RECOGNITION CRITERIA, CHARACTERISTICS AND IMPLICATIONS OF THE FLUVIAL TO MARINE TRANSITION ZONE IN ANCIENT DELTAIC DEPOSITS (LAJAS FORMATION, ARGENTINA)

Running Title: The fluvial to marine transition zone in an ancient delta

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Abstract

The seaward end of modern rivers is characterized by the interactions of marine and fluvial processes, a tract known as the fluvial to marine transition zone (FMTZ), which varies between systems due to the relative strength of these processes. To understand how fluvial and tidal process interactions and the FMTZ are preserved in the rock record, large-scale outcrops of deltaic deposits of the Middle Jurassic Lajas Formation (Neuquén Basin, Argentina) have been investigated. Fluvial-tidal indicators consist of cyclically distributed carbonaceous drapes in unidirectional, seaward-oriented cross-stratifications, which are interpreted as the result of tidal modulation of the fluvial current in the inner part of the FMTZ. Heterolithic deposits with dm-scale interbedding of coarser- and finer-grained facies with mixed fluvial and tidal affinities are interpreted to indicate fluvial discharge fluctuations (seasonality) and subordinate tidal influence. Many other potential tidal indicators are argued to be the result of fluvial-tidal interactions with overall fluvial dominance, or of purely fluvial processes. No purely tidal or tide-dominated facies were recognized in the studied deposits. Moreover, fluvial-tidal features are found mainly in deposits interpreted as interflood (forming during low river stage) in distal (delta front) or off-axis (interdistributary) parts of the system. Along major channel axes, the interpreted FMTZ is mainly represented by the fluvial-dominated section, whereas little or no tide-dominated section is identified. The system is interpreted to have been hyposynchronous with a poorly developed turbidity maximum. These conditions and the architectural elements described, including major and minor distributary channels, terminal distributary channels, mouth bars and crevasse mouth bars, are consistent with an interpretation of a fluvial-dominated, tide-influenced delta system and with an estimated short backwater length and inferred microtidal conditions. The improved identification of process interactions, and their preservation in ancient FMTZs, is fundamental to refining interpretations of ancient deltaic successions.

INTRODUCTION

Deltas and other shallow-marine coastal environments are commonly classified on a ternary diagram that attempts to summarize the interplay between fluvial, tidal and wave processes (Wright and Coleman, 1973; Coleman and Wright, 1975; Galloway, 1975; Boyd et al., 1992; Orton and Reading, 1993; Ainsworth et al., 2008; Ainsworth et al., 2011; Vakarelov and Ainsworth, 2013). Although this concept has been widely used to classify modern-day systems, in the study of ancient deposits there has been a tendency to overestimate one of the processes and force-fit examples into end-members (Bhattacharya, 2010; Vakarelov and Ainsworth, 2013).

Modern rivers can contain, in their coastal section, long tracts known as the fluvial to marine transition zone (FMTZ; Fig. 1), which are characterized by the simultaneous presence of fluvial and marine processes (Dalrymple and Choi, 2007; Dashtgard et al., 2012; La Croix and Dashtgard, 2015). In the study of ancient deposits, the fluvial to marine transition zone or similar terms have been used to describe stratigraphic changes from interpreted marine or tidal to fluvial deposits (Simpson et al., 2002; Makhlouf, 2003; Eriksson et al., 2006; Abouessa et al., 2012). The term has rarely been applied to interpret down dip changes in time-equivalent deposits that formed within a well-defined zone with mixed fluvial and marine energy (van den Berg et al., 2007; Martinius and Gowland, 2011; Martinius and Van den Berg, 2011; Martinius et al., 2015), or to describe the interaction of fluvial and marine processes during deposition (Ghosh et al., 2005; Dalrymple et al., 2015; Gugliotta et al., 2016; Jablonski and Dalrymple, 2016). Therefore, the understanding of interactions between several processes in the fluvial to marine transition zone and how these are preserved into the rock record is still poorly constrained.

The accurate interpretation of the balance between processes in ancient FMTZs will help to distinguish between different types of ancient delta system and to improve prediction of the facies distribution and architecture. Accurate assessment of the degree of tidal influence has fundamental implications for the appraisal of hydrocarbon reservoirs as deltas show significant differences in sand body morphology and depositional architecture (Reynolds, 1999) and facies-scale characteristics (Martinius et al., 2005; Nordahl et al., 2006) depending on the relative strength of different processes. The aim of this contribution is to provide criteria to assess the relative balance between tidal and fluvial processes in ancient systems using reconstructed architecture and facies associated with the fluvial to marine transition zone.

THE FLUVIAL TO MARINE TRANSITION ZONE

The FMTZ is defined as that part of the river which lies between the landward limit of observable effects of marine-induced flow deceleration on fluvial cross-bedding and the most seaward occurrence of a textural or structural fluvial signature (modified from van den Berg et al., 2007). In the FMTZ, deposition is controlled by the interplay of physical (river, tides and waves), chemical (salinity) and biological (bioturbation) processes (Fig. 1; Dalrymple and Choi, 2007).

Evidence from the principal distributary axes of tide-dominated and tide-influenced modern deltas suggests that in a large part of the FMTZ sedimentation can still be controlled by, or strongly influenced by, river currents despite the presence of tidal process. For example, in the 400 km-long FMTZ of the modern Fly River delta (Papua New Guinea), tides are able to reverse the river current only in the last 100 km (Dalrymple et al., 2003). In the modern Fraser River delta (western Canada), at low river stage, tides can influence sedimentation in the FMTZ that extends up the river for 90-100 km from the mouth (Dashtgard et al., 2012).

However, tides can control only a minor part of this zone and the salt wedge intrudes for only 30 km from the mouth, whereas in the inner 60-70 km tidal currents are unable to reverse the river currents (Dashtgard et al., 2012; La Croix and Dashtgard, 2014; La Croix and Dashtgard, 2015). River deltas flowing into microtidal areas, such as the Po (Italy) or the Wax Lake Outlet, Atchafalaya and Mississippi (Louisiana, USA), also show a zone of interaction of fluvial and marine processes that can extend up to tens or hundreds of kilometres up river from the mouth, although here marine processes have a subordinate role compared to fluvial process (Roberts, 1998; Mikhailov and Mikhailova, 2010; Allison et al., 2012; Shaw et al., 2013; Falcieri et al., 2014; Shaw and Mohrig, 2014).

A tripartite division of the FMTZ into subzones is in common use (Dalrymple and Choi, 2007; Martinius and Gowland, 2011; Dashtgard et al., 2012), and is adapted here, from proximal to distal (Fig. 1): (1) fluvially-dominated, tidally-modulated; (2) fluvially-dominated, tidally-influenced; and (3) tidally-dominated, fluvially-influenced subzones. The fluvially-dominated, tidally-modulated subzone is positioned between the landward limit of any tidal effect (landward of which the system is purely fluvial) and the limit of occurrence of flow reversals (Fig. 1). Here, tides are not able to reverse river currents, but they can modulate them (tidal modulation or tidal backwater effect), producing acceleration of the fluvial current during ebb tidal periods (tidal drawdown) and deceleration during flood tidal periods (tidal retardation) (Martinius and Gowland, 2011). Although tidal processes are present, the river plays the major role in deposition; the currents are unidirectional and seaward oriented and water is fresh (Dashtgard et al., 2012). Seaward of the fluvially-dominated, tidally-modulated subzone and through the rest of the FMTZ currents are bidirectional as flow reversals can occur during flood tide periods (Fig. 1). The most inland part of the bidirectional section (fluvially-dominated, tidally-influenced) is still mainly controlled by fluvial processes, but flow reversals can occur and salinity is highly variable

(Dashtgard et al., 2012). The tidally-dominated, fluvially-influenced subzone is characterized by the prevalence of tidal processes with more permanent marine-brackish water conditions. Here, the river has a minor role in supplying sediment (Fig. 1). An additional subzone, present mainly in estuaries and along minor and/or abandoned channels in deltas (e.g. in the modern Mahakam delta, Indonesia), consists of a purely tidal subzone, in which water is fully marine and implies complete absence or negligible river input, bidirectional currents and a landward residual movement of sediment (Dalrymple et al., 1992; Salahuddin and Lambiase, 2013). The distal subzones can also be associated with strong wave processes (Dalrymple et al., 2003; Dalrymple and Choi, 2007).

Important controls on the extent and character of the FMTZ are the coastal-plain gradient, the tidal range at the coast, and the fluvial discharge (Dalrymple et al., 2015). Over short time periods the position and length of the subzones of the FMTZ will change due to fluvial discharge variations (e.g. seasonal discharge; Sisulak and Dashtgard, 2012; Dalrymple et al., 2015; Gugliotta et al., 2016; Jablonski and Dalrymple, 2016) or cyclic fluctuations in tidal current strength (e.g. neap-spring cycles), producing landward and seaward shifts of the subzone along the river profile (Allen et al., 1980; Dalrymple and Choi, 2007; van den Berg et al., 2007; Kravtsova et al., 2009). Over longer periods, the FMTZ may vary due to physiographic changes and/or relative sea-level fluctuations. A decrease or increase in gradient might cause an inversely proportional variation in the distance landward of the coast that tidal action can be expected (Dalrymple et al., 2015). In distributive systems (i.e. deltas), the FMTZ will be different for each active channel depending on its configuration (e.g. longitudinal section, slope gradient) and the relative strength of river and tidal currents.

Deltas and estuaries with strong tides tend to be hypersynchronous along their FMTZ (Salomon and Allen, 1983) implying that tidal range and tidal speed increase landward, towards the "tidal maximum" (Dalrymple and Choi, 2007), before decreasing to zero at the "tidal limit" (Godin, 1999). The presence of strong tidal process has also been associated with high proportions of suspended sediment concentration along a section of the FMTZ known as the turbidity maximum or turbidity maximum zone (TM; Dalrymple and Choi, 2007). The TM is generally located in the inner part of the bidirectional section of the FMTZ, commonly in proximity of the brackish to freshwater limit (Fig. 1; Dalrymple and Choi, 2007; La Croix and Dashtgard, 2014; La Croix and Dashtgard, 2015). As it is part of the FMTZ, the TM is not fixed in space and time, but will be displaced along the system because of fluvial and marine process periodicity (Uncles et al., 2006; La Croix and Dashtgard, 2014). The link between tides and deposition of mud along the TM is due to the presence of brackish water that helps flocculation of clays (La Croix and Dashtgard, 2014). Moreover, this process is helped by tidal currents that can transport the suspended sediment landward whereas bedload material might still have a residual seaward transport (Dalrymple and Choi, 2007).

GEOLOGICAL BACKGROUND

The Neuquén Basin is an important hydrocarbon-producing sedimentary basin (Zambrano and Yrigoyen, 1995) located in central-western Argentina and 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 (Fig. 2A). It is bounded on its north-eastern, eastern and southern margins by wide cratonic areas and by a magmatic arc on the active western margin of the Gondwanan–South American Plate to the west (Fig. 2A; Howell et al., 2005). The cratonic areas located to the south of the basin (the Patagonian Massif) were the main source areas for the basin-fill during the Jurassic (Uliana and Legarreta, 1993).

The basin originated as a volcanic rift in the Triassic and evolved into a post-rift, back-arc basin during the Jurassic (Franzese and Spalletti, 2001; Franzese et al., 2003). The Cuyo

Group (Fig. 3) comprises marine mudstones with intercalations of sandy turbidites (Los Molles Formation; Burgess et al., 2000; Paim et al., 2008), overlain by mainly shallow-marine deposits (Lajas Formation) and coarse-grained fluvial channels and mudstone-rich floodplain deposits (Challacó Formation; Veiga, 1998; Veiga, 2002).

The Lajas Formation was deposited diachronously as a series of N and NW prograding wedges (Zavala and González, 2001; Vicente, 2006) during the Middle Jurassic (Fig. 3) and comprises more than 400 m of sandstone-, heterolithic, and mudstone-dominated deposits that accumulated in a variety of marginal-marine settings (Zavala, 1996a; Zavala, 1996b; McIlroy et al., 2005; Gugliotta et al., 2015; Gugliotta et al., 2016). 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 western margin of Gondwana. The palaeoclimate of the study area has been interpreted by several palynological studies as warm and mainly arid (Quattrocchio et al., 2001; Martinez et al., 2002; Garcia et al., 2006; Iglesias et al., 2011; Stukins et al., 2013), but with variable precipitation through the year (Gugliotta et al., in review) and evidence for wildfires is reported (Marynowski et al., 2011).

The deltaic nature of most of the Lajas Fm. has been recognized in several studies (Spalletti, 1995; Zavala, 1996a; Zavala, 1996b; McIlroy et al., 2005; Kurcinka, 2014; Gugliotta et al., 2015; Gugliotta et al., 2016; Rossi and Steel, 2016), but the dominant process controlling its deposition is still a matter of debate. For the last two decades the Lajas Fm. has been interpreted as a tide-dominated system forming in macrotidal conditions and sharing affinities with the modern Fly River delta (McIlroy et al., 1999; Brandsaeter et al., 2005; McIlroy et al., 2005; Morgans-Bell and McIlroy, 2005; McIlroy, 2007). More recently, several studies carried out in the same area have highlighted the importance, and even dominance, of fluvial processes in large parts of the stratigraphy (Kurcinka, 2014; Dalrymple et al., 2015; Gugliotta et al., 2015; Gugliotta et al., 2016).

METHODS AND DATASET

The Lajas Fm. has been investigated along a 10 km-long major cliff-line exposure in proximity to the village of Los Molles, 40 km south of the town of Zapala (Fig. 2B). The cliff-line is SSW-NNE-oriented and forms an oblique angle with the regional palaeoflow, which is broadly toward the NW (Zavala and González, 2001; McIlroy et al., 2005). Numerous canyon exposures provide three dimensional constraints on the stratigraphic architecture. This study focused on the upper 200 m of the 400-m-thick Lajas Fm. and a minor part of the overlying Challacó Fm. (Fig. 3). The section is oblique to the palaeoflow, but shows a clear dip component with proximal to distal trend from SSW to NNE. The section also shows a subordinate lateral component on the scale of a few kilometres. The stratigraphic interval corresponds to a large part of sequence J5 and the basal part of sequence J6 of Zavala (1996a, 1996b) and the Komplott and Owl sequences of McIlroy et al. (2005).

The methods used included the collection of detailed measured stratigraphic sections, integrated with interpreted photopanels, acquired with a Gigapan camera system, in order to document the stratal architecture, correlate key stratigraphic surfaces and constrain lateral and vertical facies variations. Verification of the majority of photopanel correlations was possible by physical tracing (walking out) of stratal contacts. More than 50 GPS-located sections were logged at 1:50 and 1:25 scale (Fig. 4). 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 fossils and trace fossils.

FACIES ASSOCIATIONS AND LARGE-SCALE ARCHITECTURE

Eleven facies associations (Fig. 5; Table 1; FA 1 to FA 11) have been described, interpreted and ascribed to depositional environments based on facies, process sedimentology and stratigraphic context (Fig. 6). Bioturbation is generally low, but highly variable in intensity, and is considered in terms of bioturbation index (BI) from 0 to 6 (Taylor and Goldring, 1993; MacEachern et al., 2010). Of the eleven facies associations, five consist of channelized deposits (FA 1, FA 2, FA 3, FA 5 and FA 8). The deposits of FA 1 (Fig. 5A) form units up to 12 m thick and show common lateral accretion (up to 80% of the channel body) and are interpreted as more sinuous channels. They are commonly associated with well-drained floodplain deposits (FA 4). The deposits of FA 2 (Fig. 5B) show less common lateral accretion (up to 30% of the channel body) and are interpreted as distributary channels. They are usually associated with subaerial and submarine delta plain deposits (FA4, FA 6 and FA 7). FA 2 is interpreted as the distal expression of FA 1. Minor distributary channel deposits (FA 5; Fig. 5E) are also associated with FA 2, FA 4, FA 6 and FA 7, but are smaller in size compared to FA 2. The deposits of FA 5 do not exceed 1.5 m in thickness and are laterally continuous for a maximum of a few tens of metres. FA 5 is also commonly more heterolithic than FA 1 and FA 2. The deposits of FA 3 (Fig. 5C) are interpreted as abandoned channel deposits and they are filled almost entirely by mudstone. They are interpret as the result of avulsion and meander cut-off processes and are usually found in the same intervals of FA 1 and FA 2. The deposits of FA 8 (Fig. 5G) form units up to 3 m thick and are commonly associated with delta front deposits (FA 9). They are interpreted as the distalmost part of the distributary channel (terminal distributary channels) (Olariu and Bhattacharya, 2006). FA 6 (Fig. 5F) and FA 9 (Fig. 5G) are interpreted as deposits that formed at the mouth of minor and major channels, respectively. FA 4 (Fig. 5D) and FA 7 are mud-prone and were interpreted as the off-axes parts of the subaerial and submarine delta plain. FA 10 is also mud-prone, commonly associated with FA 9 and was interpreted as prodelta deposits. FA 11 groups shell-beds (Fig. 5H) and siliciclastic deposits that were considered as formed during phases of transgression or local abandonment of the delta.

The studied deposits consist of an overall regressive succession showing a shallowing upward trend (Fig. 6 and 7). Prodelta deposits (FA 10) are progressively overlain by delta front deposits (FA 8 and FA 9), lower delta plain deposits (FA 2, FA 5, FA 6 and FA 7) and upper delta plain deposits (FA 2, FA 3, FA 4 and FA 5; Fig. 6 and 7). Laterally, upper delta plain deposits (FA 2, FA 3, FA 4 and FA 5) pass down dip (NW) into lower delta plain deposits (FA 2, FA 5, FA 6 and FA 7) and eventually delta front (FA 8 and FA 9) and prodelta deposits (FA 10). This trend is visible in the correlation panel (Fig. 6) from right to left. Transgressive deposits (FA 11) mark specific intervals and often form boundaries between regressive packages ranging from a few metres to maximum 15 m in thickness (Fig. 6 and 7). Toward the top of the succession, fluvial channel deposits of FA 1, associated with subordinate FA 3, form packages of amalgamated deposits with numerous erosional surfaces (Fig. 7). A regional unconformity, with up to 25m of incision, separates this package from the underlying deposits and is interpreted as a sequence boundary.

