typically as a monospecific assemblage. This is the trace of an opportunistic colonizer, mainly found in river-dominated deltas. It is commonly associated with rapid, episodic sedimentation, the presence of organic matter and high turbidity in the water column (Agirrezabala and de Gibert 2004). These conditions are fully consistent with the interpretation of variable river discharge. Synaeresis cracks are also present in the Lajas Fm. (Fig. 4E). They form because high discharge events during river floods may lead to the temporary introduction of reduced-salinity waters immediately above the sediment–water interface (MacEachern et al. 2010).

Discussion

Seasonal discharge variations in the Lajas Fm.

The studied portions of the Lajas Fm. show decimetre-scale interbedded coarser-grained beds (river flood deposits) and finer-grained beds with tidal affinity (interflood deposits). The alternations of these two types of bed create non-cyclic rhythmites that are interpreted to be the result of variations in river discharge. This is because the magnitude of river floods varies stochastically, rather than cyclically and predictably like tides. This interpreted fluvial signature is present in a variety of deposits ranging from distal (mouth bar deposits, FA 6) to more proximal facies such as the point bars of fluvial and distributary channels (FA 1). The presence of preserved bar deposits suggests seasonal rather than ephemeral rivers because barforms are commonly reworked and cannibalised in ephemeral systems (Fielding et al. 2009; Fielding et al. 2011; Wilson et al. 2014). Key characteristics of channels with flashy discharge, such as abundant, pedogenically modified mud partings, abundance of upper-flow-regime sedimentary structures and *in situ* trees (Fielding 2006; Fielding et al. 2009; Fielding et al. 2011; Gulliford et al. 2014; Wilson et al. 2014) are missing from the Lajas Formation. The high levels of bioturbation (commonly BI 4-6) and the increased size of burrows in the interflood beds suggests that it would take burrowers at least several months to re-establish the degree of bioturbation to such a high level after a flooding event, if they were emplaced by larvae (Gingras et al. 2002; Gingras and MacEachern 2012). This pattern of bioturbation intensity supports the interpretation of a seasonal origin for the beds. Furthermore, because of the relatively large size of the river channels (sand bodies up to 12 m thick) and the location of the source area, the Sierra Pintada belt and the Patagonian Massif (Fig. 2), both of which are located at least 100 km away (Uliana and Legarreta 1993), the Lajas Fm. rivers likely drained large catchments that were able to absorb local precipitation and therefore primarily record seasonal discharge fluctuations.

Fluvial versus tidal control on the bedding of the Lajas Fm.

As highlighted in the introduction, heterolithic deposits are often considered tidal in origin. Semidiurnal or diurnal cycles are required to account for mm-scale interlamination that is visible in the fine-grained, interflood beds. A tidal origin for the decimetre-scale interbedding of coarser- and finer-grained deposits would require the operation of a longer duration tidal periodicity, such as neap-spring cycles. However, this assertion does not fit with the almost total absence of a clear tidal signal within the coarser-grained beds (Fig. 8). If these beds were deposited during spring tides, it might be expected that the tidal signal would be more strongly developed in them rather than in the intervening, fine-grained neap-tide deposit. This is because spring tides are stronger and able to entrain more mud into suspension than neap tides, which could result in more pronounced cyclical rhythmites and therefore a clearer tidal signal in the spring-tide deposits (Nio and Yang 1991). By the same principles, if formed under spring-tidal periods, landward-oriented and bidirectional cross-stratification and cross-lamination would be more common in the sandstone beds than in the intervening deposits, in contrast with our observations that the tidal signal is most pronounced in the fine-grained beds. Alternatively, a single coarser-grained bed could theoretically be considered as the result of a single tidal phase (flood or ebb); however, because of the short duration of a single phase of the tide, the thickness of a sand layer that can be deposited by a single tide is limited. Published results from modern and ancient tidal rhythmites (De Boer et al. 1989; Dalrymple et al. 1991; Archer 1995; Kvale et al. 1995; Archer 1996; Mazumder and Arima 2005; Choi 2011; Dalrymple et al. 2012; Kvale 2012; Longhitano et al. 2012; Johnson and Dashtgard 2014) suggest that the deposit of a single tidal phase is commonly less than 2-3 cm in thickness (and rarely above 5 cm), and thus thinner than most of the sand beds described herein.

In our interpretation, evidence for river discharge variations and tidal processes are both present in the Lajas Fm. deposits, but they can be decoupled. The seasonal fluctuations of the river discharge are interpreted to be the controlling influence on sedimentation. They produce a change in strength and regime of the fluvial current, which is reflected in the distinct alternation of coarser- and finer-grained beds. This interpretation is supported by the absence of a cyclical pattern in the coarser-grained beds (river floods) and the seaward orientation of cross-stratification. Furthermore, the regular alternation of burrowed and unburrowed layers in marginal-marine deposits have also been associated with seasonal variations in sedimentary conditions (Gingras and MacEachern 2012).

The waxing phase of the river flood period is responsible for the development of the basal erosion surface of each coarse-grained bed (Fig. 9A). Deposition starts during the waning stage of the river flood (Bridge 2003) when the coarser-grained bed is formed under fluvial-dominated conditions (Fig. 9B). Waning river energy during the late stage of the river flood results in deposition of finer grain sizes and subordinate modification by tidal currents (Fig. 9C). Finally, during the interflood period at low river stage, sediment is reworked by tidal processes (Fig. 9D).

Distribution and trends of seasonal and tidal deposits: facies control on preservation

Seasonal bedding is interpreted to be present in the Lajas Fm. in mouth-bar deposits (FA 6), crevasse-mouth-bar deposits (FA 4) and both point bars and side-attached bars within major and minor channel deposits (FA 1 and 3; Fig. 10). In the upper (proximal) part of crevasse-mouth-bar units, river flood beds are thicker and more amalgamated than in the lower section of the body. This is interpreted as due to erosion of interflood beds by strong river currents at high river stage. River flood-interflood couplets are well-developed in the medial part of mouth bars because river flood erosion is less significant, but they become less well-developed in the distal part of the crevasse mouth bar because of tidal and biological reworking during interflood periods (Gugliotta et al., 2015). A similar pattern is visible also in main mouth-bar deposits (FA 6), which show a similar upward trend of decreasing preservation of interbedding and lack of interflood beds in the top part, where river flood beds are thicker and more amalgamated (Fig. 10).