According to previous studies, the deposits of the entire Lajas Fm. are divisible into two depositional sequences separated by an unconformity, known as the intra-Bajocian unconformity, and a mudrock section interpreted as marking a major transgressive event (Zavala, 1996a; Zavala, 1996b; Zavala and González, 2001). The major transgressive event has been recognized in this study and the associated mudstone has been used as the basal datum (Fig. 6). The intra-Bajocian unconformity is lower in the stratigraphy. The studied regressive succession consists mainly of highstand system tract deposits of the upper sequence of the Lajas Formation. The overlying package of amalgamated channels is interpreted to represent the lowstand and transgressive system tracts of an overlying sequence and correspond to the basal part of the Challacó Formation.

KEY FEATURES AND INTERPRETATION OF FLUVIAL AND FLUVIAL-TIDAL FACIES

In this section, the main fluvial and fluvial-tidal facies (Fig. 8) recognized within the facies associations of the Lajas Fm. are discussed in terms of the balance between fluvial and tidal processes during deposition. The presence of fluvial and/or tidal processes in some facies could be interpreted with confidence, whereas other facies are ambiguous, meaning that there are no criteria to assess with certainty the dominant process. A traffic light rating system is employed (Fig. 8). A red colour refers to a facies that is interpreted as purely fluvial and green for facies in which the presence of tidal process could be inferred with confidence (i.e. signs of tidal process, but not necessarily implying tidal dominance). Amber code was used for ambiguous facies that could either form through tidal or fluvial processes or that have limited data due to poor and/or limited exposure. The basis for the final interpretation of the sedimentary processes is the facies with green and red colours, where the confidence for the interpretation is higher, and the facies marked with amber will have a minor weighting. The traffic light rating system is used herein to classify fluvial and tidal facies recognized in the Lajas Fm. and it is not comprehensive of all the facies that were described in other studies on the FMTZ or that can be find in this type of systems. Our approach is restricted to the use of sedimentary structures (Fig. 8). The use of biogenic features as tidal and/or salinity indicators will be discussed separately.

Red: purely fluvial features

Re1: unidirectional, seaward-oriented, cross-stratified and cross-laminated sandstones

Fine to very coarse sandstones forming up to 0.4 m thick unidirectional cross-sets of both planar-tabular and trough cross-stratification or cm-scale cross-lamination are commonly found in FA 1, FA 2, FA 5, FA 6, FA 8 and FA 9 (Fig. 8). Palaeocurrents are commonly toward NW to N, but with a relatively high spread from W to NE.

Re1 is interpreted to form as the result of the migration of 2D and 3D subaqueous dunes and ripples that are interpreted as controlled by fluvial currents because of the consistent unidirectionality and orientation toward the N and NW (palaeo-seaward).

Re2: cross-stratified sandstone with apparent bidirectionality

Re2 is similar to Re1, with a similar spatial distribution (FA 1, FA 2, FA 5, FA 6, FA 8 and FA 9); however it differs due to apparent bidirectional orientation of the cross-stratification (Fig. 8). Commonly, the facies consists of concave-up cross-stratification (trough cross-stratification) with cross-sets oriented in one direction at a much lower angle of inclination than in the opposite direction. Alternatively, a bidirectional pattern is preserved as planar-tabular and trough cross-stratification or cross-lamination in stacked different units.

The presence of 3D exposures at small to medium scale allowed identification of the trough axes and to clarify that the bidirectionality can be an apparent 2D feature, particularly when one side has much lower foresets angle than the other (Fig. 9). The palaeocurrent analysis does not support the bidirectional pattern either and would suggest a similar general palaeo-orientation as Re1 (seaward-oriented). The cross-beds with bidirectionality shown in different units did not form simultaneously and it is not a tidal feature. For example, this situation is seen in stacked crevasse-mouth-bar units that represent the progradation of crevasse subdeltas in a range of directions within the interdistributary bay (see Fig. 7 of Gugliotta et al. 2015). Therefore, Re2 is of similar fluvial origin to Re1.

Re3: dm-scale interbedded coarser- and finer-grained deposits

Decimetre-scale interbedding of coarser-grained and finer-grained beds that forms non-cyclic alternations (Fig. 8) are found in FA 1 and FA 2. The coarser-grained beds typically have erosional bases, can contain mudstone clasts and are structureless or show unidirectional, N- to NW- (seaward-) directed, trough and planar-tabular, cross-stratification and current-ripple cross-lamination. Contacts are gradational with the overlying finer-grained sandstones and siltstones. The trace-fossil content is absent or low (BI 0-2), generally consisting of Planolites and concentrated in the finer grained beds. Alternatively, the finer-grained intervening beds may show high concentrations of carbonaceous matter.

Re3 is interpreted to be the result of seasonal fluctuation in river discharge and is considered as evidence of fluvial processes. The sandstone beds with erosional bases and unidirectional, seaward-directed palaeocurrents are interpreted as the deposits of river floods, with deposition during high river stage. The intervening, finer-grained beds with bioturbation or plant matter are interpreted as interflood deposits formed during low river stage.

Amber: ambiguous fluvial or tidal features

Am1: non-cyclically distributed carbonaceous drapes

Drapes made of carbonaceous debris, with subordinate non-carbonaceous plant matter and mica crystals (Fig. 8), are common in the Lajas Fm. and are observed in FA 1, FA 2, FA 5, FA 6, FA 8 and FA 9. Organic and mica particles are a few millimetres up to 1 cm in diameter. These drapes are found as single or multiple drapes on the lower part of foresets and bottomsets of cross-stratification or at cross-sets boundaries or dispersed in structureless sandstones. No cyclical patterns or any degree of organization in the distribution of these drapes is observed.

Because of the hydraulic behaviour of both the fine-grained “tea leaves” that comprise the organic detritus and mica grains, these may be deposited from relatively low energy fluvial currents, but do not require slack water conditions (Martinius and Gowland, 2011). These types of drapes are commonly reported from purely fluvial settings (Reesink and Bridge, 2011; Reesink et al., 2015). Their presence, without evidence of cyclical patterns, cannot be ascribed with confidence to a tidal origin.

Am2: non-cyclically distributed reactivation surfaces in cross-stratification

Reactivation surfaces are rarely found in unidirectional cross-stratification similar to Re1 (Fig. 8) in FA 1, FA 2, FA 5, FA 6, FA 8 and FA 9. The reactivation surfaces mark abrupt changes in foresets angles and are randomly distributed rather than having a cyclical and predictable pattern. A similar feature could form because of tidal reversals, but also because of superposition of dunes migrating at different rates or changes in the river discharge in purely fluvial conditions. Reactivation surfaces are common in modern and ancient purely fluvial systems (Rubin and Hunter, 1982; Reesink and Bridge, 2011; Reesink et al., 2015). Pontén and Plink-Björklund (2007) suggested that the sporadic reactivation surfaces recognized in the Devonian fluvial-tidal deposits of the Baltic Basin were fluvial in origin. Because of the lack of a cyclical and predictable pattern, and because they are rare, the reactivation surfaces herein cannot be interpreted with confidence as tidal in origin, although this cannot be excluded either.

Am3: ambiguous bidirectionality in cross-lamination and cross-stratification

Am3 consists of a similar facies of Re1 and Re2, has a similar spatial distribution (FA 1, FA 2, FA 5, FA 6, FA 8 and FA 9) and shows ambiguous bidirectionality in cross-stratification and cross-lamination (Fig. 8). Evidence of cyclical patterns is missing and palaeocurrents were difficult to collect due to limited 2D exposures.

In this case, the absence of 3D exposures at small- to medium-scale does not allow clarification of whether the bidirectionality is an apparent feature or due to tidal processes. Bidirectionality at ripple scale could be due to tides or could also form for other reasons, such as counter vortices below flow separation points at the base of the subaqueous dune (Collinson et al., 2006; Nichols, 2009), or at the margin of the channel (La Croix and Dashtgard, 2014). The fluvial or tidal origin of Am3 is not always distinguishable particularly if the ripple crests are not exposed and if the bidirectionality is restricted to the bottomsets of larger dunes or bars. At dune-scale, the bidirectionality could be tidal or an apparent feature due to 2D exposure of trough cross-bedding or of the fluvial bar. For example, detailed work from the Ferron Sandstone in Utah, USA (Wu et al., 2015) indicated a high spread of palaeocurrents that was explained by the stacking pattern of point-bar deposits, and probably purely fluvial conditions.

Am4: heterolithic deposits

Heterolithic deposits (Fig. 8) composed of up to coarse-grained sandstones and mudstones, including flaser, wavy and lenticular bedding, are relatively common in the Lajas Fm. and are present in all FAs with the exception of FA 11. They may show ripples and ripple cross-lamination in which bidirectional patterns or tidal rhythmites are not recognized.

Heterolithic deposits indicate intermittent currents which are common in a tidal setting; however variations in fluvial discharge or overbanking in purely fluvial settings can produce similar deposits. The deposits discussed herein show that rivers had discharge variations (Re3, Gr3; see Gugliotta et al., 2016); therefore in the absence of clear tidal rhythmites or bidirectionality, a tidal origin for these heterolithic deposits cannot be concluded.

Green: fluvial-tidal features

Gr1: cyclical carbonaceous drapes in unidirectional cross-stratification

Cross–stratification similar to Re1 can show a distribution of drapes composed of carbonaceous debris, often associated with plant debris and mica grains (Figs. 8 and 10). The organic and mica particles are from a few millimetres up to 1 centimetre in diameter. This facies is found in FA 2, FA 5, FA 7, FA 8 and FA 9. Commonly, the drapes are found in groups of up to ten drapes that are separated by a few millimetres to centimetres. The groups of drapes show spacing in the cross-sets of several decimetres between each group (Fig. 10). Cyclical patterns are recognized in the distribution of drapes and groups of drapes. This facies can also show cyclical patterns in the height reached by the drapes on the foresets (Fig. 10).

Gr1 is the most common fluvial-tidal facies in the studied deposits. Gr1 is interpreted as the result of tidal modulation of fluvial currents in the fluvially-dominated, tidally-modulated subzone of the FMTZ, similarly to Martinius and Gowland (2011). The presence of tidal process is inferred with certainty, but the fluvial process is predominant and currents unidirectional. Tidal currents are not able to produce flow reversals, but only to accelerate and decelerate the river current (tidal modulation or tidal backwater effect), through the tidal cycle.

Gr2: cross-stratified sandstone with cyclical carbonaceous drapes and non-cyclic reactivation surfaces

Gr2 consists of cross–stratified sandstone with cyclically distributed carbonaceous drapes, similarly to Gr1, but with reactivation surfaces (Fig. 8). The reactivation surfaces do not show any cyclical pattern, but are randomly distributed. Gr2 is rarer than Gr1 and is found in FA 5, FA 7, FA 8 and FA 9.

The cyclical pattern in distribution of carbonaceous drapes can be ascribed to tidal modulation of river currents, similarly to Gr1. Reactivation surfaces can either be the result of superposition of fluvial dunes or due to flow reversals by tides. In the case that cyclical carbonaceous drapes is the only confident indication of tidal processes the deposit might have formed in the fluvially-dominated, tidally-modulated (unidirectional currents) subzone of the FMTZ, as Gr1. However, if the reactivation surfaces are confidently considered as tidal, the deposit might have formed in the fluvially-dominated, tidally-influenced (bidirectional currents) subzone of the FMTZ, where tidal flow reversals are possible, but fluvial processes are still dominant.

Gr3: cross-stratified sandstone with cyclical carbonaceous drapes and ambiguous bidirectionality

Gr3 consists of cross–stratified sandstone with cyclically distributed carbonaceous drapes, similarly to Gr1, but with opposite directed cross-stratification or cross-lamination (Fig. 8). Cross-lamination is commonly restricted to the bottomsets and does not show clear set climbers on the foresets. Cross-stratification is commonly recognized in limited 2D exposures. Gr3 is rarer than Gr1 and is found in FA 5, FA 7, FA 8 and FA 9.

The cyclical pattern in distribution of carbonaceous drapes can be ascribed to tidal modulation of river currents, similarly to Gr1. Bidirectionality is never interpreted with confidence as tidal but resembles the examples described in Am3. In the case that cyclical carbonaceous drapes is the only confident indication of tidal processes the deposit might have formed in the fluvially-dominated, tidally-modulated (unidirectional currents) subzone of the FMTZ, as Gr1. However, if the opposite directed structures are confidently considered as tidal, the deposit might have formed in the fluvially-dominated, tidally-influenced (bidirectional currents) subzone of the FMTZ, where tidal flow reversals are possible, but fluvial processes are still dominant.

Gr4: dm-scale interbedded coarser- (unidirectional) and finer- (bidirectional) grained heterolithic deposits

Decimetre-scale interbedding of coarser-grained and finer-grained beds form non-cyclic alternations is identified in FA 5, FA 6 and FA 9 (Fig. 8). Typically, the coarser-grained beds have erosional bases, can contain mudstone clasts and are structureless or show N- to NW- (seaward-) directed, unidirectional trough or planar-tabular cross-stratification and current-ripple cross-lamination. Contacts are gradational with the overlying finer-grained sandstones and siltstones that may contain mudstone or carbonaceous and micaceous drapes, forming mm-scale couplets associated with bidirectional ripples and a more abundant and diverse suite of trace fossils (e.g. Palaeophycus, Ophiomorpha, Dactyloidites, Thalassinoides, Planolites). The trace-fossil content is absent or extremely low (BI 0-1) and generally of low diversity in the coarser-grained beds whereas the intensity of bioturbation can be either low (BI 2-3), or can obliterate all sedimentary structures (BI 5-6) in the finer-grained beds.

Gr4 is interpreted as the result of seasonal fluctuations in the fluvial discharge plus subordinate tidal currents. The sandstone beds with erosional bases and unidirectional, seaward-directed palaeocurrents are interpreted as the deposits of river floods, which formed under strongly or entirely fluvial conditions. The intervening, finer-grained beds with bidirectional ripples, mm-scale cyclical rhythmites, and increased bioturbation levels are interpreted as interflood deposits formed during low river stage and under temporal dominance of tidal processes and brackish to marine conditions. Because river flood beds indicate deposition with little to no tidal action, whereas tidal indicators are primarily restricted to the interflood beds, tidal action in this facies is considered as a subordinate process.

Gr5: bidirectional heterolithic deposits

Gr5 consists of heterolithic deposits composed of sandstones and mudstone, including flaser, wavy and lenticular bedding that may show ripples and ripple cross-lamination with bidirectional patterns and/or tidal rhythmites (Fig. 8). Gr5 is rare in the studied deposits and is found in FA 5 or very rarely as a distal expression of Gr4 in FA 6 and FA 9.

The presence of cyclical rhythmites and bidirectionality could be used to infer a tidal origin; however Gr5 might form still because of a combination of fluvial and tidal currents. In the distal parts of FA 6 and FA 9, this facies forms as a result of local reworking of Gr4.

Trace and body fossils

Sandstone, heterolithic or mudstone deposits with trace fossils are present in FA 1, FA 2, FA 5, FA 6, FA 7, FA 8, FA 9 and FA 10, but a high level of BI is present only in FA 7, FA 10 and at the bottom of FA 6 and FA 9 units. Traces consist of Palaeophycus, Ophiomorpha, Dactyloidites, Thalassinoides, Planolites, Teichichnus, Rosselia and Skolithos, but in the majority of the cases the assemblages consist of only one or a few types of traces. Body fossils are found in shell beds of FA 11, and consist of oysters, Trigonia, corals and echinoderms. Shells can show borings of Gastrochaenolites.

In general, the low intensity and diversity of infaunal populations suggest a stressed environment (MacEachern et al., 2010) that is interpreted to reflect low and variable salinity due to changes in fluvial discharge and subordinate tidal processes. The majority of the trace and body fossils described herein suggest brackish to marine-water conditions that may be related to the tidal processes. However, the assemblage of trace and body fossils observed do not directly indicate the occurrence of tidal processes during deposition. Trace fossils that contain indicators of tidal processes, such as tidal rhythmites in the passive filling of open burrows have been described from other formations (tubular tidalites; Wetzel et al., 2014; Gingras and Zonneveld, 2015), but these were not recognized in this study. Some other traces (e.g. Planolites) are characteristic of a wide range of environments and salinity conditions and can form also in freshwater conditions (Gérard and Bromley, 2008).

SPATIAL AND TEMPORAL DISTRIBUTION OF THE FMTZ IN THE LAJAS FORMATION

Differentiating fluvial, tidal and fluvial-tidal facies and their spatial (i.e. proximal or distal, along major or minor axis or off-axis) and temporal context (i.e. high or low river stage) is crucial in order to understand the process regime and evolution of deltaic depositional systems. In this section, we describe the spatial and temporal distribution of fluvial and fluvial-tidal features in the studied deposits and their association with particular facies associations and to the FMTZ. The description of stratigraphic relationships is based on well constrained facies distributions from the extensive outcrops. The relationships and distributions described and the associated illustrations (Figs. 11, 12 and 13) are based on continuously exposed outcrops of the studied deposits, which are representative of the stratigraphic succession. Each figure presented in this section comprises a part with the presentation of data and observations (part A of each figure) and part with interpretation (part B of each figure). The depositional patterns and relationships will be described as follows: 1) from proximal to distal along major distributary axes in coeval intervals; 2) in their relationships between major and minor axis and off-axis in coeval intervals; 3) in short term (annual) variations recorded at the facies scale; 4) salinity indicators across the system and; 5) turbidity maximum distribution.

Proximal to distal distribution along major axes

In this section, only the facies found in deposits that form along major axes are described, such as fluvial channel (FA 1), distributary channel (FA 2), terminal distributary channel (FA 8) and mouth bar (FA 9) deposits. This is because along these axes both fluvial and tidal processes are mainly active and the FMTZ is most clearly expressed. Constraining the position along an axis where fluvial-tidal features are recognized is critical to understanding the depositional system because the same fluvial-tidal indicator has different implications if found in facies forming in the distal part or in the proximal part of the system.

In the Lajas Formation, the presence of facies with unidirectional seaward palaeocurrents in mouth-bar deposits (FA 9) are interpreted as purely fluvial (Re1), which indicates that under certain conditions (i.e. high river stage) the system was probably strongly fluvial-dominated along active major axes and the FMTZ was compressed and almost absent.

The majority of fluvial and distributary channel deposits contain facies that are interpreted as purely fluvial (Re1, Re2, Re3), which implies that along major axes, tidal energy might have dissipated in more distal settings. Facies that indicate tidal modulation of fluvial bedforms (Gr1) were identified in deposits of FA 2. These FA 2 deposits show limited lateral migration and are laterally associated with marine interdistributary deposits (FA 6 and FA 7) that have been interpreted as lower delta plain deposits. The presence of Gr1 suggests conditions typical of the fluvially-dominated, tidally-modulated subzone of the FMTZ (Fig. 1). The bidirectional subzones, if present, must have been in more distal settings (i.e. delta front) suggesting a relatively short length of the bidirectional section of the FMTZ. This suggests that tides were able to reverse the fluvial currents only in the distal part of the system, but were modulating the fluvial currents in the lower reaches of distributary channels. Fluvial-tidal facies of type Gr1, Gr2 and Gr3 are also commonly found in terminal distributary channel (FA 8) and mouth-bar (FA 9) deposits (an example of this is shown in Fig. 11A). This implies that at times the fluvially-dominated, tidally-modulated and the fluvially-dominated, tidally-influenced subzones of the FMTZ were located at the delta front (Fig. 1, 11B). The tidally modulated fluvial facies (Gr1), found in delta front to lower delta plain deposits, suggests that under certain conditions tides were not able to reverse fluvial currents even in the distal part of the system. Heterolithic bidirectional facies, recognized in interflood beds of Gr4 and rarely in Gr5, are commonly found only in distal mouth-bar deposits (FA 9; Fig. 12A) suggesting that the bidirectional subzones of the FMTZ were present only at the delta front. In Fig. 12A, a transect through delta front to delta plain stratigraphy illustrates tidally influenced (Gr4) mouth bar deposits (FA 9) that pass into channel deposits (FA 2) in a proximal direction, where there are only fluvial facies (Re1 and Re3). This show how tidal energy was dissipated in a relatively short distance.

Because fluvial-tidal facies dominated by fluvial processes (Gr1, Gr2, Gr3 and Gr4) are common in the distal part of the system, it is arguable that the FMTZ interpreted from the Lajas Fm. has little or no tide-dominated section along major distributary axes (Fig. 11B, 12B). Moreover, the fluvial facies in relatively distal channels in the delta plain suggest that the FMTZ was relatively narrow and that tidal energy was dissipated over relatively short distances.

Major, minor axis and off-axis relationships

Commonly in deposits interpreted as representing a lower delta plain setting, there is evidence of bidirectional tidal processes in the interflood beds of Gr4 in crevasse mouth bar deposits (FA 6) that formed in interdistributary bays. However, in coeval distributary channel deposits (FA 2), which are laterally associated with interdistributary bay deposits, there is either evidence of tidal modulation of fluvial bedforms (Gr1) or fluvial-only facies (an example of this facies relationship is shown in Fig. 13A). Therefore, along major distributary channels there are facies typical of the purely fluvial part of the system, or of the fluvially-dominated, tidally-modulated subzone of the FMTZ (Fig. 13B). However, interdistributary bay deposits of the same age accumulated in the fluvially-influenced, tidally-dominated, or the tidally-dominated, fluvially-influenced subzones (Fig. 1, 13B).

Commonly, more proximal distributary channel deposits of FA 2 show seaward-oriented, unidirectional palaeocurrents and lack indicators of tidal process, even in low river stage interflood facies of Re3. Overbank deposits (FA 4) show subaerial features (e.g. root traces, palaeosols) suggesting deposition in the upper delta plain or at the transition between upper and lower delta plain. However, coeval minor distributary channels of FA 5 show a subordinate tidal influence, as recorded by fluvial-tidal unidirectional or bidirectional (Gr1, Gr2, Gr3, Gr4 and Gr5) facies. These observations suggest purely fluvial conditions in major distributary channel deposits of the upper delta plain with tidal energy dissipated before this point. Along minor distributary channel deposits (FA 5), a range of fluvial-tidal facies are present, although these commonly show fluvial dominance.

The facies relationships described here indicate that tidal processes were relatively stronger along minor axes and weaker or absent along major fluvial axes. This situation is typical of a system in which tides are stronger in the distal part and are dissipated more quickly along major axes where they are overwhelmed by strong fluvial currents, compared to areas where the fluvial current is weaker such as interdistributary areas and minor channels.

Short-term temporal variations (annual)

The dm-scale alternations of finer- and coarser-grained beds (Re3 and Gr4; Fig.8, 14A) are interpreted to have formed due to seasonal fluctuations in river discharge and to reflect periods of high and low river stages (Sisulak and Dashtgard, 2012; Dalrymple et al., 2015;

Gugliotta et al., 2016; Jablonski and Dalrymple, 2016). River flood beds are usually composed of coarser-grained, erosionally-based, structureless and seaward-oriented cross-stratified sandstones, which are interpreted to have formed during strongly fluvial conditions. This inference is supported by seaward-oriented, unidirectional cross-bedding in delta front deposits in the distal part of the system. Indicators of tidal processes (mud drapes, tidal rhythmites, bidirectional ripples) and of brackish to marine conditions (trace fossils) are concentrated in interflood beds. Mixed fluvial-tidal conditions were present mainly during low river stage, because the lower strength of the river currents allowed a greater intrusion of tidal processes. This suggests that the FMTZ was better developed at low river stage, whereas during high river stage the system was more strongly fluvial with a poorly developed FMTZ (Fig. 14B, C). This dynamic FMTZ is interpreted to be the result of the seasonal fluctuations of the fluvial discharge discussed above. Longer duration tidal cycles, such as spring-neap cycles, are not recognized, probably because they were subordinate to the seasonal fluvial discharge pattern, and had a minor influence on the temporal variability of the FMTZ.

Salinity in the system

Trace and body fossils suggest the presence of brackish to marine water conditions in part of the system and at specific times. The presence of trace and body fossils in the interdistributary areas of the lower delta plain (FA 6 and FA 7), in the delta front (FA 8 and FA 9) and in the prodelta (FA 10) deposits suggest that these areas experienced brackish to marine conditions. This is consistent with these sub-environments being at the interface between the fluvio-deltaic and the marine environments. In this part of the system, the salinity levels can increase during low river stage, because of the lower relative strength of the fluvial process. As described above, tidal structures (e.g. rhythmites, bidirectional ripples) can be associated with these interflood intervals, suggesting some degree of tidal influence.

The presence of trace fossils in major and minor distributary channel deposits (FA 2 and FA 5) suggests that the river axes also experienced some brackish water conditions. However, in these deposits the trace fossil assemblage is less well developed and the intensity is low (Table 1). This suggests that the brackish water conditions were present for less time and with lower salinity levels compared to the more distal and off-axis sub-environments. Moreover, the trace fossils are commonly restricted to the interflood beds, especially in the major channel deposits (FA 2). The presence of these trace fossils can be explained by incursions of the saline water wedge at low river stages. This process occurs in the majority of modern delta systems, including in rivers that discharge into settings with a few tens of centimetres of tidal range, such as the Po River in the Adriatic Sea (Nelson, 1970) and the Mississippi River in the Gulf of Mexico (Mikhailov and Mikhailova, 2010).

Transgressive deposits (FA 11) show diverse types of body fossils that suggest brackish- to marine-water conditions, but these probably formed in periods when the system shifted landward or laterally, and generally comprise deposits not directly related to the delta system.

Distribution of the turbidity maximum in the system

Mudstone drapes are recognized in the interflood beds of minor distributary channel (FA 5), crevasse mouth bar (FA 6) and mouth bar (FA 9) deposits. Fluid muds (i.e. mudstone drapes thicker than 0.5-1 cm; Dalrymple et al., 2003; Ichaso and Dalrymple, 2009) are commonly absent. The delta front (FA 8 and 9) and distributary channel (FA 2) deposits are sand-rich, although abandoned channel deposits (FA 3), minor axis deposits (FA 5 and FA 6), off-axis deposits (FA 4 and FA 7) and distal deposits (FA 10) are muddier. The presence of mudstone drapes in the delta front and interdistributary deposits suggest that the TM, when present, was mainly located in the distal part of the system or off-major-axes, rather than along distributary channels, which are instead extremely sand-rich. The TM is interpreted to have reached the delta front area at low river stage, but without entering the major channels for significant distances. At high river stage the TM was probably pushed toward more distal positions and restricted to off-axis interdistributary and prodelta areas with prevalence of mud deposition. Due to the absence of fluid muds and the general paucity of mudstone drapes, the turbidity maximum is also believed to have been poorly developed.

DISCUSSION

The fluvial to marine transition zone in the rock record and its implications

The geographical extent and process regime of the FMTZ in modern systems is well constrained by observational data. However, how this tract is represented into the stratigraphic record is hard to constrain due to temporal and spatial variations in process interactions and physiography. The approach advocated here is that once fluvial-tidal facies (Figs. 8, 9 and 10) are interpreted within their stratigraphic and palaeogeographic context (Figs. 6 and 7) and in terms of subzones of the FMTZ (Fig. 1), they can be used to estimate the characteristics and distribution of the FMTZ in the rock record (Figs. 11, 12, 13 and 14). The interpreted FMTZ of the Lajas Fm., at low river stage, comprises a relatively narrow FMTZ, mainly consisting of the fluvial-dominated section, whereas little or no tide-dominated section (Figs. 11 and 12), which differs from FMTZs observed from modern tide-dominated deltas (Dalrymple et al., 2003; Dalrymple and Choi, 2007). The fluvial-dominated section of the Lajas FMTZ seems shifted seaward compared to the same section in FMTZs of modern strongly tidal systems (Figs. 11 and 12). The stronger evidence for tidal processes away from major axes suggests hyposynchronous conditions (Fig. 13), and together with the poorly developed TM, contrasts with observations in tide-dominated. Commonly, tide-dominated deltas are hypersynchronous and have a well-developed TM along major distributary channels (Dalrymple et al., 2003; Ichaso and Dalrymple, 2009). The resulting deposits of tide-dominated deltas might be expected to be strongly tidal within the major distributary channels, and associated with high amount of mud drapes and fluid mud deposits (Ichaso and Dalrymple, 2009; MacKay and Dalrymple, 2011). Commonly, in the deposits of the Lajas Fm., tidal influence is restricted to the interflood beds suggesting that tidal processes were mainly recorded during periods of low river stage (Fig. 14) and linked to the seasonality of the rivers (Gugliotta et al., 2016). Tidal processes were only able to partially rework bars accreted during periods of high river stage (Fig. 14). In tide-dominated or strongly tide-influenced deltas, the seasonal signature of the river, at least in the distal part of the system, may be overprinted by tidal processes and/or that some effects of tidal processes will be recorded in deposits of high river stage (Dalrymple et al., 2015).

In agreement with previous interpretations of the Lajas Fm. (e.g. McIlroy et al., 2005), tidal processes are considered to have been present during large periods during the accumulation of the succession. However, we interpret a mixed processes system in which the dominant energy source was fluvial, leading to a relatively narrow and overall fluvially-dominated FMTZ. The majority of the studied deposits could therefore have formed in a fluvial-dominated, tide-influenced system, although some intervals of the Lajas Fm., in the unstudied part of the stratigraphy and/or other areas may be tide-dominated (see Zavala, 1996a; Zavala, 1996b).

Weak tidal process or low preservation of tidal sedimentary structures?

The paucity of tide-dominated indicators in the studied portion of the Lajas Fm. could be due to a preservation issue, such that tidal processes may have had more temporal influence, but the record was suppressed or destroyed by shorter periods of stronger fluvial activity. Similarly, the interpreted hyposynchronous conditions and the absence of a well-developed turbidity maximum zone could be argued to be the result of low preservation potential in channelized areas. Further complications can be due to the temporal variations of the FMTZ. Fluvial-tidal indicators might have developed mainly in conditions favourable to fluvial process dominance, such as neap tide and/or high river stage, whereas periods of tidal dominance or stronger tidal influence are not represented in the deposits. However, the described architectural elements, such as major and minor distributary channels, terminal distributary channels, mouth bars and the presence of interdistributary areas (Figs. 5, 6 and 7), all characterize fluvial-dominated deltas (Bhattacharya, 2006; Olariu and Bhattacharya, 2006). Tidal flats, tidal channels, tidal bars and tidal dunes, which are typical of tide-dominated or more strongly tide-influenced deltas (Dalrymple et al., 2003; Willis, 2005; Dalrymple and Choi, 2007; Tänavsuu-Milkeviciene and Plink-Björklund, 2009; Dashtgard et al., 2012; Goodbred and Saito, 2012) are missing in the studied deposits. In particular, the presence of crevasse subdeltas (Figs. 5, 6 and 7), which are typical of deltas forming in lakes or in semi-enclosed and enclosed seas with little or no tidal process, suggests strong fluvial dominance with possible microtidal conditions (Gugliotta et al., 2015). These architectural elements would be difficult to explain in a system with a stronger tidal influence that was not preserved. Moreover, the channel deposit thicknesses suggest that the larger river channels in the Lajas system were commonly about 5 m deep in the delta plain (Fig. 6). The predominance of medium to coarse sand in dune-scale cross beds suggest a relatively steep gradient fluvial system (Holbrook and Wanas, 2014; Bhattacharya et al., 2016). This would in turn indicate a relatively short backwater length, on the order of a few kilometres to a few tens of kilometres. This fits with the observed landward limit of brackish water facies and inferred microtidal setting. Therefore, our interpretation based on the facies calibrated with the traffic light approach (Fig. 8), and the FMTZ concepts (Fig. 1), are in agreement with the interpretation made on the basis of the type of architectural elements and the estimation of the backwater zone.

Tide-dominated deltas in the rock record: have they been described yet?

This study aligns with a recent trend of reducing emphasis on the importance of tidal process in ancient deltaic successions. Following an increase in understanding of facies along the FMTZ (Dalrymple and Choi, 2007; van den Berg et al., 2007; Martinius and Gowland, 2011), the establishment of detailed recognition criteria (Pontén and Plink-Björklund, 2007; Tänavsuu-Milkeviciene and Plink-Björklund, 2009) and refined classification schemes for deltas and other coastal systems (Ainsworth et al., 2011; Vakarelov and Ainsworth, 2013), several other regressive successions with evidence of tidal process have been interpreted in large part as fluvial-dominated, tide-influenced rather than tide-dominated. These include the Middle Devonian Gauja Fm., in the Baltic Basin (Pontén and Plink-Björklund, 2007), the Jurassic Tilje Fm. of the Norwegian shelf (Ichaso and Dalrymple, 2009; Ichaso and Dalrymple, 2014), the Upper Cretaceous Dorotea Fm., Magallanes-Austral Basin, Patagonia (Schwartz and Graham, 2015), the Neslen Fm. of Utah (Shiers et al., 2014), the Schrader Bluff–Prince Creek Fms., Alaska, USA (Van Der Kolk et al., 2015) and the Campanian Horseshoe Canyon Fm., Alberta, Canada (Ainsworth et al., 2015) .

The majority of interpreted ancient “tide-dominated” deltaic successions are sand-rich whereas modern tide-dominated deltas are typically mud-rich. It is therefore possible that ancient tide-dominated delta successions are mainly represented by fine-grained, and probably poorly exposed, deposits (see also discussion in Goodbred and Saito, 2012). Following the discussion above, we argue that sand-rich successions similar to the Lajas Fm. and the other examples mentioned above, are likely to be fluvial-dominated, tide-influenced (although they can still have tide-dominated intervals and some successions might be overall more strongly tide-influenced than others). Tide-dominated deltas might not have been described adequately yet from the rock record.

CONCLUSIONS

Application of the fluvial to marine transition zone concept from modern deltas to the Jurassic highstand systems tract deposits of the upper sequence of the Lajas Formation suggests that the stratigraphic expression of the Lajas FMTZ comprises a seaward-shift of the fluvial-dominated subzone with little or no tide-dominated section preserved. The deposits show more tidal influence and higher amounts of mud away from the distributary axes, which suggests a hyposynchronous system, and a poor developed turbidity maximum. Tide-influenced deposits are mainly restricted to the interflood beds, suggesting that tidal processes were recorded only during times of low river stage. The alternative argument that evidence for greater tidal influence is not preserved is considered unlikely due to the architectural elements being largely fluvial in character and an estimated relatively short backwater length based on channel depth and grainsize.

In agreement with previous interpretations, the tidal process regime is considered to have been present during the accumulation of the entire succession, although in most of the deposits this was subordinate to the fluvial process. The studied deposits of the Lajas Fm. are considered as fluvial-dominated, tide-influenced, rather than tide-dominated. Furthermore, because of the type and distribution of fluvial-tidal indicators, at least part of these deposits accumulated in a system with only weak tidal influence and possible microtidal conditions.

The identification and correct characterization of the range of fluvial, fluvial-tidal and tidal deltaic deposits in the rock record is possible through a careful identification of process interactions and interpretation of the characteristics and distribution of the FMTZ. This approach would in turn improve depositional and reservoir models.

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REFERENCES

Abouessa, A., Pelletier, J., Duringer, P., Schuster, M., Schaeffer, P., Métais, E., Benammi, M., Salem, M., Hlal, O., Brunet, M., Jaeger, J.-J. and Rubino, J.-L. (2012) New insight into the sedimentology and stratigraphy of the Dur At Talah tidal-fluvial transition sequence (Eocene–Oligocene, Sirt Basin, Libya). *Journal of African Earth Sciences*, **65,** 72-90.

Ainsworth, R.B., Flint, S.S. and Howell, J.A. (2008) Predicting coastal depositional style: influence of basin morphology and accommodation to sediment supply ratio within a sequence stratigraphic framework. In: *Recent advances in models of siliciclastic shallow-marine stratigraphy* (Eds G.J. Hampson, R.J. Steel, P.M. Burgess and R.W. Dalrymple), **90**, pp. 237-263. SEPM Special Publication.

Ainsworth, R.B., Vakarelov, B.K., Lee, C., MacEachern, J.A., Montgomery, A.E., Ricci, L.P. and Dashtgard, S.E. (2015) Architecture and Evolution of A Regressive, Tide-Influenced Marginal Marine Succession, Drumheller, Alberta, Canada. *Journal of Sedimentary Research*, **85,** 596-625.

Ainsworth, R.B., Vakarelov, B.K. and Nanson, R.A. (2011) Dynamic spatial and temporal prediction of changes in depositional processes on clastic shorelines; toward improved subsurface uncertainty reduction and management. *American Association Petroleoum Geologists Bulletin*, **95,** 267-297.