In the channel deposits, seasonal bedding is poorly-developed in the channel thalweg because of the high energy erosion during river floods but is well developed in side-bar and point-bar deposits of FA 1 and FA 3 (i.e. in areas that are more strongly depositional; Fig. 10). Terminal distributary channels (FA 5) do not show clear seasonal bedding also because of the strongly erosive conditions therein. Channel thalweg deposits are dominated by the presence of dunes and some of them show evidence for a tidal signature (i.e. rhythmically distributed carbonaceous drapes; Fig. 5), but they do not show a clear sign of seasonality. Although the life-span of dunes is poorly constrained, it is considered unlikely that a single cross-bed would record one complete year of deposition or let alone several years, because of the erosion of the stoss side as the dune migrates. In the case that deposition occurs continuously, modern fluvial and tidal dunes have migration rates on the order of tens of centimetres to tens of metres per day (Visser 1980; Van Den Berg 1987; Dalrymple and Rhodes 1995; Harbor 1998; Villard and Church 2003; Martinius and Gowland 2011). Assuming that the seasonal control will be due to annual changes in river discharge and that at least a few cycles are required to permit recognition, a single cross bed would have to be exposed continuously over a distance of hundreds to thousands of metres, something that is highly unlikely to exist. A tidal modulation cycle, that is needed to produce cyclically-distributed carbonaceous drapes, lasts only 6 or 12 hours, depending on whether the system is semi-diurnal or diurnal, and could be recorded in a few metres of continuous sedimentation. This implies that some facies will tend to record preferentially one process rather than another (in this case tides rather than seasonality). However, this does not mean that the tidal signal is the main control on deposition in the entire environment. To avoid misinterpretation we need to base our evaluation on examination of the whole system rather than on a single facies.

Other deposits described in this paper show little or no evidence of seasonal bedding; these include all of the mud-rich deltaic deposits, such as floodplain (FA 2) and interdistributary bay-mud and prodelta deposits (FA 7). The reason why seasonal bedding is not present in these facies associations is ascribed to the lack or sporadic nature of sand input in these distal, low-energy areas and/or obliteration of all bedding by bioturbation. In transgressive deposits (FA 8) seasonal bedding is not developed because these deposits form in distal settings, far removed from the influence of the river.

The preservation of seasonal bedding in the Lajas Fm. is strongly facies controlled. Seasonal deposits are present only in facies that form under steady rates of sedimentation over several seasons with little erosion. These conditions are usually met in bars that form both within (side bars and point bars) and at the mouth (crevasse mouth bars and mouth bars) of channels. Thus, the basic conditions needed to preserve seasonal bedding are: 1) presence of seasonal discharge in the river (which is the norm in modern rivers); 2) relatively continuous local sedimentation and little erosion during river flood periods (such conditions occur commonly on bars); and 3) relatively little reworking by tidal, wave and biological processes.

Conclusions

The studied deposits of the Lajas Formation comprise delta mouth bar, distributary channel and a range of delta plain deposits. Major and minor channel and mouth bar deposits show a ubiquitous decimetre-scale interbedding of coarser-grained beds (river flood) and finer-grained beds (interflood) that form non-cyclic rhythmites. River flood beds have unidirectional seaward-directed palaeocurrents and little evidence of tidal processes and brackish water conditions. Interflood beds show evidence of tidal process (tidal rhythmites, bidirectional palaeocurrents) and of brackish water conditions (trace fossils). The interpretation of the rhythmites is that they record variations in river discharge rather than tides because the magnitude of river floods is stochastic and does not vary regularly, whereas tides are cyclical and predictable. The deposit of a single tidal phase would be thinner than most of the river-flood deposits described herein and the almost total absence of a clear tidal signal in the coarser-grained beds would exclude their origin from a longer duration tidal cyclicity. Moreover, regular alternation of burrowed and unburrowed layers, like those described herein, has commonly been associated with seasonal variations in sedimentary conditions.

The characteristics and distribution of the bedding suggest a seasonal pattern rather than the shorter-term and more drastic fluctuations associated with flashy river discharge. Seasonal patterns of deposition from perennial rivers should represent the norm and not the exception in coast-zone rivers, because seasonal discharge fluctuations are a fundamental process in present day river systems worldwide and are expected to be preserved in the large part of ancient fluvial and deltaic deposits (Fig. 1).

The occurrence of seasonal deposits in the Lajas Fm. is facies controlled, and preferentially preserved in areas with relatively continuous sedimentation and limited erosion, such as on bars that form within or at the mouth of major and minor channels. The seasonal signal is not preserved where river flood processes are too powerful and remove the interflood deposits, such as in channel thalwegs and terminal distributary channels, or where the river input is weak and sporadic, such as in floodplain, muddy interdistributary bay, prodelta and transgressive marine deposits. Some facies, such as dunes, can record tidal modulation rather than seasonality; this must be taken into account in the evaluation of the main control on deposition. Consequently, to avoid misinterpretations, the evaluation of the dominant process in similar types of ancient deposits should be based on the whole system rather than on a single facies or facies association.

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Figure captions

Fig. 1. Pie chart highlighting the dominance of discharge fluctuations in modern rivers. Based on the database of Milliman and Farnsworth (2011).

Fig. 2. (**a**) Location map and extent of the Neuquén Basin. (**b**) Detailed location map showing the location of the study area (black rectangle).