Allen, G.P., Salomon, J.C., Bassoullet, J.P., Du Penhoat, Y. and De Grandpre, C. (1980) Effects of tides on mixing and suspended sediment transport in macrotidal estuaries. *Sedimentary Geology*, **26,** 69-90.

Allison, M.A., Demas, C.R., Ebersole, B.A., Kleiss, B.A., Little, C.D., Meselhe, E.A., Powell, N.J., Pratt, T.C. and Vosburg, B.M. (2012) A water and sediment budget for the lower Mississippi-Atchafalaya River in flood years 2008-2010: Implications for sediment discharge to the oceans and coastal restoration in Louisiana. *Journal of Hydrology*, **432-433,** 84-97.

Bhattacharya, J.P. (2006) Deltas. In: *Facies Models revisited* (Eds R.G. Walker and H. Posamentier), **84**, pp. 237-292. SEPM Special Publication.

Bhattacharya, J.P. (2010) Deltas. In: *Facies Models 4* (Eds N.P. James and R.W. Dalrymple), pp. 233-264. Geological Association of Canada.

Bhattacharya, J.P., Copeland, P., Lawton, T.F. and Holbrook, J. (2016) Estimation of source area, river paleo-discharge, paleoslope, and sediment budgets of linked deep-time depositional systems and implications for hydrocarbon potential. *Earth-Science Reviews*, **153,** 77-110.

Boyd, R., Dalrymple, R.W. and Zaitlin, B.A. (1992) Classification of clastic coastal depositional environments. *Sedimentary Geology*, **80,** 139-150.

Brandsaeter, I., McIlroy, D., Lia, O., Ringrose, P.S. and Naess, A. (2005) Reservoir modelling and simulation of Lajas Formation outcrops (Argentina) to constrain tidal reservoirs of the Halten Terrace (Norway). *Petroleum Geoscience*, **11,** 37-46.

Burgess, P.M., Flint, S. and Johnson, S. (2000) Sequence stratigraphic interpretation of turbiditic strata: an example from Jurassic strata of the Neuquen Basin, Argentina. *Geological Society of America, Bulletin*, **112,** 1650-1666.

Coleman, J.M. and Wright, L.D. (1975) Modern river deltas: variability of processes and sand bodies. In: *Deltas, models for exploration* (Ed M.L. Broussard), pp. 99-149. Houston Geol. Soc., Houston, United States.

Collinson, J., Mountney, N. and Thompson, D. (2006) *Sedimentary structures*. Terra, Harpenden, 292 pp.

Dalrymple, R.W., Baker, E.K., Harris, P.T. and Hughes, M.G. (2003) Sedimentology and stratigraphy of a tide-dominated, foreland-basin delta (Fly River, Papua New Guinea). In: *Tropical Deltas of Southeast Asia—Sedimentology, Stratigraphy, and Petroleum Geology* (Eds F.H. Sidi, D. Nummedal, P. Imbert, H. Darman and H.W. Posamentier), **76**, pp. 147-173. SEPM, Special Publication.

Dalrymple, R.W. and Choi, K. (2007) Morphologic and facies trends through the fluvial-marine transition in tide-dominated depositional systems; a schematic framework for environmental and sequence stratigraphic interpretation. *Earth-Science Reviews*, **81,** 135-174.

Dalrymple, R.W., Kurcinka, C.E., Jablonski, B.V.J., Ichaso, A.A. and MacKay, D.A. (2015) Deciphering the relative importance of fluvial and tidal processes in the fluvial-marine transition. In: *Development* *in Sedimentology, Fluvial-Tidal Sedimentology* (Eds P.J. Ashworth, J.L. Best and D.R. Parsons), **68**, pp. 3-40. Elsevier.

Dalrymple, R.W., Zaitlin, B.A. and Boyd, R. (1992) Estuarine facies models: conceptual basis and stratigraphic implications. *Journal of Sedimentary Petrology*, **62,** 1130-1146.

Dashtgard, S.E., Venditti, J.G., Hill, P.R., Sisulak, C.F., Johnson, S.M. and La Croix, A.D. (2012) Sedimentation across the tidal-fluvial transition in the Lower Fraser River, Canada. *SEPM, The Sedimentary Record*, **10,** 4-9.

Eriksson, K.A., Simpson, E.L. and Mueller, W. (2006) An unusual fluvial to tidal transition in the mesoarchean Moodies Group, South Africa: A response to high tidal range and active tectonics. *Sedimentary Geology*, **190,** 13-24.

Falcieri, F.M., Benetazzo, A., Sclavo, M., Russo, A. and Carniel, S. (2014) Po River plume pattern variability investigated from model data. *Continental Shelf Research, Oceanography at coastal scales*, **87,** 84–95.

Franzese, J., Spalletti, L., Gomez Perez, I. and Macdonald, D. (2003) Tectonic and paleoenvironmental evolution of Mesozoic sedimentary basins along the Andean foothills of Argentina (32 degrees -54 degrees S). *Journal of South American Earth Sciences*, **16,** 81-90.

Franzese, J.R. and Spalletti, L.A. (2001) Late Triassic-Early Jurassic continental extension in southwestern Gondwana; tectonic segmentation and pre-break-up rifting. *Journal of South American Earth Sciences*, **14,** 257-270.

Galloway, W.E. (1975) Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In: *Deltas, Models for Exploration* (Ed M.L. Broussard), pp. 87-98. Houston Geological Society Houston, United States.

Garcia, V.M., Quattrocchio, M.E., Zavala, C.A. and Martinez, M.A. (2006) Palinofacies, paleoambientes y paleoclima del Grupo Cuyo (Jurásico Medio) en la Sierra de Chacaico, Cuenca Neuquina, Argentina. *Revista Española de Micropaleontología*, **38,** 269-288.

Gérard, J.R.F. and Bromley, R.G. (2008) *Ichnofabrics in Clastic Sediments: Applications to Sedimentological Core Studies*. R.F. Gerard, 97 pp.

Ghosh, S.K., Chakraborty, C. and Chakraborty, T. (2005) Influence of fluvial-tidal interactions on the nature of cross-stratified packages in a deltaic setting: examples from the Barakar Coal Measure (Permian), Satpura Gondwana Basin, central India. *Geological Journal*, **40,** 65-81.

Gingras, M.K. and Zonneveld, J.-P. (2015) Tubular Tidalites: A Biogenic Sedimentary Structure Indicative of Tidally Influenced Sedimentation. *Journal of Sedimentary Research*, **85,** 845-854.

Godin, G. (1999) The Propagation of Tides up Rivers With Special Considerations on the Upper Saint Lawrence River. *Estuarine, Coastal and Shelf Science*, **48,** 307-324.

Goodbred, S.L.J. and Saito, Y. (2012) Tide-dominated deltas. In: *Principles of Tidal Sedimentology* (Eds R.A. Davis Jr and R.W. Dalrymple), pp. 129-149. Springer Berlin.

Gugliotta, M., Fairman, J.G.J., Schultz, D.M. and Flint, S.S. (in review) Sedimentological and Paleoclimate Modeling Evidence for Preservation of Jurassic Annual Cycles in Sedimentation, Western Gondwana. *Earth Interactions*.

Gugliotta, M., Flint, S.S., Hodgson, D.M. and Veiga, G.D. (2015) Stratigraphic Record of River-Dominated Crevasse Subdeltas With Tidal Influence (Lajas Formation, Argentina). *Journal of Sedimentary Research*, **85,** 265-284.

Gugliotta, M., Kurcinka, C.E., Dalrymple, R.W., Flint, S.S. and Hodgson, D.M. (2016) Decoupling seasonal fluctuations in fluvial discharge from the tidal signature in ancient deltaic deposits: an example from the Neuquén Basin, Argentina. *Journal of the Geological Society*, **173,** 94–107.

Holbrook, J. and Wanas, H. (2014) A Fulcrum Approach To Assessing Source-To-Sink Mass Balance Using Channel Paleohydrologic Paramaters Derivable From Common Fluvial Data Sets With An Example From the Cretaceous of Egypt. *Journal of Sedimentary Research*, **84,** 349-372.

Howell, J.A., Schwarz, E., Spalletti, L.A. and Veiga, G.D. (2005) The Neuquen Basin: an overview. In: *The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics* (Eds G.D.

Veiga, L.A. Spalletti, J.A. Howell and E. Schwartz), **252**, pp. 1-14. Geological Society of London, London, United Kingdom, Geological Society of London, Special Publication.

Ichaso, A.A. and Dalrymple, R.W. (2009) Tide- and wave-generated fluid mud deposits in the Tilje Formation (Jurassic), offshore Norway. *Geology (Boulder)*, **37,** 539-542.

Ichaso, A.A. and Dalrymple, R.W. (2014) Eustatic, tectonic and climatic controls on an early syn-rift mixed-energy delta, Tilje Formation (Early Jurassic, Smørbukk field, offshore mid-Norway). In: *IAS Special Publication, From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin* (Eds A.W. Martinius, R. Ravnås, J.A. Howell, R.J. Steel and J.P. Wonham), **46**, pp. 339-388. John Wiley & Sons, Ltd.

Iglesia Llanos, M.P. (2012) Palaeomagnetic study of the Jurassic from Argentina: magnetostratigraphy and palaeogeography of South America. *Revue de Paléobiologie***,** 151-168.

Iglesia Llanos, M.P., Riccardi, A.C. and Singer, S.E. (2006) Palaeomagnetic study of Lower Jurassic marine strata from the Neuquen Basin, Argentin: a new Jurassic apparent polar wander path for South America. *Earth and Planetary Science Letters*, **252,** 379-397.

Iglesias, A.R.I., Artabe, A.E. and Morel, E.M. (2011) The evolution of Patagonian climate and vegetation from the Mesozoic to the present. *Biological Journal of the Linnean Society*, **103,** 409-422.

Jablonski, B.V.J. and Dalrymple, R.W. (2016) Recognition of strong seasonality and climatic cyclicity in an ancient, fluvially dominated, tidally influenced point bar: Middle McMurray Formation, Lower Steepbank River, north-eastern Alberta, Canada. *Sedimentology***,** Article first published online: 11 JAN 2016.

Kravtsova, V.I., Mikhailov, V.N. and Kidyaeva, V.M. (2009) Hydrological regime, morphological features and natural territorial complexes of the Irrawaddy River Delta (Myanmar). *Water Resources*, **36,** 243-260.

Kurcinka, C.E. (2014) *Sedimentology and facies achitecture of the tide-influenced, river-dominated delta-mouth bars in the lower Lajas Fm (Jurassic), Argentina*, Queen's University, Kingston, Ontario, Canada, 157 pp.

La Croix, A.D. and Dashtgard, S.E. (2014) Of sand and mud: Sedimentological criteria for identifying the turbidity maximum zone in a tidally influenced river. *Sedimentology*, **61,** 1961-1981.

La Croix, A.D. and Dashtgard, S.E. (2015) A Synthesis of Depositional Trends In Intertidal and Upper Subtidal Sediments Across the Tidal–Fluvial Transition In the Fraser River, Canada. *Journal of Sedimentary Research*, **85,** 683-698.

MacEachern, J.A., Pemberton, S.G., Gingras, M.K. and Bann, K.L. (2010) Ichnology and facies models. In: *Facies Models 4* (Eds N.P. James and R.W. Dalrymple), pp. 19-58. Geological Association of Canada, St. John's.

MacKay, D.A. and Dalrymple, R.W. (2011) Dynamic mud deposition in a tidal environment; the record of fluid-mud deposition in the Cretaceous Bluesky Formation, Alberta, Canada. *Journal of Sedimentary Research*, **81,** 901-920.

Makhlouf, I.M. (2003) Fluvial/tidal interaction at the southern Tethyan strandline during Triassic Mukheiris times in central Jordan. *Journal of Asian Earth Sciences*, **21,** 377-385.

Martinez, M.A., Quattrocchio, M.E. and Zavala, C.A. (2002) Análisis palinofacial de la Formación Lajas (Jurásico Medio), Cuenca Neuquina, Argentina: significado paleoambiental y paleoclimático. *Revista Española de Micropaleontología*, **34,** 81-104.

Martinius, A.W. and Gowland, S. (2011) Tide-influenced fluvial bedforms and tidal bore deposits (Late Jurassic Lourinha Formation, Lusitanian Basin, western Portugal). *Sedimentology*, **58,** 285-324.

Martinius, A.W., Jablonski, B.V.J., Fustic, M., Strobl, R. and Van den Berg, J.H. (2015) Fluvial to tidal transition zone facies in the McMurray Formation (Christina River, Alberta, Canada), with emphasis on the reflection of flow intensity in bottomset architecture. In: *Developments in Sedimentology, Fluvial-Tidal Sedimentology* (Eds P.J. Ashworth, J.L. Best and D.R. Parsons), **68**, pp. 445 - 480. Elsevier,, Amstredam.

Martinius, A.W., Ringrose, P.S., Brostrom, C., Elfenbein, C., Naess, A. and Ringas, J.E. (2005) Reservoir challenges of heterolithic tidal sandstone reservoirs in the Halten Terrace, mid-Norway. *Petroleum Geoscience*, **11,** 3-16.

Martinius, A.W. and Van den Berg, J.H. (2011) *Atlas of sedimentary structures in estuarine and tidally-influenced river deposits of the Rhine-Meuse-Scheldt system: Their application to the interpretation of analogous outcrop and subsurface depositional systems*. EAGE Publications, Houten, 298 pp.

Marynowski, L., Scott, A.C., Zaton, M., Parent, H. and Garrido, A.C. (2011) First multi-proxy record of Jurassic wildfires from Gondwana: evidence from the Middle Jurassic of the Neuquén Basin, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **299,** 129-136.

McIlroy, D. (2007) Ichnology of a macrotidal tide-dominated deltaic depositional system: Lajas Formation, Neuquén Province, Argentina. In: *Sediment-Organism Interactions: A Multifacted Ichnology* (Eds R.G. Bromley, L.A. Buatois, G. Mangano, J.F. Genise and R.N. Melchor), *Society for Sedimentary Geology Special Publication*, **88**, pp. 195-211. SEPM, Special Publication.

McIlroy, D., Flint, S. and Howell, J.A. (1999) Sequence stratigraphy and facies architecture of tidal succession, in an extensional basin; Neuquén Basin, Argentina. *American Association of Petroleum Geologists, Annual Meeting Expanded Abstracts* **1999,** A91-A92.

McIlroy, D., Flint, S., Howell, J.A. and Timms, N. (2005) Sedimentology of the tide-dominated Jurassic Lajas Formation, Neuquén Basin, Argentina. In: *The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics* (Eds G.D. Veiga, L.A. Spalletti, J.A. Howell and E. Schwartz), **252**, pp. 83-107. Geological Society of London, Special Publications.

Mikhailov, V.N. and Mikhailova, M.V. (2010) Delta formation processes at the Mississippi River mouth. *Water Resources*, **37,** 595-610.

Morgans-Bell, H.S. and McIlroy, D. (2005) Palaeoclimatic implications of Middle Jurassic (Bajocian) coniferous wood from the Neuquen Basin, west-central Argentina. In: *The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics* (Eds G.D. Veiga, L.A. Spalletti, J.A. Howell and E. Schwartz), **252**, pp. 267-278. Geological Society of London, Special Publication.

Nelson, B.W. (1970) Hydrography, sediment dispersal, and recent historical development of the Po River delta, Italy. In: *Deltaic Sedimentation, Modern and Ancient* (Eds J.P. Morgan and R.H. Shaver), **15**, pp. 152-184. SEPM Special Publication, Tulsa, OK, United States.

Nichols, G. (2009) *Sedimentology and stratigraphy*. John Wiley & Sons, 432 pp.

Nordahl, K., Martinius, A.W. and Kritski, A. (2006) Time-series analysis of a heterolithic, ripple-laminated deposit (Early Jurassic, Tilje Formation) and implications for reservoir modelling. *Marine Geology*, **235,** 255-271.

Olariu, C. and Bhattacharya, J.P. (2006) Terminal distributary channels and delta front architecture of river-dominated delta systems. *Journal of Sedimentary Research*, **76,** 212-233.

Orton, G.J. and Reading, H.G. (1993) Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size. *Sedimentology*, **40,** 475-512.

Paim, P.S.G., Silveira, A.S., Lavina, E.L.C., Faccini, U.F., Leanza, H.A., Teixeira de Oliveira, J.M.M. and D'Avila, R.S.F. (2008) High resolution stratigraphy and gravity flow deposits in the Los Molles Formation (Cuyo Group, Jurassic) at La Jardinera region, Neuquén Basin. *Revista de la Asociación Geológica Argentina*, **63,** 728-753.

Pontén, A. and Plink-Björklund, P. (2007) Depositional environments in an extensive tide-influenced delta plain, Middle Devonian Gauja Formation, Devonian Baltic Basin. *Sedimentology*, **54,** 969-1006.

Quattrocchio, M., Garcia, V., Martinez, M. and Zavala, C. (2001) A hypothetic scenario for the Middle Jurassic in the southern part of the Neuquén Basin, Argentina. In: *Asociación Paleontológica Argentina, Publicación Especial*, **7**, pp. 163-166.

Reesink, A.J.H. and Bridge, J.S. (2011) Evidence of bedform superimposition and flow unsteadiness in unit-bar deposits, South Saskatchewan river, Canada. *Journal of Sedimentary Research*, **81,** 814-840.

Reesink, A.J.H., Van den Berg, J.H., Parsons, D.R., Amsler, M.L., Best, J.L., Hardy, R.J., Orfeo, O. and Szupiany, R.N. (2015) Extremes in dune preservation: Controls on the completeness of fluvial deposits. *Earth-Science Reviews*, **150,** 652-665.

Reynolds, A.D. (1999) Dimensions of paralic sandstone bodies. *AAPG Bulletin*, **83,** 211-229.

Roberts, H.H. (1998) Delta switching; early responses to the Atchafalaya River diversion. *Journal of Coastal Research*, **14,** 882-899.

Rossi, V.M. and Steel, R.J. (2016) The role of tidal, wave and river currents in the evolution of mixed-energy deltas: Example from the Lajas Formation (Argentina). *Sedimentology***,** n/a-n/a.

Rubin, D.M. and Hunter, R.E. (1982) Bedform climbing in theory and nature. *Sedimentology*, **29,** 121-138.

Salahuddin, H. and Lambiase, J.J. (2013) Sediment dynamics and depositional systems of the Mahakam Delta, Indonesia; ongoing delta abandonment on a tide-dominated coast. *Journal of Sedimentary Research*, **83,** 503-521.

Salomon, J.-C. and Allen, G.-P. (1983) Role sedimentologique de la mare dans les estuaires a fort marnage. Compagnie Francais des Petroles. *Notes and Memoires*, **18,** 35-44.

Schwartz, T.M. and Graham, S.A. (2015) Stratigraphic architecture of a tide-influenced shelf-edge delta, Upper Cretaceous Dorotea Formation, Magallanes-Austral Basin, Patagonia. *Sedimentology*, **62,** 1039-1077.

Shaw, J.B. and Mohrig, D. (2014) The importance of erosion in distributary channel network growth, Wax Lake Delta, Louisiana, USA. *Geology*, **42,** 31-34.

Shaw, J.B., Mohrig, D. and Whitman, S.K. (2013) The morphology and evolution of channels on the Wax Lake Delta, Louisiana, USA. *Journal of Geophysical Research: Earth Surface*, **118,** 1562-1584.

Shiers, M.N., Mountney, N.P., Hodgson, D.M. and Cobain, S.L. (2014) Depositional controls on tidally influenced fluvial successions, Neslen Formation, Utah, USA. *Sedimentary Geology*, **311,** 1-16.

Simpson, E.L., Dilliard, K.A., Rowell, B.F. and Higgins, D. (2002) The fluvial-to-marine transition within the post-rift Lower Cambrian Hardyston Formation, Eastern Pennsylvania, USA. *Sedimentary Geology*, **147,** 127-142.

Sisulak, C.F. and Dashtgard, S.E. (2012) Seasonal controls on the development and character of inclined heterolithic stratification in a tide-influenced, fluvially dominated channel; Fraser River, Canada. *Journal of Sedimentary Research*, **82,** 244-257.

Spalletti, L. (1995) Depósitos de tormenta en un frente deltaico. Jurásico medio de la Cuenca Neuquina, República Argentina. *Revista de la Sociedad Geológica de España*, **8,** 261-272.

Stukins, S., Jolley, D.W., McIlroy, D. and Hartley, A.J. (2013) Middle Jurassic vegetation dynamics from allochthonous palynological assemblages: An example from a marginal marine depositional setting; Lajas Formation, Neuquén Basin, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **392,** 117-127.

Tänavsuu-Milkeviciene, K. and Plink-Björklund, P. (2009) Recognizing tide-dominated versus tide-influenced deltas: Middle Devonian strata of the Baltic Basin. *Journal of Sedimentary Research*, **79,** 887-905.

Taylor, A.M. and Goldring, R. (1993) Description and analysis of bioturbation and ichnofabric. *Geological Society of London, Journal* **150,** 141-148.

Uliana, M.A. and Legarreta, L. (1993) Hydrocarbons habitat in a Triassic-to-Cretaceous sub-Andean setting: Neuquen Basin, Argentina. *Journal of Petroleum Geology*, **16,** 397-420.

Uncles, R.J., Stephens, J.A. and Law, D.J. (2006) Turbidity maximum in the macrotidal, highly turbid Humber Estuary, UK: Flocs, fluid mud, stationary suspensions and tidal bores. *Estuarine, Coastal and Shelf Science*, **67,** 30-52.

Urien, C.M. and Zambrano, J.J. (1994) Petroleum systems in the Neuquen Basin, Argentina. In: *The petroleum system–from source to trap* (Eds L.B. Magoon and W.G. Dow), **60**, pp. 513-534, AAPG Memoir.

Vakarelov, B.K. and Ainsworth, R.B. (2013) A hierarchical approach to architectural classification in marginal-marine systems: Bridging the gap between sedimentology and sequence stratigraphy. *AAPG Bulletin*, **97,** 1121-1161.

van den Berg, J.H., Boersma, J.R. and van Gelder, A. (2007) Diagnostic sedimentary structures of the fluvial-tidal transition zone; evidence from deposits of the Rhine and Meuse. *Geologie en Mijnbouw. Netherlands Journal of Geosciences*, **86,** 287-306.

Van Der Kolk, D.A., Flaig, P.P. and Hasiotis, S.T. (2015) Paleoenvironmental Reconstruction of A Late Cretaceous, Muddy, River-Dominated Polar Deltaic System: Schrader Bluff–Prince Creek Formation Transition, Shivugak Bluffs, North Slope of Alaska, U.S.A. *Journal of Sedimentary Research*, **85,** 903-936.

Veiga, G.D. (1998) Estratigrafíasecuencial en series continentales: aplicación a los depósitos de la Formación Challacó, Jurásico de la cuenca neuquina austral (Republica Argentina). *Revista*, **11,** 95-109.

Veiga, G.D. (2002) Evolución paleogeográfica y paleoambiental de los depósitos continentales del Jurásico Medio en el sector austral de la Cuenca Neuquina, República Argentina. *Asociación Argentina de Sedimentología, Revista*, **9,** 83-108.

Vicente, J.C. (2006) Dynamic paleogeography of the Jurassic Andean basin; pattern of regression and general considerations on main features. *Asociación Geológica Argentina, Revista*, **61,** 408-437

Wetzel, A., Carmona, N. and Ponce, J. (2014) Tidal signature recorded in burrow fill. *Sedimentology*, **61,** 1198-1210.

Willis, B.J. (2005) Deposits of tide-influenced river deltas. In: *River Deltas—Concepts, Models, and Examples: SEPM, Special Publication* (Eds J.P. Bhattacharya and L. Giosan), **83**, pp. 87-129. Society for Sedimentary Geology (SEPM) Tulsa, OK, United States.

Wright, L.D. and Coleman, J.M. (1973) Variations in Morphology of Major River Deltas as Functions of Ocean Wave and River Discharge Regimes. *The American Association of Petroleum Geologists Bulletin*, **57,** 370-398.

Wu, C., Bhattacharya, J.P. and Ullah, M.S. (2015) Paleohydrology and 3D Facies Architecture of Ancient Point Bars, Ferron Sandstone, Notom Delta, South-Central Utah, U.S.A. *Journal of Sedimentary Research*, **85,** 399-418.

Zambrano, C.U.J. and Yrigoyen, M. (1995) Petroleum basins of southern South America: an overview. In: *Petroleum basins of South America* (Eds A.J. Tankard, S.R. Suárez and W.H. J.), **62**, pp. 63-77. Petroleum Basins of South America.

Zavala, C. (1996a) High-resolution sequence stratigraphy in the Middle Jurassic Cuyo Group, South Neuquén Basin, Argentina. *GeoResearch Forum*, **1-2,** 295-303.

Zavala, C. (1996b) Sequence stratigraphy in continental to marine transitions; an example from the Middle Jurassic Cuyo Group, South Neuquén Basin, Argentina. *GeoResearch Forum*, **1-2,** 285-293.

Zavala, C. and González, R. (2001) Estratigrafía del Grupo Cuyo (Jurásico inferior-medio) en la Sierra de la Vaca Muerta, Cuenca Neuquina. *Boletín de Informaciones Petroleras*, **Tercera Época, año XVII,** 52-64.

FIGURE CAPTIONS

Fig. 1. Character and distribution of the fluvial to marine transition zone (FMTZ) with indication of the balance of fluvial and tidal processes, net sediment transport orientation, salinity and suspended-sediment concentrations. Wave process is not considered for this study as the sedimentary structures suggest that wave process is negligible in the studied deposits.

Fig. 2 A) Location of the Neuquén Basin across central Argentina and Chile. B) Detail of the study area south of Zapala.

Fig. 3. Middle Jurassic stratigraphy of the Neuquén Basin. On the right, a detailed stratigraphic column of the Cuyo Group in the study area with a generalized palaeoenvironmental interpretation. Abbreviations in the grain size bar (m, s and p), at the bottom of the log indicate mud, sand and pebble. The stratigraphic subdivisions on the left of the column are from Zavala (1996a, 1996b) and McIlroy et al. (2005).

Fig. 4. Detail of the study area and location of the studied sections. See location in Fig. 2B. Image from Google Earth Pro.

Fig. 5. Representative photographs of the facies associations of the upper Lajas Formation. A) Amalgamated fluvial channel deposits (FA 1) with large mud clasts. Note person for scale. B) Low angle inclined bedding in distributary channel deposits (FA 2). The base of the channel is erosional into poorly drained delta plain deposits (FA 4). Note person for scale. C) Abandoned channel deposits (FA 3) filled almost entirely by mudstone. Note circled person for scale. D) Multi-coloured mudstone interpreted as subaerial floodplain deposits (FA 4).

Note circled person for scale. E) Small-scale, minor distributary channel deposits (FA 5) associated with floodplain deposits (FA 4). Hammer for scale is 33 cm long. F). Crevasse mouth bar deposits (FA 6) erosionally overlain by minor distributary channels deposits (FA 5). G) Mouth bar deposits (FA 9) erosionally overlain by terminal distributary channel deposits (FA 8) and distributary channel deposits (FA 2). Note circled person for scale. H) Shell bed interpreted as transgressive or abandonment deposits (FA 11). Lens for scale is 5 cm in diameter.

Fig. 6. Correlation panel for the upper 200 metres of the Lajas Formation. Note the overall shallowing upward trend from prodelta deposits (FA 10) to delta front deposits (FA 8 and 9) and delta plain deposits (FA 2, 3, 4, 5, 6 and 7). A similar trend is also visible from right (SW) to left (NE) in the panel, which is a proximal to distal trend. The top of the section is represented by amalgamated fluvial channel deposits (FA 1) which are separated by the underlain deposits by a regional erosional surface. Abbreviations in the grain size bar (m, s and p), at the bottom of the log indicate mud, sand and pebble. See locations of the sections in Fig. 4 and descriptions of the facies in table 1.

Fig. 7. Los Molles section. The section shows delta front deposits (FA 8), overlain by lower delta plain deposits (FA 6, 7) and upper delta plain deposits (FA 4), forming a shallowing-upward trend. All the delta plain deposits are associated with numerous channel deposits (FA 2, 3, 5). The top of the section consists primarily of amalgamated fluvial channel deposits (FA 1), which are separated from the underlying deposits by a regional erosional surface. Yellow lines indicate positions of measured logs. Note the carbonaceous shale horizon, which is used as a datum. See location of the section in Fig. 4 and stratigraphic context and key in Fig. 6.

Fig. 8. Summary of main fluvial and fluvial-tidal facies in the Lajas Formation. The facies are marked following a traffic light rating system with horizontal bands and according to the subzones of the FMTZ with vertical bands. The majority of the facies are interpreted as forming in purely fluvial or fluvially-dominated conditions. See Fig. 1 for reference to the FMTZ and the characteristics of each subzone.

Fig. 9. A) Example of unidirectional trough cross-stratification that could potentially be confused with "herringbone" cross-stratification if the outcrop would have been more limited in extent (B). Greater chance of misinterpretation would be possible in cores, because of their extremely narrow lateral extent (C). This example is interpreted confidently as purely fluvial and the bidirectionality is apparent, but other examples in the Lajas Fm. are dubious. Pencil for scale is about 12 cm long.

Fig. 10. Facies of the Lajas Fm. with cyclically distributed carbonaceous drapes interpreted as the result of tidal flood deceleration and tidal ebb acceleration (tidal modulation or tidal backwater) of the fluvial bedform. Yellow arrows indicate cyclical patterns in the distribution of the carbonaceous drapes on the dune foresets whereas white arrows mark the cycles in the spacing of the group of beds. Black arrows and numbers indicate palaeocurrents. Note how these facies are consistently directed broadly toward N (palaeo-seaward). Pencil for scale is about 12 cm long, compass is 6.5 cm long.

Fig. 11. A) Example of Gr1 and Gr3 facies in delta front deposits (FA 8 and FA 9). These facies suggest conditions typical of the fluvial-dominated parts of the FMTZ recorded in the distal part of the fluvio-deltaic system. B) The interpretation of FMTZ for this interval

consists of a seaward-shifted, fluvial-dominated FMTZ. See Fig. 1 for explanation of the FMTZ and the characteristics of each subzone and Fig. 6 and Fig. 7 for the wider stratigraphic context. Compass for scale is 6.5 cm long.

Fig. 12. A) Fluvial and fluvial-tidal facies along major axis deposits in a specific stratigraphic interval of the Lajas Formation. B) The distribution of fluvial and fluvial-tidal facies in the deposits suggests a FMTZ mainly composed of its fluvially-dominated part and located in the distal part of the system. This reconstruction does not consider short term temporal variation of the FMTZ due to tidal cyclicity or fluvial seasonality, but it could be argued that the majority of fluvial-tidal facies formed during low river stage conditions. See Fig. 1 for explanation of the FMTZ and the characteristics of each subzone, Fig. 6 for the wider stratigraphic context and Fig. 11 for the key of the stratigraphic logs.

Fig. 13. A) Example of a part of the system showing evidence of bidirectional tides in the interflood beds of facies Gr4 in crevasse mouth bar deposits (FA 6) forming in the interdistributary bay. Purely fluvial conditions are found in the major distributary channel deposits (FA 2). Similar intervals can be associated with evidence of Gr1 in the distributary channel deposits as described by Gugliotta et al. (2015). B) The reconstructed FMTZ highlights a system with stronger tides away from major axes, thus interpreted as hyposynchronous. See Fig. 1 for explanation of the FMTZ and the characteristics of each subzone, Fig. 6 and Fig. 7 for the wider stratigraphic context and Fig. 11 for the key of the stratigraphic log. Hammer for scale is 33 cm long, pencil is 12 cm long.

Fig. 14. A) Gr4 and Re features that highlight the temporal variations of the FMTZ at high and low river stages. B-C) Interpreted development of the FMTZ in the system at low and

high river stages. Note as the FMTZ is more developed at low river stage conditions. See Fig. 1 for explanations of the FMTZ and the characteristics of each subzone and Fig. 8 for description of the fluvial and fluvial-tidal facies. The tags in the logging pole are 10 cm spaced, compass for scale is 6.5 cm long, the pencil is 12 cm long and the lens cap is 5 cm in diameter.

Table 1. List of facies associations of the studied deposits with main sedimentological and biogenic features.