Fig. 3. Middle Jurassic stratigraphy of the Neuquén Basin. Modified from Howell *et al.* (2005) and McIlroy *et al.* (2005). On the right, a detailed stratigraphic column of the Cuyo Group in the study area with a generalized palaeoenvironmental interpretation. The stratigraphic subdivisions on the left of the column are from Zavala (1996a, 1996b) and McIlroy et al. (2005).

Fig. 4. Representative photographs of the coarser- and finer-grained interbedding in major and minor channel deposits in the Lajas Fm. interpreted as river flood and interflood beds formed in response to fluctuations in river discharge. Photos are from the upper part of the stratigraphy. (**a**) Distributary channels deposits (FA 1) overlying floodplain deposits (FA 2).

The channel deposits show a structureless part and a low-angle interbedded part with coarser- (river flood) and finer-grained (interflood) deposits. Dashed lines indicate erosional surfaces at the base of the unit. Triangles indicate fining- and thinning-upward trends. Person for scale is 1.75 m tall. (**b-c**) Detail of distributary channel deposits (FA 1) with alternation of coarser- (river flood) and finer-grained (interflood) beds. Finer-grained beds are marked by abundant carbonaceous material (**b**) and trace fossils (**c**) indicating lower energy. Compass for scale is 6.5 cm long and pencil for scale is 12 cm long. (**d**) Minor distributary channel deposits (FA 3) showing alternations of coarser- (river flood) and finer-grained (interflood) beds. Dashed lines indicate erosional surfaces at the base of the unit. Triangles indicate fining- and thinning-upward trends. (**e**) Detail of minor distributary channel deposits (FA 3) with alternation of coarser- (river flood) and finer-grained (interflood) beds. Synaeresis cracks in the interflood bed mark a salinity contrast. Pencil for scale is 12 cm long.

Fig. 5. (**a-b**) Cyclical pattern in carbonaceous drapes in unidirectional, seaward-oriented cross-stratification interpreted as the result of tidal modulation of fluvial currents. Arrows show tidal modulation cycles indicated by spacing of the drapes or the height reached by drapes in the dune foresets. Grain size card for scale in (**a**) is 8 cm long. Note 10 cm scale bar in (**b**).

Fig. 6. (**a-c**) Representative photographs of the coarser- and finer-grained interbedding in crevasse mouth bars (FA 4) of the Lajas Fm., interpreted as river flood and interflood beds formed as a result of river discharge fluctuations. Photos are from the upper part of the stratigraphy. The triangle indicates coarsening- and thickening-upward trend. Notebook for scale is approximately 20 cm long and lens cap is 52 mm in diameter. See key for the sedimentary log in Fig. 4.

Fig. 7. Representative photographs of the coarser- and finer-grained interbedding in mouth bars (FA 6) of the Lajas Fm., interpreted as river flood and interflood beds formed as a result of river discharge fluctuations. Photos are from the lowest 200 m of the stratigraphy. (**a**) Two stacked mouth bar units with the associated sedimentary log. Person for scale is 1.75 m tall. Triangles indicate coarsening- and thickening-upward trends. See key for the sedimentary log in Fig. 4. (**b**) Amalgamated river flood beds in the upper part of the FA 6 unit. (**c**) River flood and interflood beds in the medial part of the unit. (**d-e**) Interbedding formed by fluvial discharge fluctuations from the lower 100 m of the stratigraphy. Note that interflood beds are highly bioturbated (BI 6) compared to unbioturbated river flood beds. Pencil for scale is about 12 cm long and coin is about 2.5 cm in diameter.

Fig. 8. Summary of the key characteristics of river flood and interflood beds from mouth-bar deposits (FA 6). Pen for scale is 12 cm long.

Fig. 9. Formation of bedding in a mouth-bar setting in response to seasonal discharge variations with a weak tidal overprint during the interflood period. Length of arrow represents strength/velocity of fluvial and tidal currents.

Fig. 10. Schematic depositional model for the studied sections of the Lajas Fm. showing the distribution of facies with and without seasonal bedding.

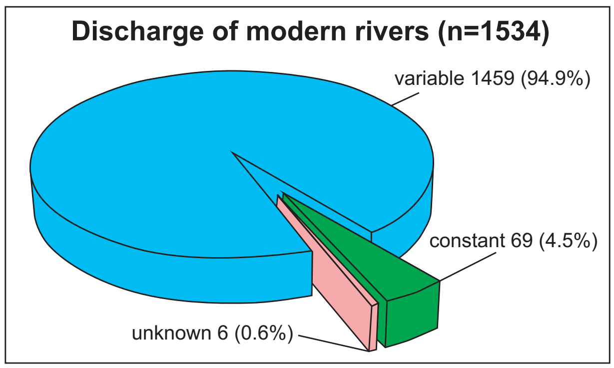

Discharge of modern rivers (n=1534)
variable 1459 (94.9%)
constant 69 (4.5%)
unknown 6 (0.6%)

Figure 1

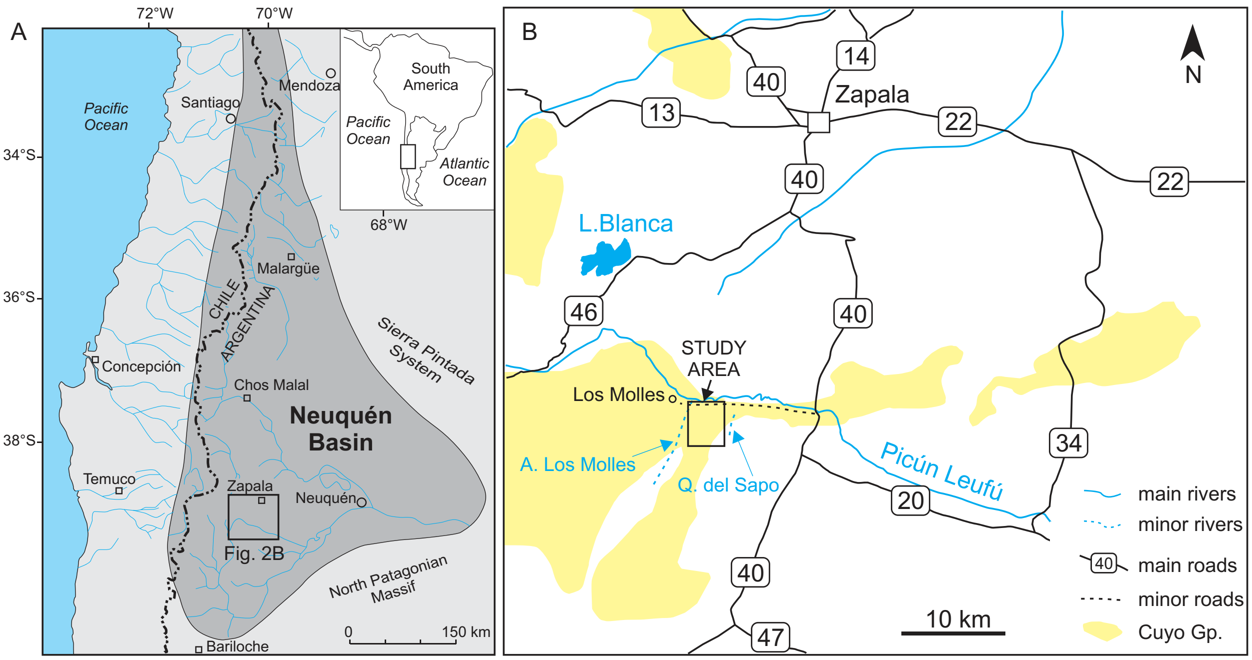
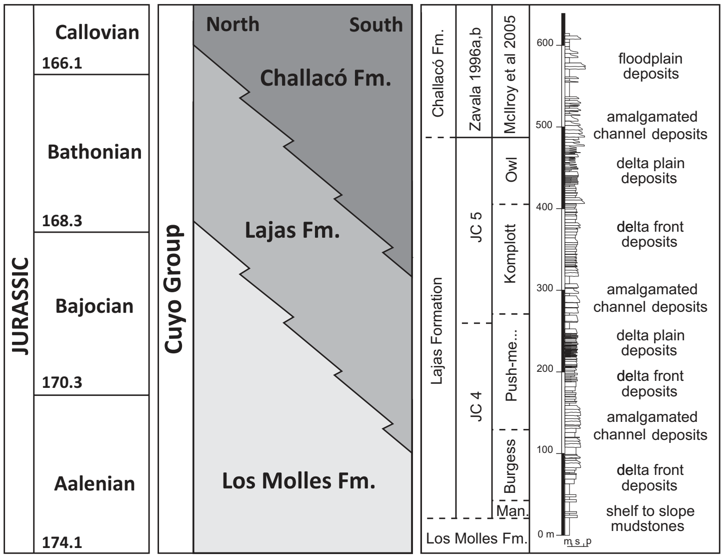

A
72°W
70°W
34°S
36°S
38°S
Pacific Ocean
Santiago
Mendoza
South America
Pacific Ocean
Atlantic Ocean
68°W
Malargüe
CHILE
ARGENTINA
Concepción
Chos Malal
Neuquén Basin
Sierra Pintada System
Temuco
Zapala
Neuquén
Fig. 2B
North Patagonian Massif
0
150 km
Bariloche
B
N
14
40
Zapala
13
22
40
22
L.Blanca
46
40
STUDY AREA
Los Molles
A. Los Molles
Q. del Sapo
Picún Leufú
34
20
40
47
10 km
main rivers
minor rivers
40
main roads
minor roads
Cuyo Gp.

Figure 2



JURASSIC
Callovian
166.1
Bathonian
168.3
Bajocian
170.3
Aalenian
174.1
Cuyo Group
North
South
Challacó Fm.
Lajas Fm.
Los Molles Fm.
Challacó Fm.
Lajas Formation
Los Molles Fm.
Zavala 1996a,b
JC 5
JC 4
McIlroy et al 2005
Owl
Komplott
Push-me...
Burgess
Man.
0 m
100
200
300
400
500
600
m s p
floodplain deposits
amalgamated channel deposits
delta plain deposits
delta front deposits
amalgamated channel deposits
delta plain deposits
delta front deposits
amalgamated channel deposits
delta front deposits
shelf to slope mudstones