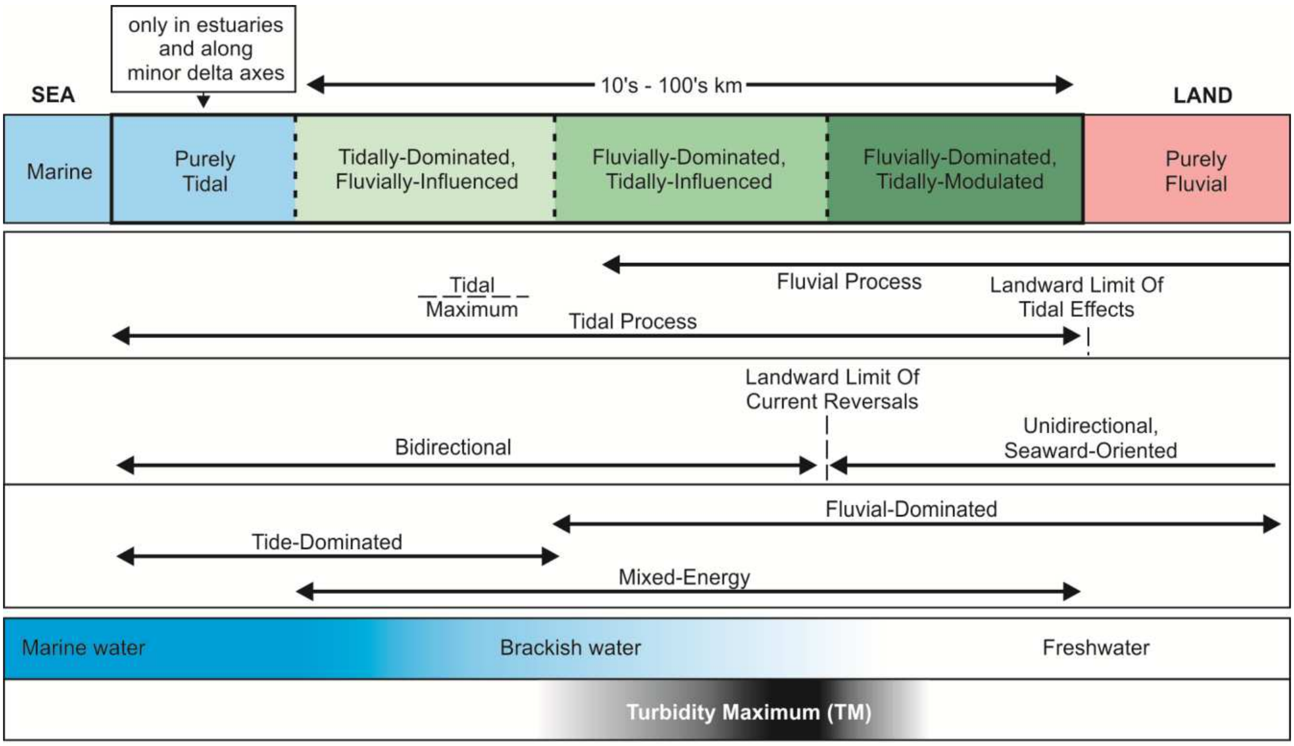


Figure 1

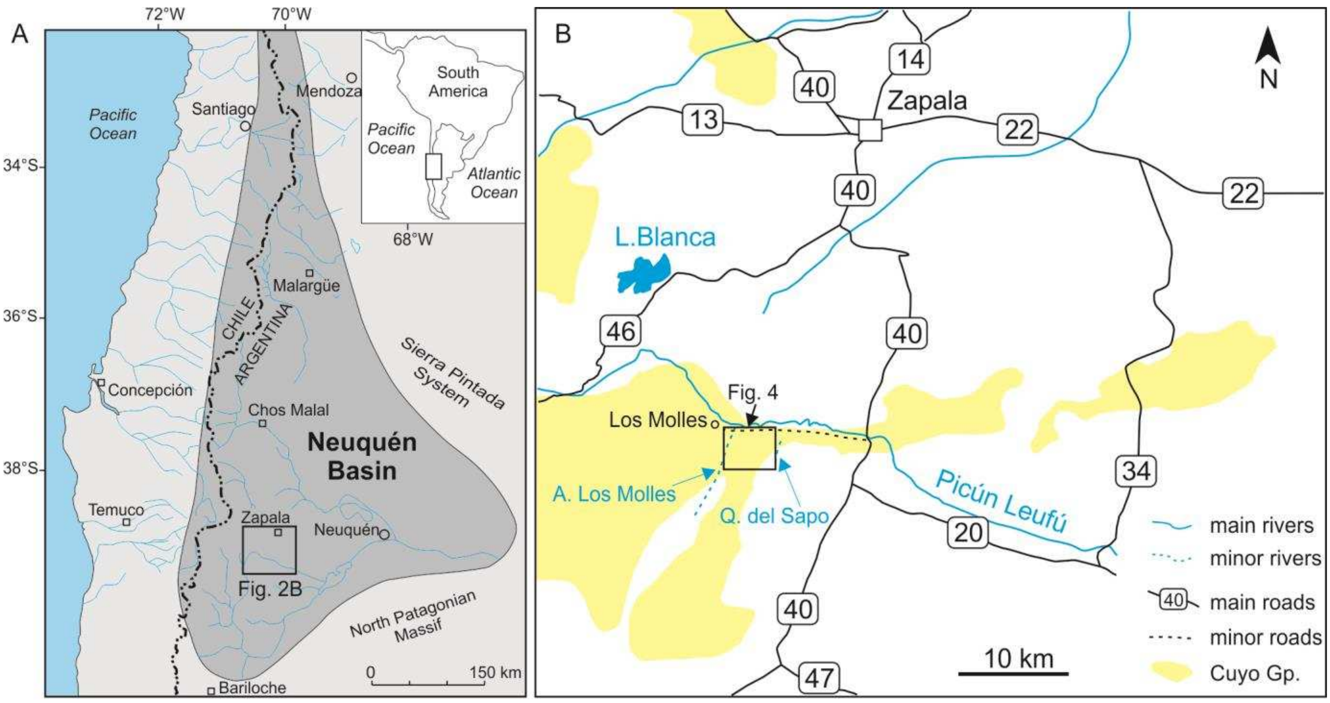

A
72°W
70°W
34°S
36°S
38°S
Pacific Ocean
Santiago
Mendoza
South America
Pacific Ocean
Atlantic Ocean
68°W
Malargüe
CHILE
ARGENTINA
Sierra Pintada System
Concepción
Chos Malal
Neuquén Basin
Temuco
Zapala
Neuquén
Fig. 2B
North Patagonian Massif
0
150 km
Bariloche
B
14
40
Zapala
13
22
N
40
22
L.Blanca
46
40
Fig. 4
Los Molles
A. Los Molles
Q. del Sapo
Picún Leufú
34
20
40
47
10 km
main rivers
minor rivers
main roads
minor roads
Cuyo Gp.

Figure 2

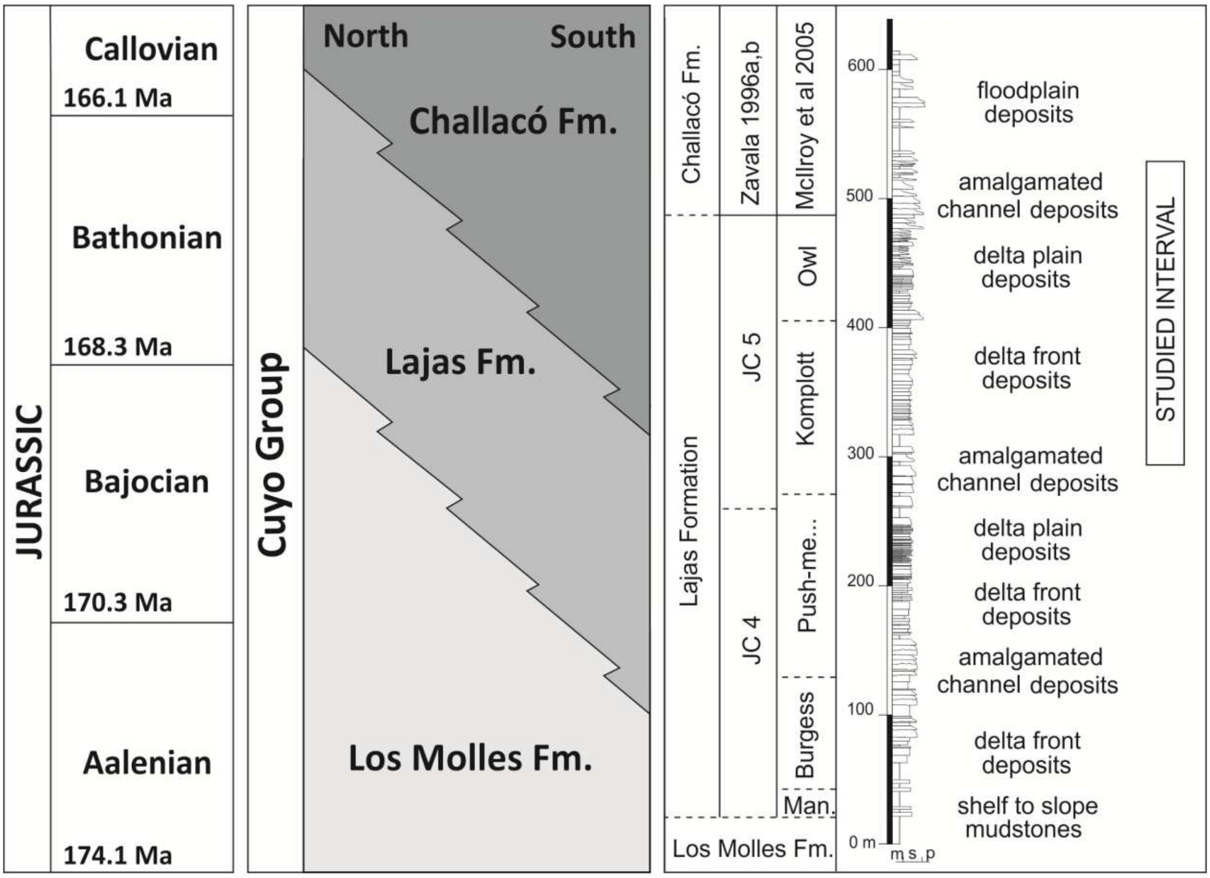


Figure 3

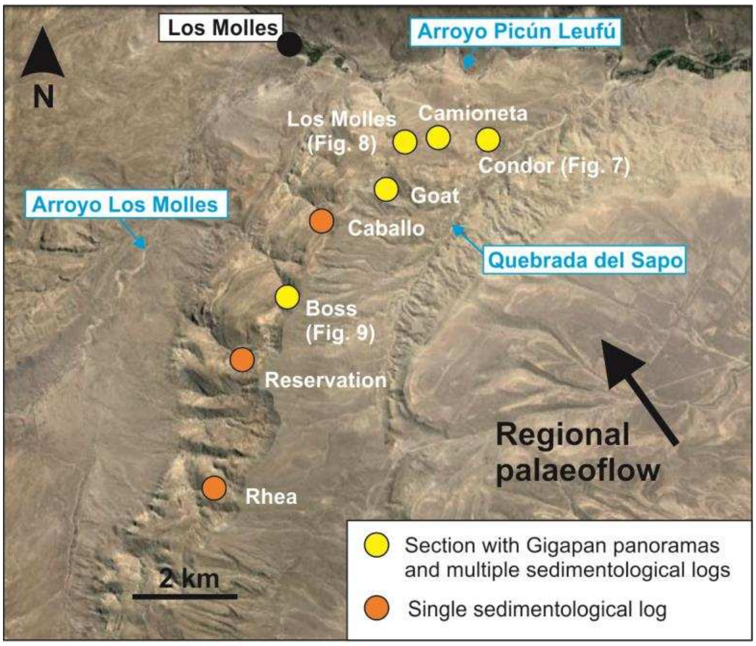


Figure 4

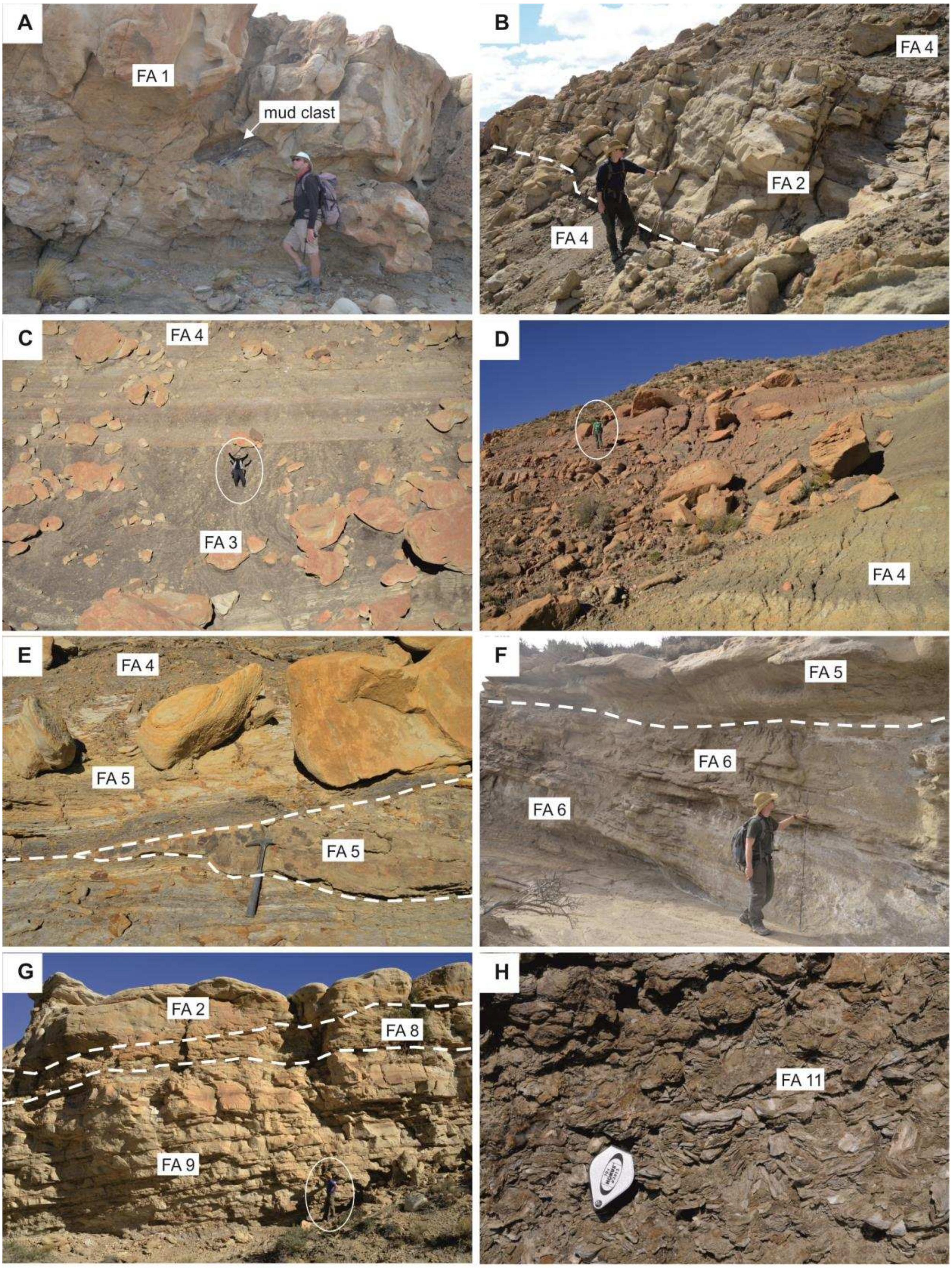

A
FA 1
mud clast
B
FA 4
FA 2
FA 4
C
FA 4
FA 3
D
FA 4
E
FA 4
FA 5
FA 5
F
FA 5
FA 6
FA 6
G
FA 2
FA 8
FA 9
H
FA 11

Figure 5

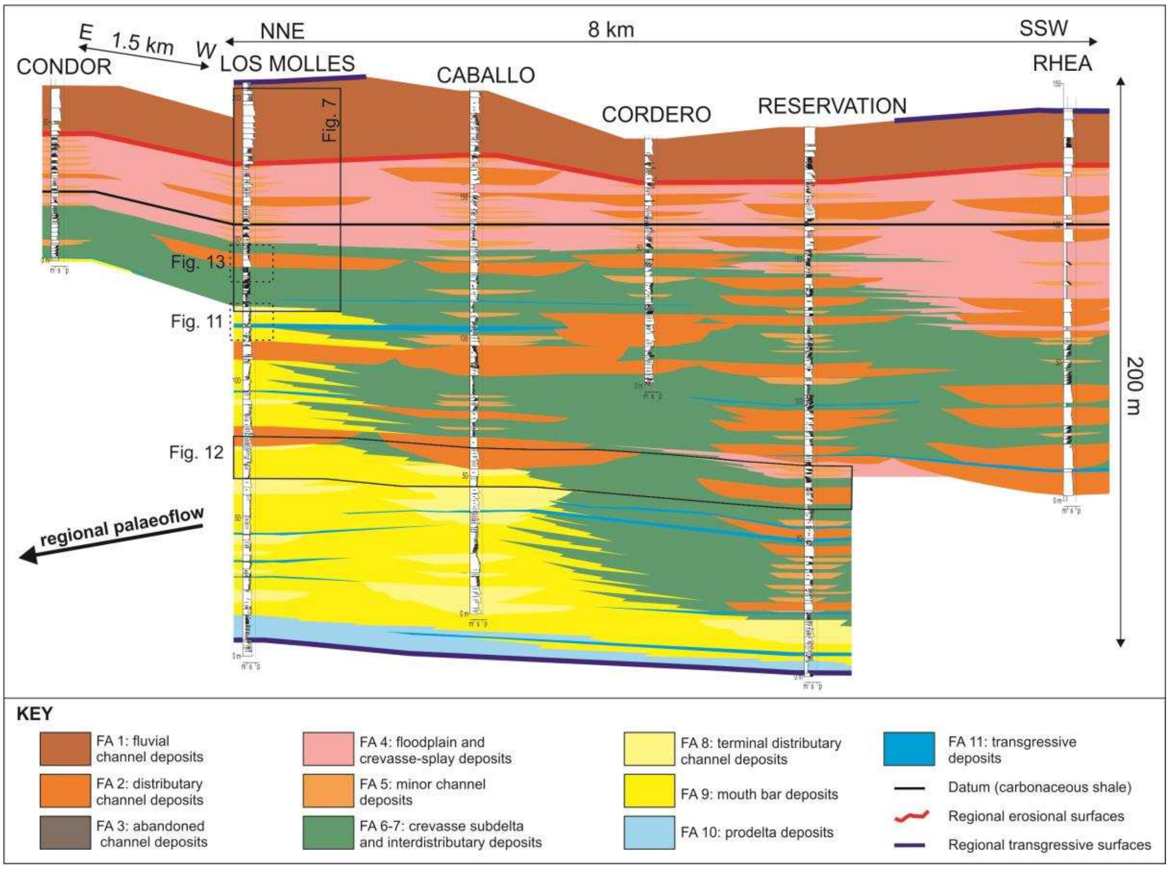

E
1.5 km
W
CONDOR
NNE
8 km
SSW
LOS MOLLES
CABALLO
CORDERO
RESERVATION
RHEA
Fig. 7
Fig. 13
Fig. 11
Fig. 12
200 m
regional palaeoflow
KEY
FA 1: fluvial channel deposits
FA 2: distributary channel deposits
FA 3: abandoned channel deposits
FA 4: floodplain and crevasse-splay deposits
FA 5: minor channel deposits
FA 6-7: crevasse subdelta and interdistributary deposits
FA 8: terminal distributary channel deposits
FA 9: mouth bar deposits
FA 10: prodelta deposits
FA 11: transgressive deposits
Datum (carbonaceous shale)
Regional erosional surfaces
Regional transgressive surfaces

Figure 6

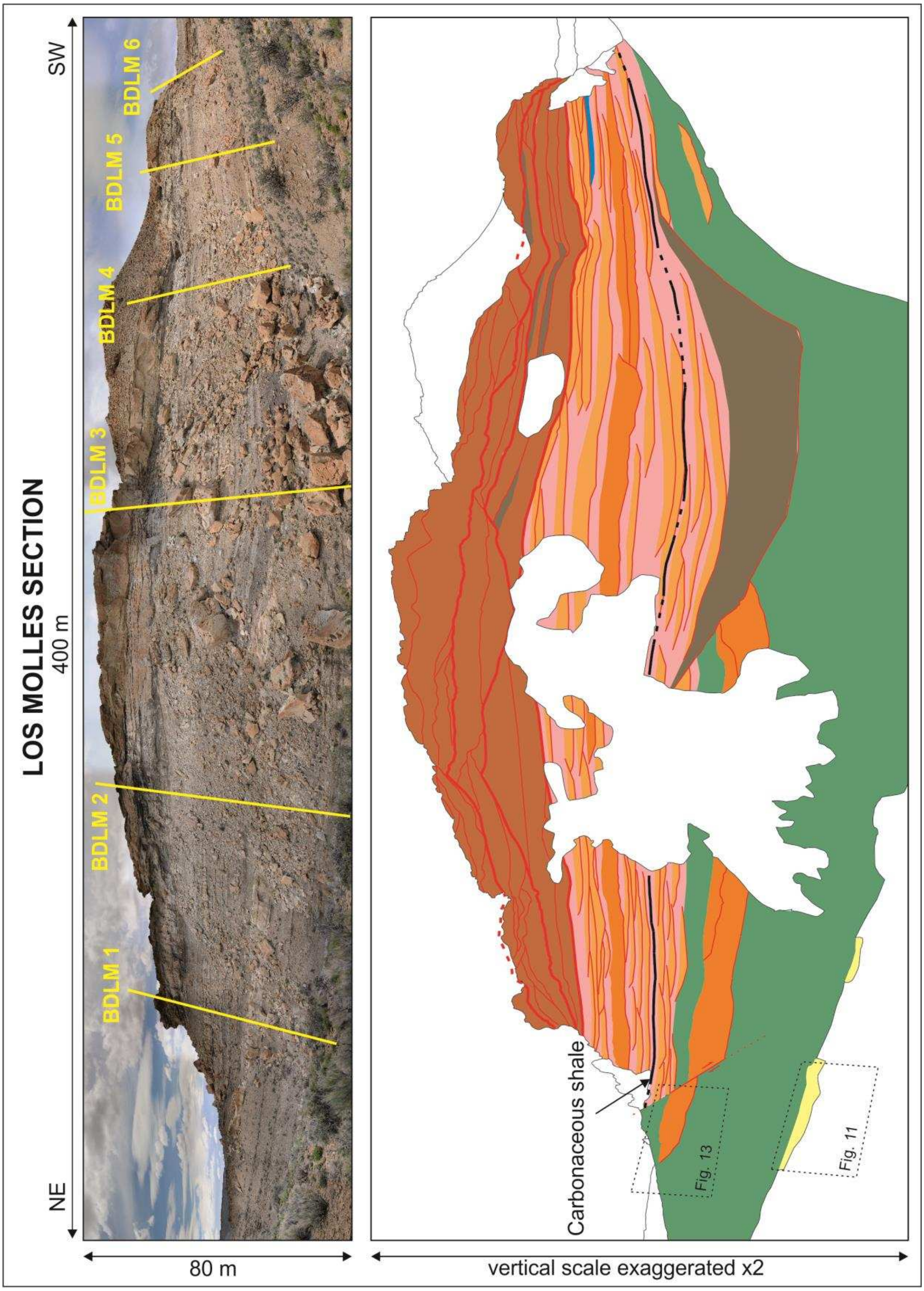
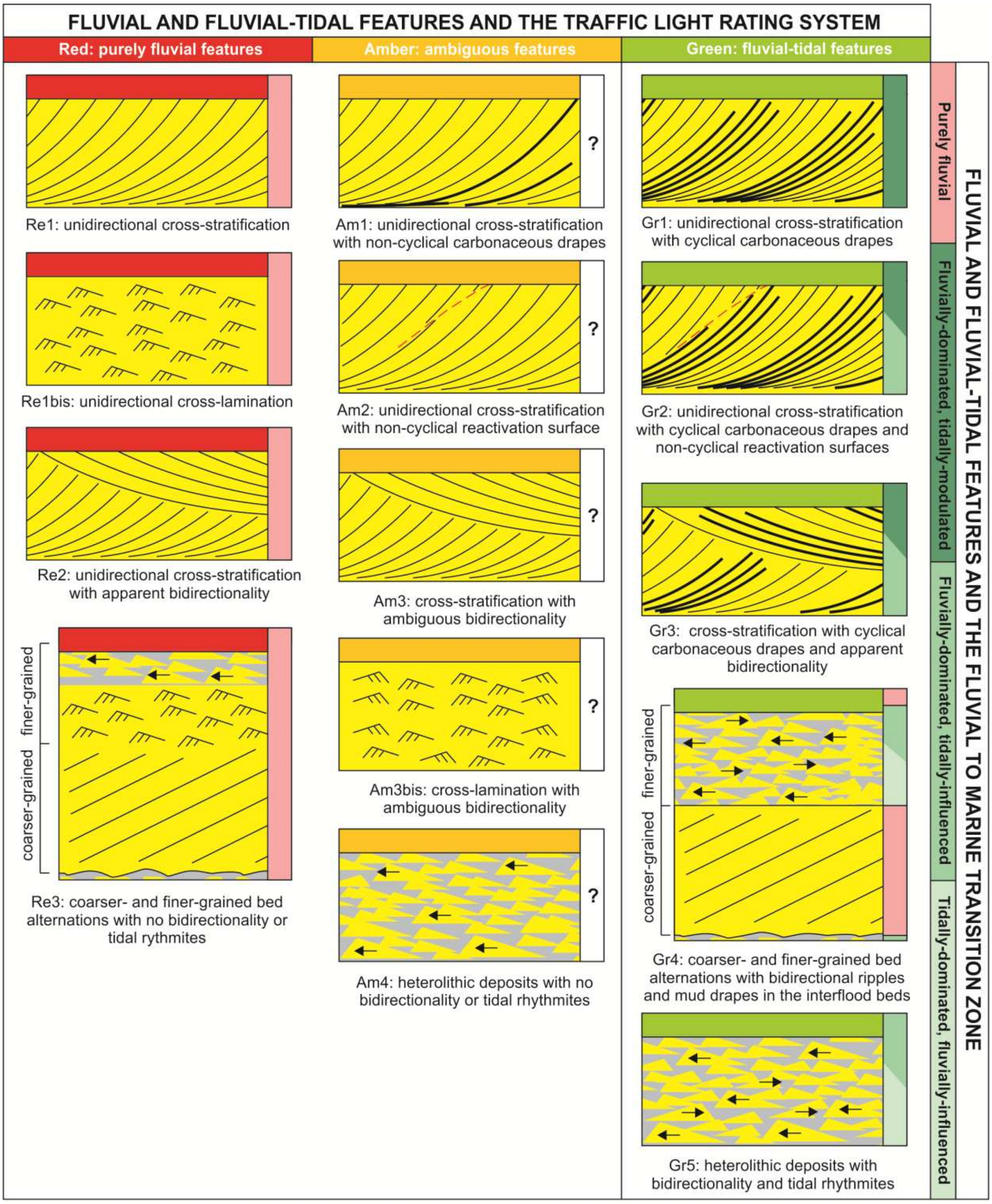

LOS MOLLES SECTION
400 m
SW
NE
BDLM 1
BDLM 2
BDLM 3
BDLM 4
BDLM 5
BDLM 6
80 m
vertical scale exaggerated x2
Carbonaceous shale
Fig. 13
Fig. 11

Figure 7



FLUVIAL AND FLUVIAL-TIDAL FEATURES AND THE TRAFFIC LIGHT RATING SYSTEM
Red: purely fluvial features
Amber: ambiguous features
Green: fluvial-tidal features
Re1: unidirectional cross-stratification
Re1bis: unidirectional cross-lamination
Re2: unidirectional cross-stratification with apparent bidirectionality
finer-grained
coarser-grained
Re3: coarser- and finer-grained bed alternations with no bidirectionality or tidal rythmites
Am1: unidirectional cross-stratification with non-cyclical carbonaceous drapes
Am2: unidirectional cross-stratification with non-cyclical reactivation surface
Am3: cross-stratification with ambiguous bidirectionality
Am3bis: cross-lamination with ambiguous bidirectionality
Am4: heterolithic deposits with no bidirectionality or tidal rhythmites
?
Gr1: unidirectional cross-stratification with cyclical carbonaceous drapes
Gr2: unidirectional cross-stratification with cyclical carbonaceous drapes and non-cyclical reactivation surfaces
Gr3: cross-stratification with cyclical carbonaceous drapes and apparent bidirectionality
Gr4: coarser- and finer-grained bed alternations with bidirectional ripples and mud drapes in the interflood beds
Gr5: heterolithic deposits with bidirectionality and tidal rhythmites
FLUVIAL AND FLUVIAL-TIDAL FEATURES AND THE FLUVIAL TO MARINE TRANSITION ZONE
Purely fluvial
Fluvially-dominated, tidally-modulated
Fluvially-dominated, tidally-influenced
Tidally-dominated, fluvially-influenced

Figure 8

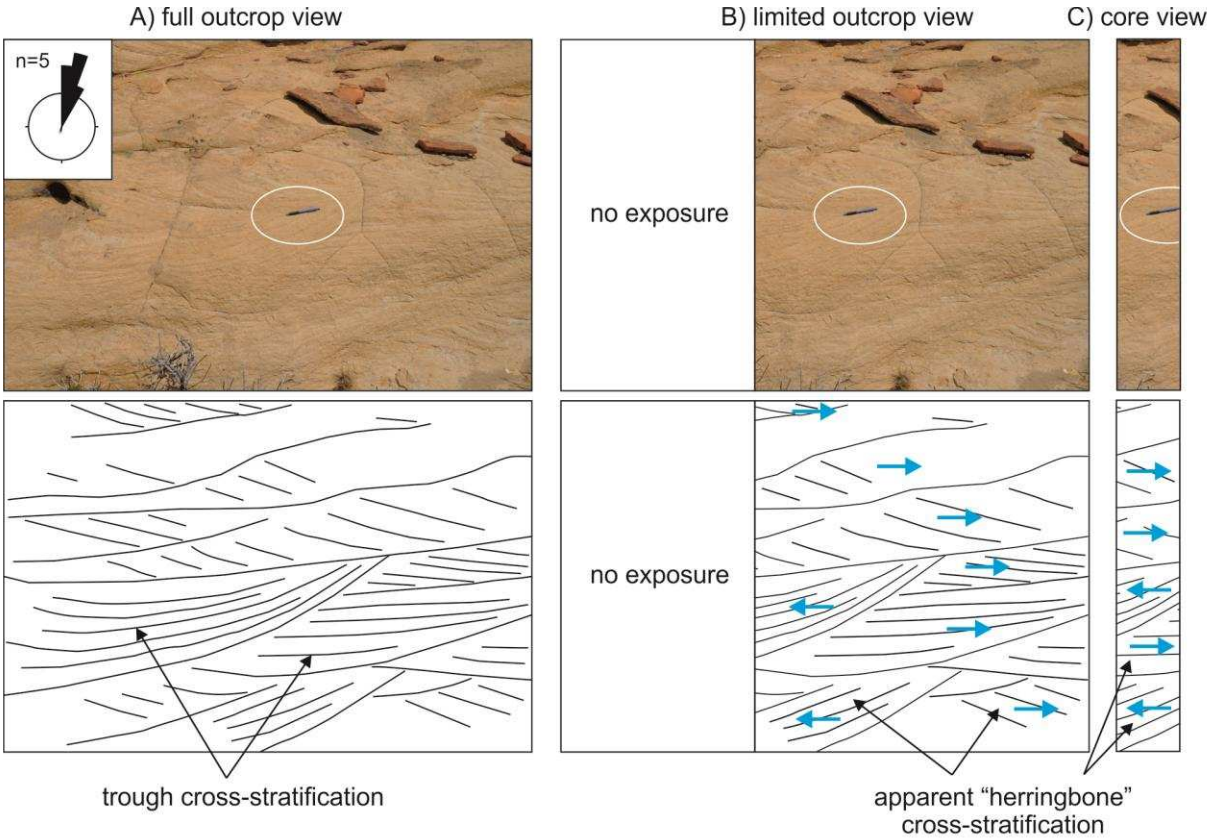
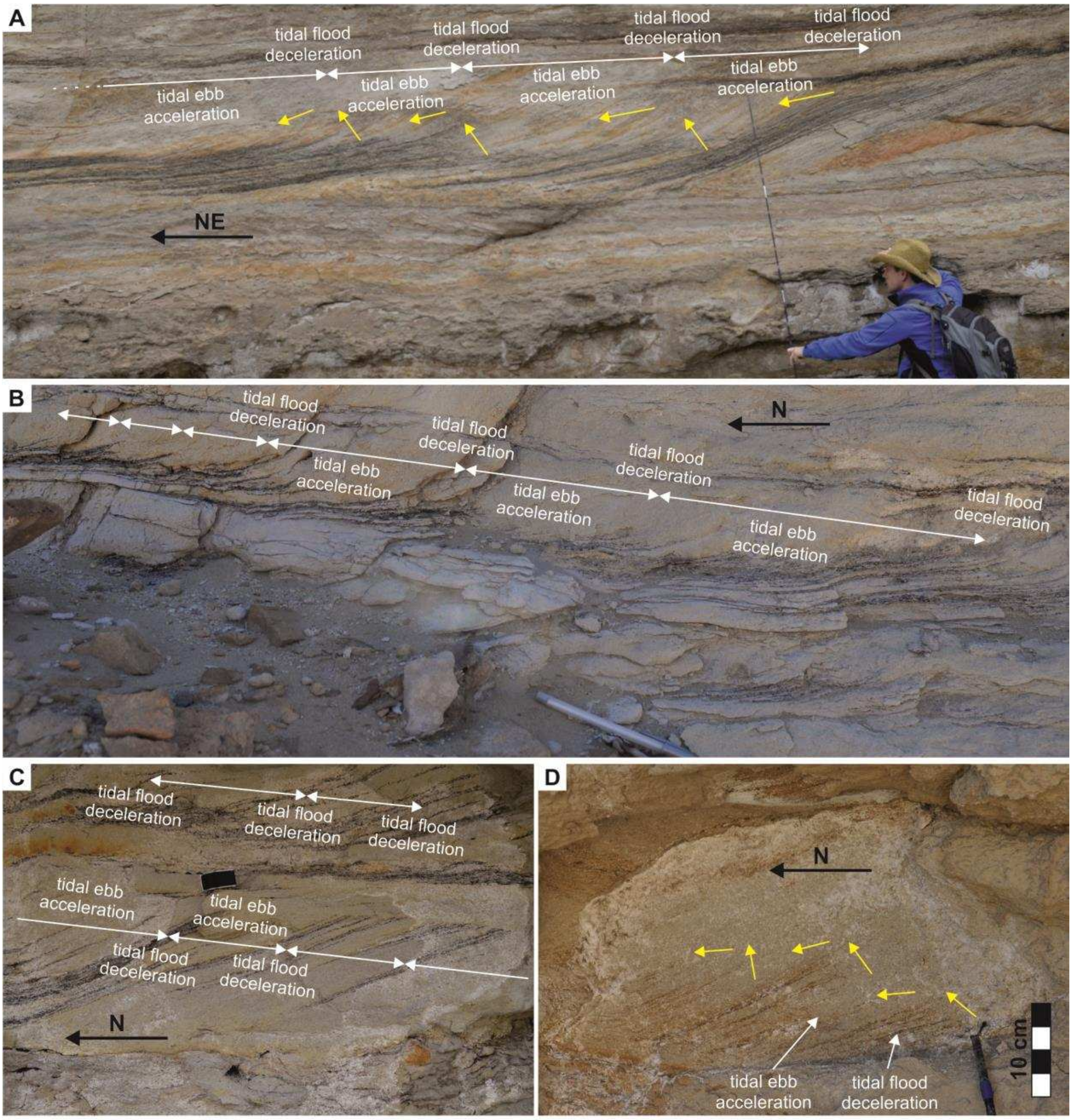
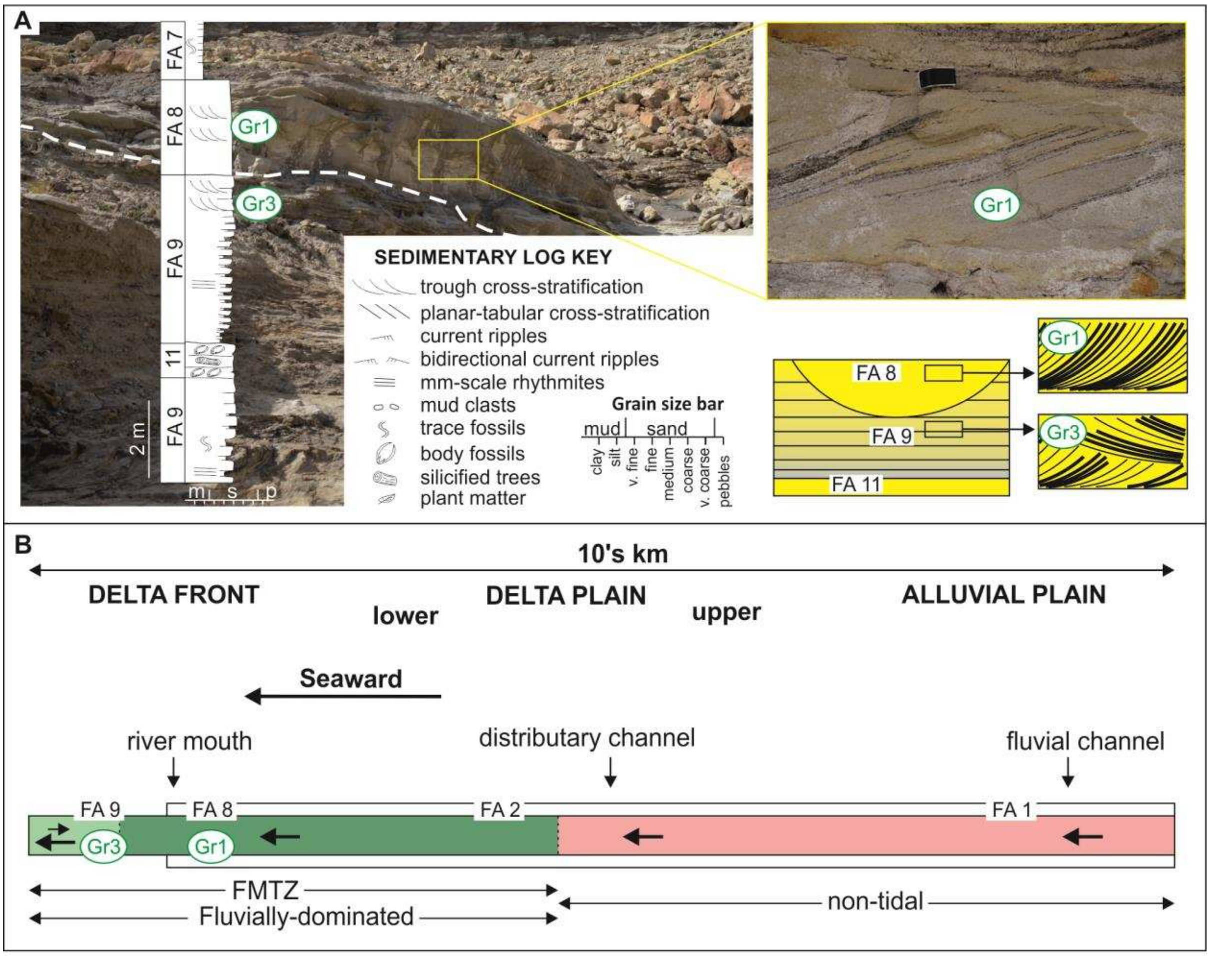

A) full outcrop view
B) limited outcrop view
C) core view
n=5
no exposure
no exposure
trough cross-stratification
apparent "herringbone" cross-stratification