Figure 3

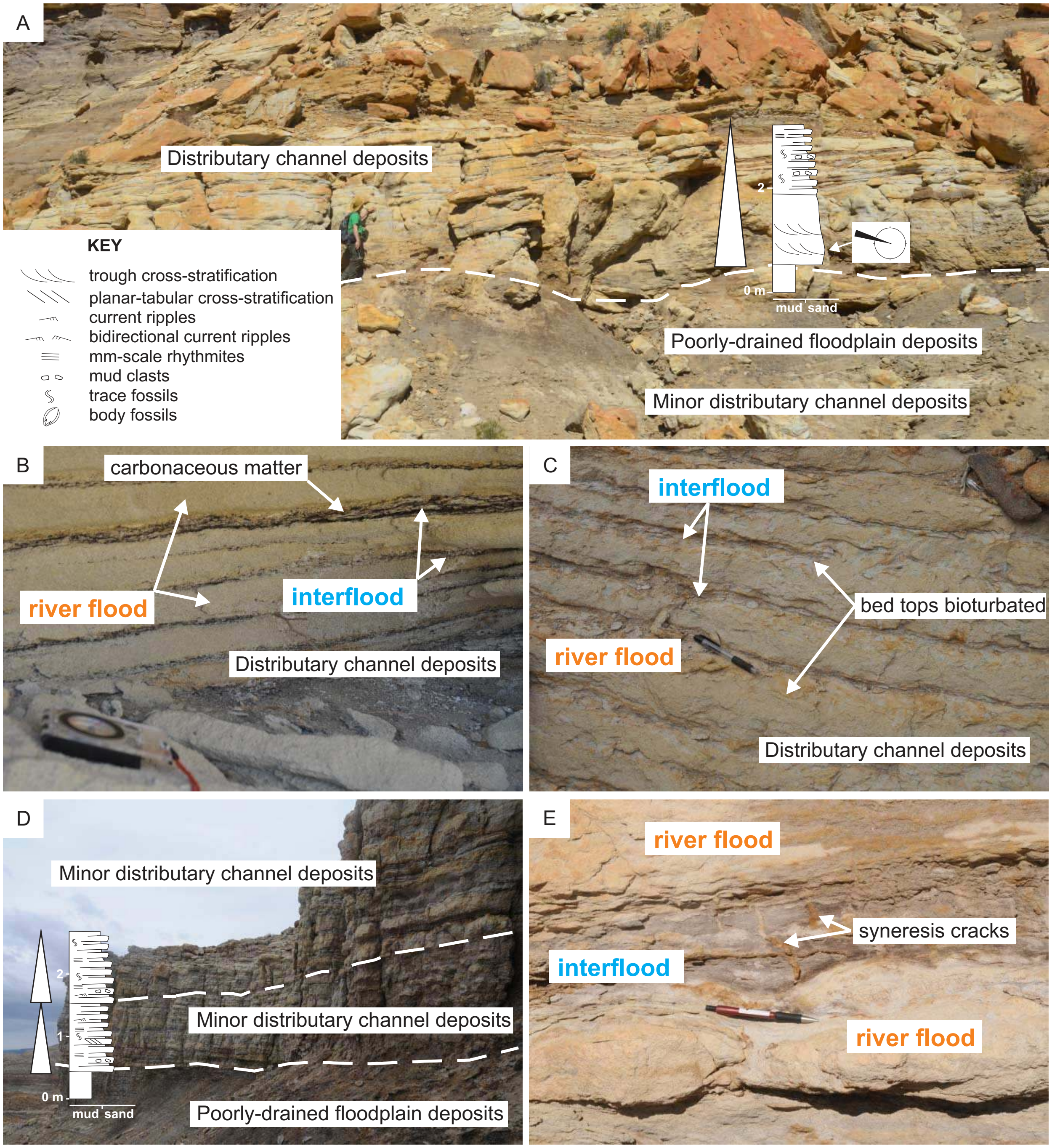

A
Distributary channel deposits
KEY
trough cross-stratification
planar-tabular cross-stratification
current ripples
bidirectional current ripples
mm-scale rhythmites
mud clasts
trace fossils
body fossils
2
0 m
mud sand
Poorly-drained floodplain deposits
Minor distributary channel deposits
B
carbonaceous matter
river flood
interflood
Distributary channel deposits
C
interflood
bed tops bioturbated
river flood
Distributary channel deposits
D
Minor distributary channel deposits
2
1
0 m
mud sand
Minor distributary channel deposits
Poorly-drained floodplain deposits
E
river flood
syneresis cracks
interflood
river flood

Figure 4

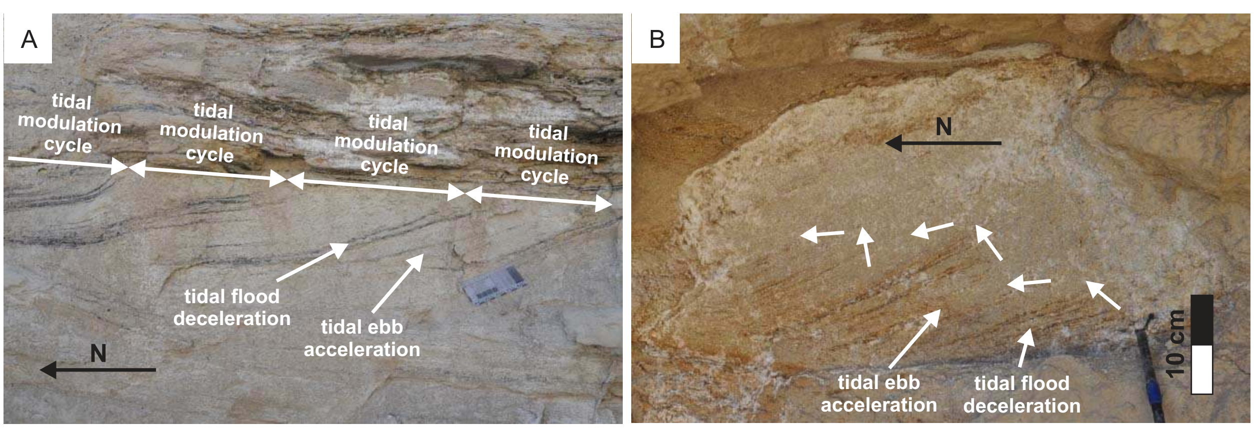

A
tidal modulation cycle
tidal modulation cycle
tidal modulation cycle
tidal modulation cycle
tidal flood deceleration
tidal ebb acceleration
N
B
N
tidal ebb acceleration
tidal flood deceleration
10 cm

Figure 5

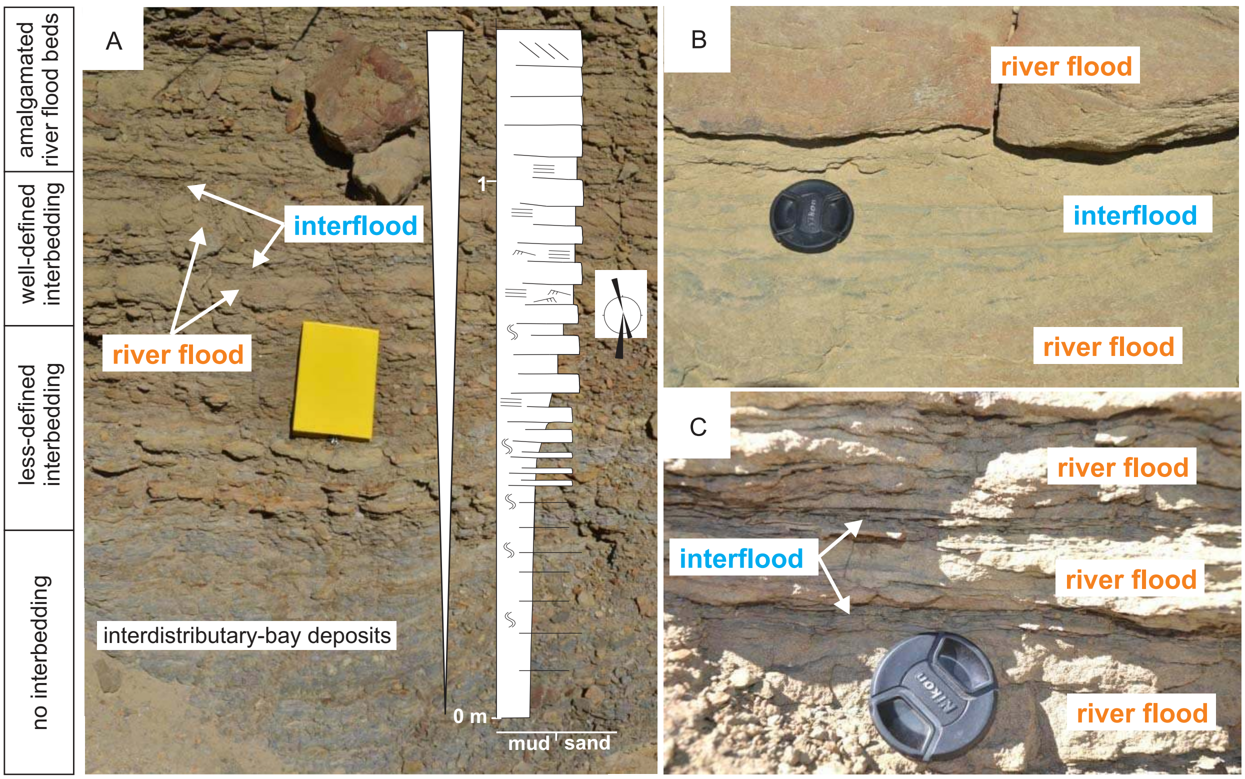
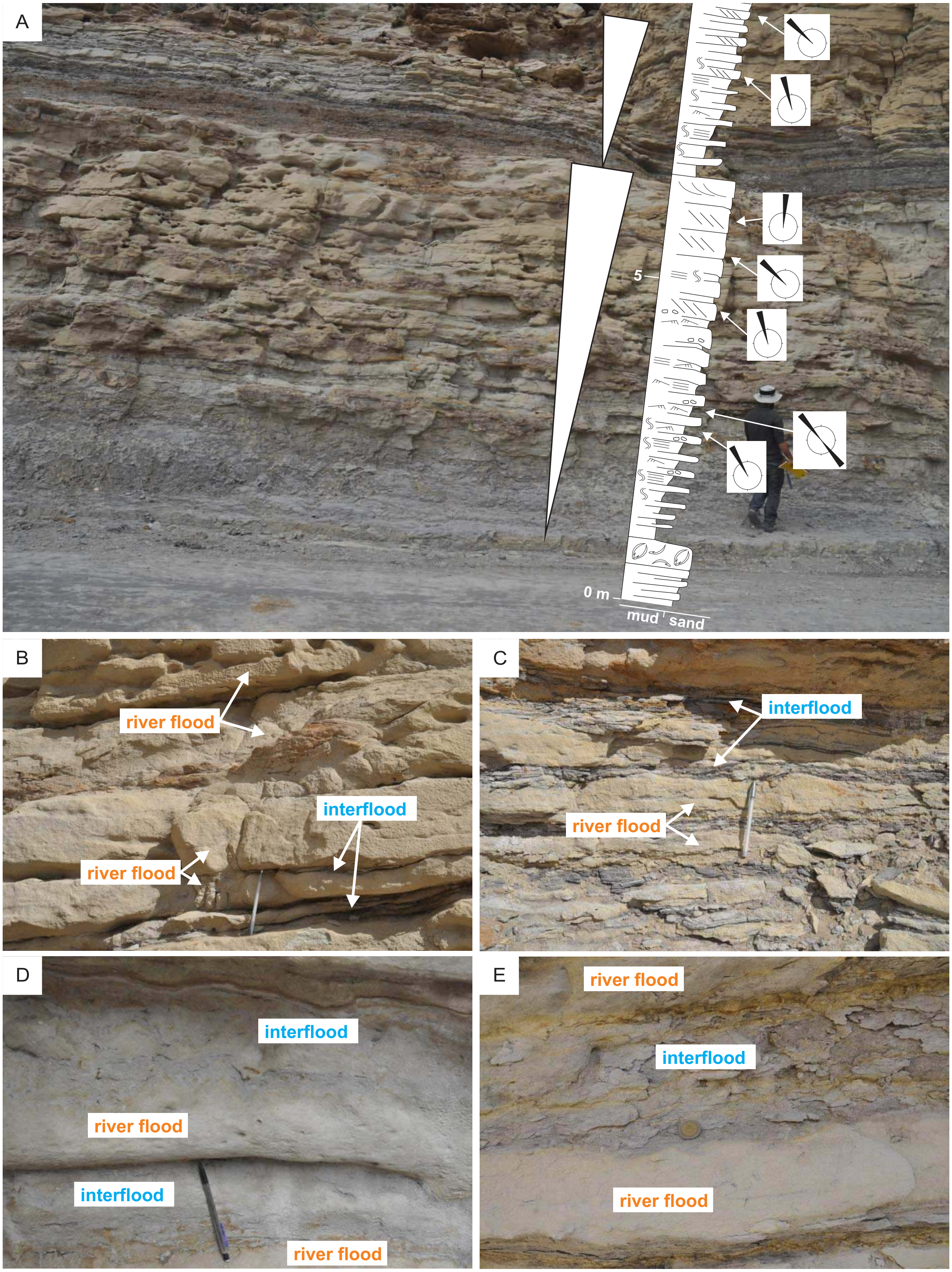

amalgamated river flood beds
well-defined interbedding
less-defined interbedding
no interbedding
A
interflood
river flood
interdistributary-bay deposits
1
0 m
mud
sand
B
river flood
interflood
river flood
C
river flood
interflood
river flood
river flood