Figure 9



A
tidal flood deceleration
tidal flood deceleration
tidal flood deceleration
tidal flood deceleration
tidal ebb acceleration
tidal ebb acceleration
tidal ebb acceleration
tidal ebb acceleration
NE
B
tidal flood deceleration
tidal flood deceleration
tidal flood deceleration
tidal flood deceleration
tidal ebb acceleration
tidal ebb acceleration
tidal ebb acceleration
N
C
tidal flood deceleration
tidal flood deceleration
tidal flood deceleration
tidal ebb acceleration
tidal ebb acceleration
tidal flood deceleration
tidal flood deceleration
N
D
N
tidal ebb acceleration
tidal flood deceleration
10 cm

Figure 10



A
FA 7
FA 8
Gr1
Gr3
FA 9
11
FA 9
2 m
m s p
SEDIMENTARY LOG KEY
trough cross-stratification
planar-tabular cross-stratification
current ripples
bidirectional current ripples
mm-scale rhythmites
mud clasts
trace fossils
body fossils
silicified trees
plant matter
Grain size bar
mud sand
clay silt v. fine fine medium coarse v. coarse pebbles
FA 8
FA 9
FA 11
B
10's km
DELTA FRONT
lower
DELTA PLAIN
upper
ALLUVIAL PLAIN
Seaward
river mouth
distributary channel
fluvial channel
FA 9
FA 8
FA 2
FA 1
FMTZ
non-tidal
Fluvially-dominated

Figure 11

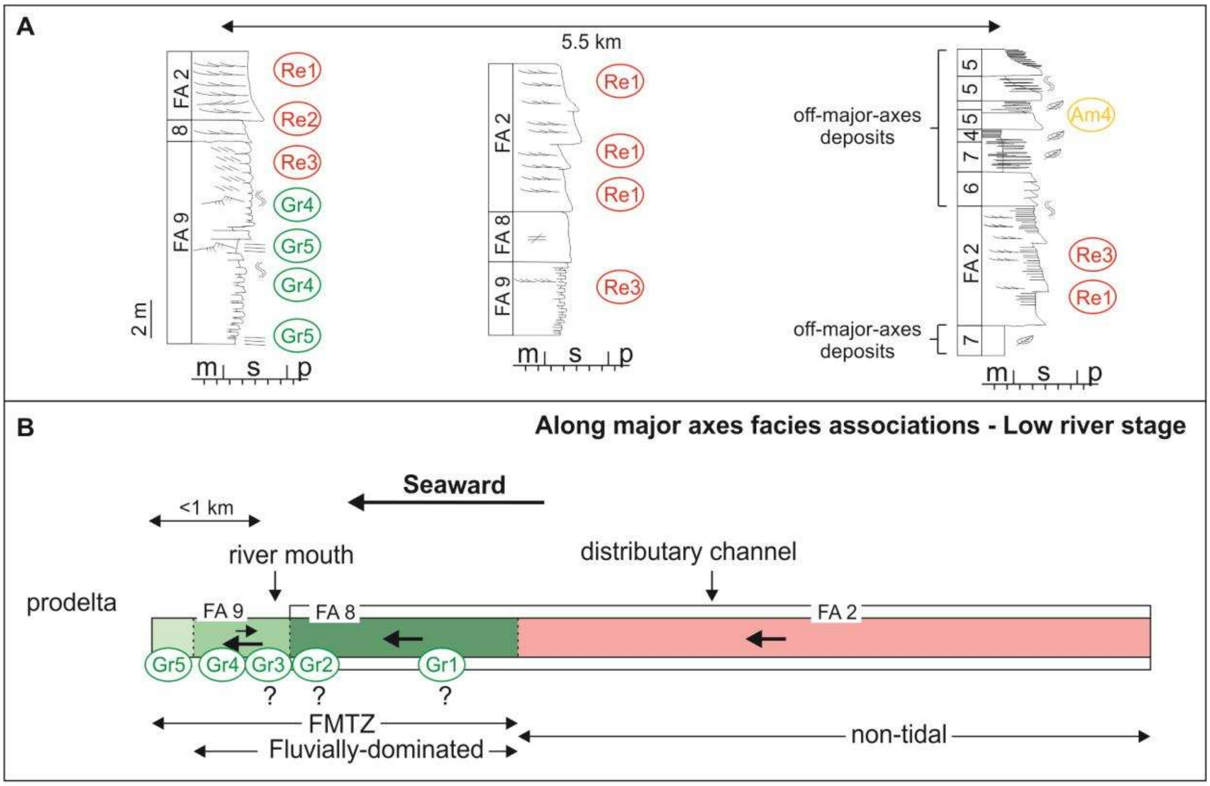

A
5.5 km
FA 2
8
FA 9
Re1
Re2
Re3
Gr4
Gr5
Gr4
Gr5
2 m
m s p
FA 2
FA 8
FA 9
Re1
Re1
Re1
Re3
m s p
off-major-axes deposits
5
5
5
4
7
6
Am4
FA 2
Re3
Re1
off-major-axes deposits
7
m s p
B
Along major axes facies associations - Low river stage
Seaward
<1 km
river mouth
distributary channel
prodelta
FA 9
FA 8
FA 2
Gr5
Gr4
Gr3
Gr2
Gr1
?
?
?
FMTZ
Fluvially-dominated
non-tidal

Figure 12

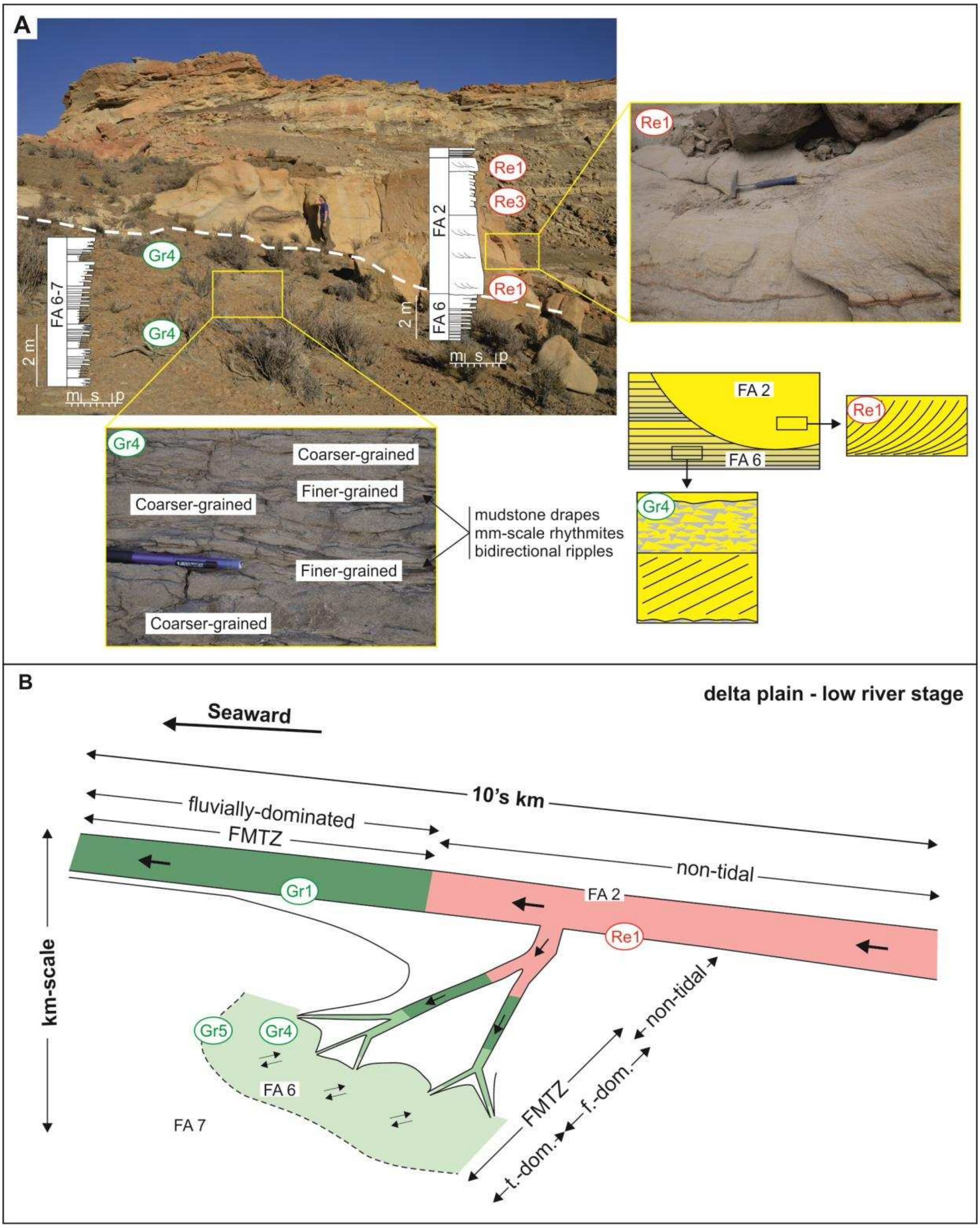

A
Re1
Re3
FA 2
Re1
FA 6
2 m
m s p
Gr4
FA 6-7
Gr4
2 m
m s p
FA 2
Re1
FA 6
Gr4
Coarser-grained
Finer-grained
Coarser-grained
Finer-grained
Coarser-grained
mudstone drapes
mm-scale rhythmites
bidirectional ripples
B
delta plain - low river stage
Seaward
10's km
fluvially-dominated
FMTZ
non-tidal
Gr1
FA 2
Re1
km-scale
Gr5
Gr4
FA 6
FA 7
FMTZ
non-tidal
f.-dom.
t.-dom.

Figure 13

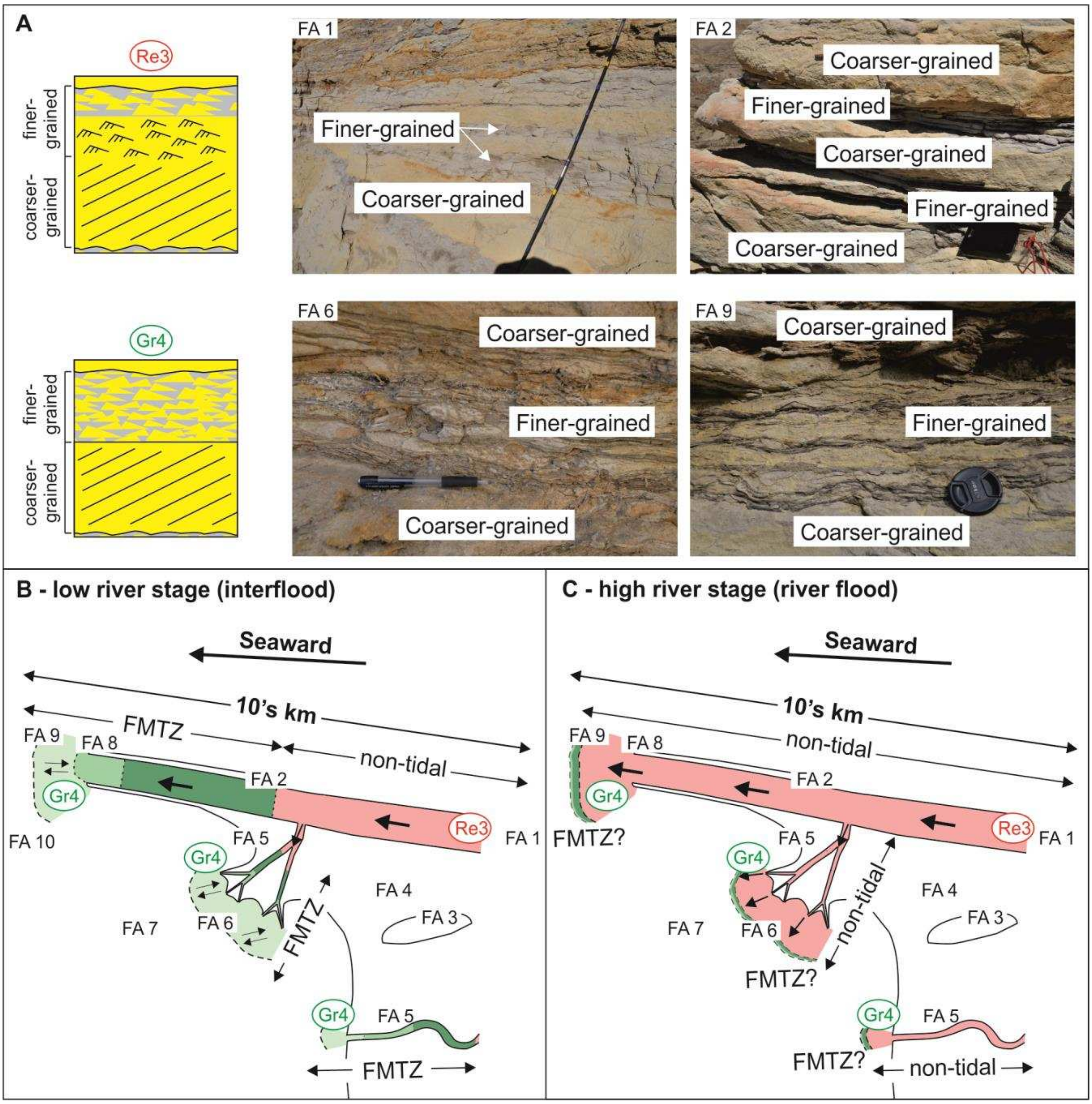

A
Re3
finer-grained
coarser-grained
Gr4
finer-grained
coarser-grained
FA 1
Finer-grained
Coarser-grained
FA 2
Coarser-grained
Finer-grained
Coarser-grained
Finer-grained
Coarser-grained
FA 6
Coarser-grained
Finer-grained
Coarser-grained
FA 9
Coarser-grained
Finer-grained
Coarser-grained
B - low river stage (interflood)
Seaward
10's km
FMTZ
non-tidal
FA 9
FA 8
FA 2
Gr4
Re3
FA 1
FA 10
FA 5
Gr4
FA 4
FA 3
FA 7
FA 6
FMTZ
Gr4
FA 5
FMTZ
C - high river stage (river flood)
Seaward
10's km
non-tidal
FA 9
FA 8
FA 2
Gr4
Re3
FA 1
FMTZ?
FA 5
Gr4
non-tidal
FA 4
FA 3
FA 7
FA 6
FMTZ?
Gr4
FA 5
FMTZ?
non-tidal

Figure 14

FA	Architecture	Size	Lithology	Main sedimentological features	Trace fossils	BI
FA 1: Fluvial channel deposits	Lenticular; erosional base; fining- and thinning-upward; extensive lateral accretion	Up 12 m thick; laterally extensive for several hundred metres to over one kilometre	Sandstone; pebbly sandstone	Structureless sandstones; unidirectional, seaward-directed, trough and planar-tabular cross-stratification; coarser- and finer-grained interbedding; non-cyclical carbonaceous drapes	Planolites	0-2
FA 2: Distributary channel deposits	Lenticular; erosional base; fining- and thinning-upward; limited lateral accretion	Up 8 m thick; laterally extensive up several hundred metres	Sandstone; heterolithic	Structureless sandstones; unidirectional, seaward-directed, trough and planar-tabular cross-stratification; coarser- and finer-grained interbedding; cyclically-distributed and non-cyclical carbonaceous drapes	Planolites and Dactyloidites	0-3
FA 3: Abandoned channel deposits	Lenticular; erosional base; fining- and thinning-upward; lateral accretion	Up 12 m thick; laterally extensive up to tens of metres	Mudstone	Structureless mudstones; horizontal lamination	/	0
FA 4: Floodplain and crevasse-splay deposits	Tabular	Up to several tens of metres thick; laterally extensive for several kilometres	Mudstone; sandstone beds	Multi-coloured poorly sorted, structureless or weakly laminated mudstones; tabular, structureless sandstone beds	Root traces	6
FA 5: Minor distributary channel deposits	Lenticular; erosional base	Up to 1.5 m thick; laterally extensive up to a few tens of metres	Heterolithic; sandstone	Structureless sandstones; unidirectional, seaward-directed, trough and planar-tabular cross-stratification; flaser, wavy and lenticular bedding; coarser- and finer-grained interbedding; cyclically-distributed and non-cyclical carbonaceous drapes; non-cyclical mudstone drapes	Planolites and Dactyloidites	0-2
FA 6: Crevasse mouth bar deposits	Lobate; coarsening- and thickening-upward; forward accretion	Up to 2 m thick; laterally extensive up to hundreds of metres	Sandstone; heterolithic	Coarser- and finer-grained interbedding; unidirectional, seaward-directed, trough and planar-tabular cross-stratification; unidirectional and bidirectional ripples; cyclically-distributed and non-cyclical mudstone drapes	Dactyloidites, Palaeophycus, Teichichnus, Planolites and Thalassinoides	0-6
FA 7: Interdistributary-bay mudstones	Tabular	Up to several m thick; laterally extensive up to hundreds of metres	Mudstone	Structureless blue to grey mudstones with sandstone and coarse siltstone thin layers	Rosselia, Palaeophycus, Planolites and Skolithos	5-6
FA 8: Terminal distributary channel deposits	Lenticular; erosional base; fining- upward	Up to 3 m thick; laterally extensive up to a few tens of metres	Sandstone; heterolithic	Structureless sandstones; unidirectional, seaward-directed, trough cross-stratification; landward-directed ripples; cyclically-distributed carbonaceous drapes	Ophiomorpha and Planolites	0-5
FA 9: Mouth bar deposits	Lobate; coarsening- and thickening-upward; forward accretion	Up to 12 m thick; laterally extensive up to hundreds of metres	Sandstone; heterolithic	Coarser- and finer-grained interbedding; unidirectional, seaward-directed, trough and planar-tabular cross-stratification; unidirectional and bidirectional ripples; cyclically-distributed and non-cyclical mudstone drapes	Ophiomorpha, Thalassinoides and Planolites	0-6
FA 10: Prodelta mudstones	Tabular	Up to several tens of m thick; laterally extensive up to several kilometres	Mudstone	Structureless blue to grey mudstones with sandstone and coarse siltstone thin layers	Rosselia, Rhizocorallium?, Palaeophycus, Planolites and Skolithos	5-6
FA 11: Transgressive and abandonment deposits	Tabular; sharp base and top	Up to 1.5 m thick; laterally extensive up to several kilometres	Sandstone; shell-bed	Hummocky cross-stratification; dune-scale bedforms; shell-beds	Gastrochaenolites (on shells)	0