Figure 6



A
5
0 m
mud
sand
B
river flood
interflood
river flood
C
interflood
river flood
D
interflood
river flood
interflood
river flood
E
river flood
interflood
river flood

Figure 7

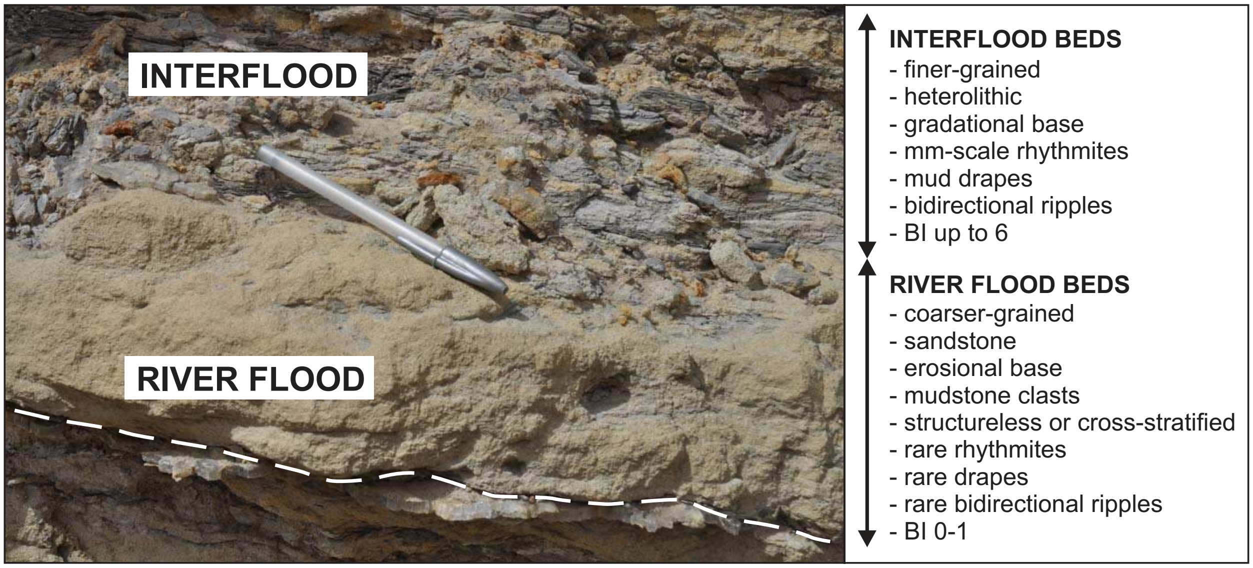

INTERFLOOD
RIVER FLOOD
INTERFLOOD BEDS
- finer-grained
- heterolithic
- gradational base
- mm-scale rhythmites
- mud drapes
- bidirectional ripples
- BI up to 6
RIVER FLOOD BEDS
- coarser-grained
- sandstone
- erosional base
- mudstone clasts
- structureless or cross-stratified
- rare rhythmites
- rare drapes
- rare bidirectional ripples
- BI 0-1

Figure 8

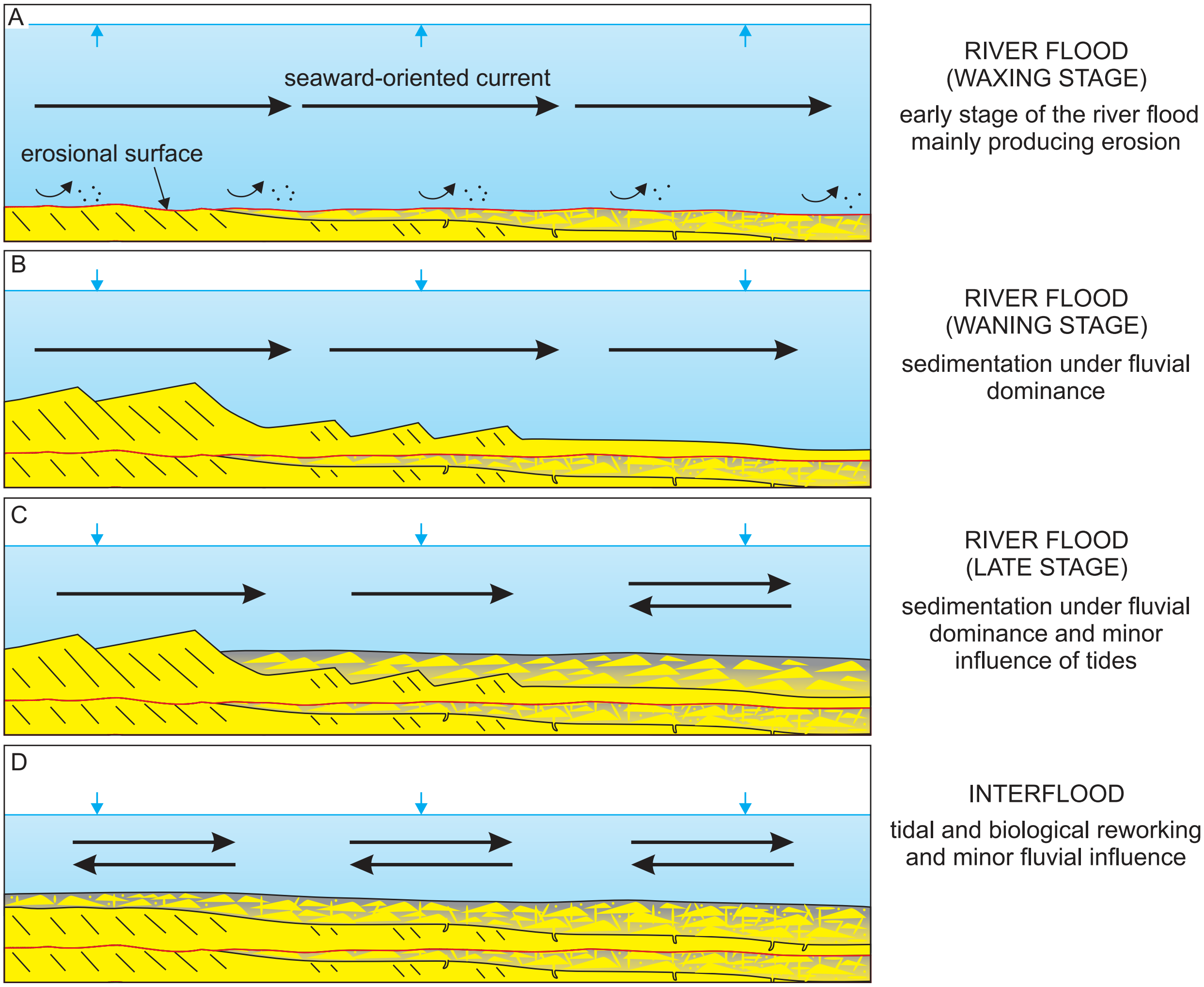

A
seaward-oriented current
erosional surface
RIVER FLOOD
(WAXING STAGE)
early stage of the river flood mainly producing erosion
B
RIVER FLOOD
(WANING STAGE)
sedimentation under fluvial dominance
C
RIVER FLOOD
(LATE STAGE)
sedimentation under fluvial dominance and minor influence of tides
D
INTERFLOOD
tidal and biological reworking and minor fluvial influence

Figure 9

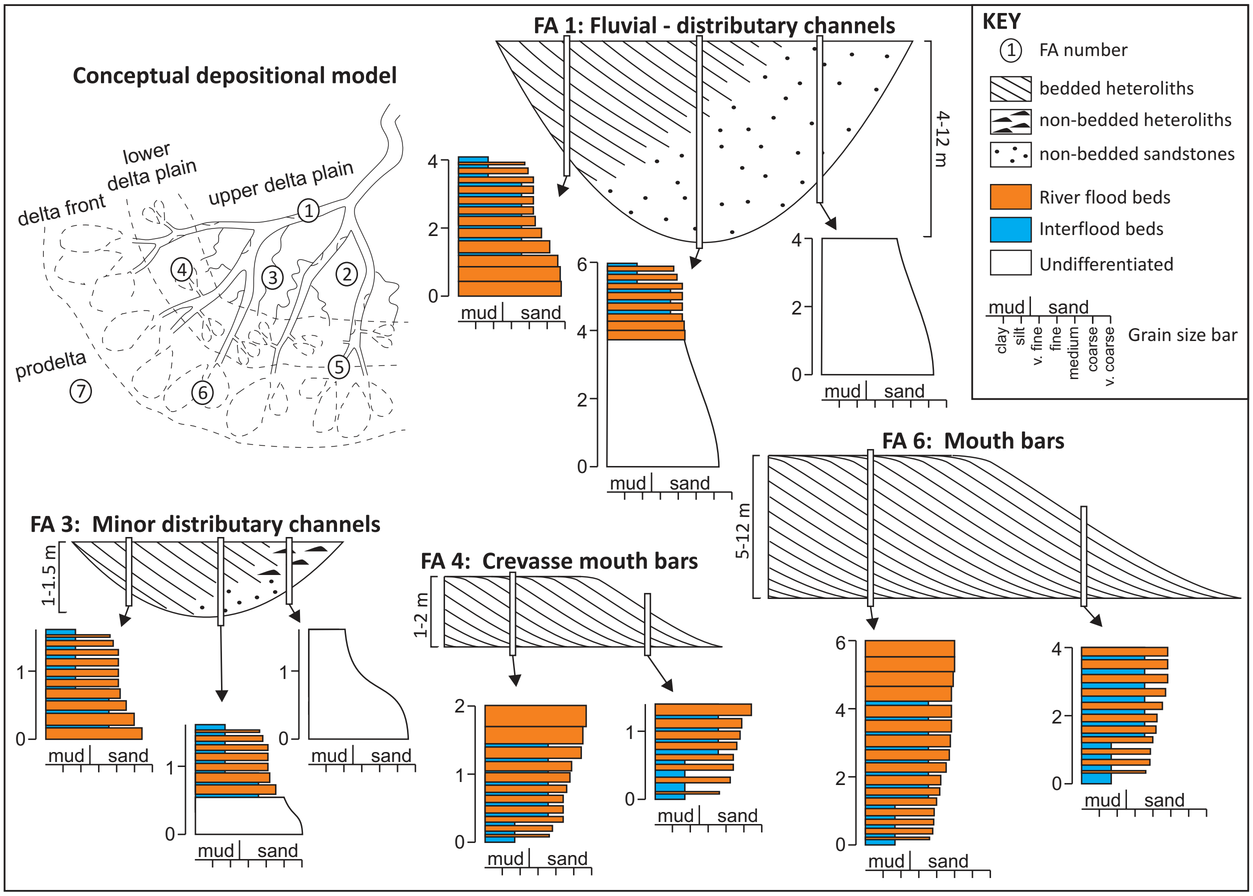

Conceptual depositional model
upper delta plain
lower delta plain
delta front
prodelta
FA 1: Fluvial - distributary channels
4-12 m
KEY
FA number
bedded heteroliths
non-bedded heteroliths
non-bedded sandstones
River flood beds
Interflood beds
Undifferentiated
mud sand
clay silt v. fine fine medium coarse v. coarse
Grain size bar
FA 6: Mouth bars
5-12 m
FA 3: Minor distributary channels
1-1.5 m
FA 4: Crevasse mouth bars
1-2 m
mud sand

Figure 10