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STRATIGRAPHIC RECORD OF RIVER-DOMINATED CREVASSE SUBDELTAS WITH TIDAL INFLUENCE (LAJAS FORMATION, ARGENTINA)

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ABSTRACT: **Crevasse subdeltas develop on modern river-dominated delta plains, and may be affected by the interaction of river currents and marine processes. However, their sedimentology and stratigraphic architecture is poorly constrained, leading to simplistic depositional models of delta-plain systems in the ancient record. Extensive exposures of the Middle Jurassic Lajas Formation permit the architecture, main stratigraphic surfaces, and lateral and vertical facies variations of crevasse subdelta deposits to be constrained. Lower-delta-plain successions studied in the Lajas Formation consist of up to 5-m-thick distributary channels and interdistributary-bay deposits, interpreted as crevasse subdeltas. Crevasse subdelta deposits consist of small-scale lenticular units (~ 1–2 m thick) interpreted as crevasse channels and upward-coarsening and upward-thickening packages (~ 2 m thick) with clinothems interpreted as crevasse mouth bars. These deposits preserve interbedding of coarser and finer sediments that are interpreted as river flood and interflood couplets associated with variations in river discharge. River flood beds are commonly structureless and erosionally based, and show little evidence of tidal action and brackish-water conditions. Interflood deposits show rhythmically distributed mudstone drapes, bimodality, and brackish trace fossils. This study highlights an important but largely undocumented component of interdistributary deposits consisting of tide-influenced, but strongly river-dominated, prograding depositional bodies. An implication is that some coarsening-upward, forward-accreting units previously interpreted from the rock record as interchannel "tidal bars" may instead represent minor mouth bars of tide-influenced crevasse subdeltas. Furthermore, present-day crevasse subdeltas are restricted to river-dominated delta systems that flow into semi-enclosed or enclosed seas and lakes with microtidal conditions and limited wave action, which is comparable to paleogeographic reconstructions for the Neuquén Basin during the Middle Jurassic.**

INTRODUCTION

Depositional styles of deltas have been widely studied in the modern because they are highly populated areas with elevated flood risks (Syvitski et al. 2005; Goodbred and Saito 2012), and in ancient systems because they can form excellent subsurface hydrocarbon reservoirs (Morse 1994; Slatt 2006). Deltaic successions are regressive, and show a distributive channel system and well-developed subaqueous clinoforms (Bhattacharya 2010). Detailed facies models (Miall 1976; Elliott 1986; Bhattacharya 2006, 2010) have been developed for a range of delta systems, which attempt to capture the geomorphology, depositional architecture, and grain-size distribution of ancient deltaic successions, and in particular the interplay of fluvial, tidal, and wave processes (Wright and Coleman 1973; Coleman and Wright 1975; Galloway 1975; Orton and Reading 1993). The interaction of these three process regimes and relative sea-level changes control the morphology of deltas and adjacent shallow-marine coastal environments (Boyd et al. 1992; Dalrymple et al. 1992; Ainsworth et al. 2008; Ainsworth et al. 2011).

Many studies of ancient deltaic deposits have focused on sedimentary facies and depositional architecture of the delta-front area (Mutti et al. 2000; Olariu and Bhattacharya 2006; Edmonds and Slingerland 2007; Enge et al. 2010) while delta-plain deposits have received less attention, in part because they are commonly fine-grained and poorly exposed, and also due to many ancient delta successions being top-truncated during transgressive phases (Bhattacharya 2006). An important component of delta-plain successions are subdeltas, which build into marine, brackish, or fresh permanent water bodies such as bays, lagoons, and lakes (Elliott 1974). This results in a hierarchy of elements in the stratigraphic record of ancient delta systems (Bhattacharya 2010). Crevasse subdeltas, which are a particular type of these minor systems, have significantly lower discharge compared with larger deltas; however, the presence of numerous synchronous small systems can result in a cumulative large volume of dispersed sediments. The understanding of preserved delta-plain deposits is therefore important for accurate reconstruction of sediment dispersal patterns and related geometries of depositional bodies in delta-plain settings, thus refining geological models for the larger delta. Extensive outcrops up to 10 km long of the Middle Jurassic Lajas Fm, Neuquén Basin, Argentina, facilitate the study of the distribution of sedimentary facies and depositional styles in an ancient lower-delta-plain succession. The objectives of this contribution are to better understand the sedimentology and depositional architecture of the component crevasse subdelta systems in the Lajas Formation, thus extending current facies models for such systems. Specific research questions addressed here are: 1) what are the key recognition criteria to help identify mixed energy

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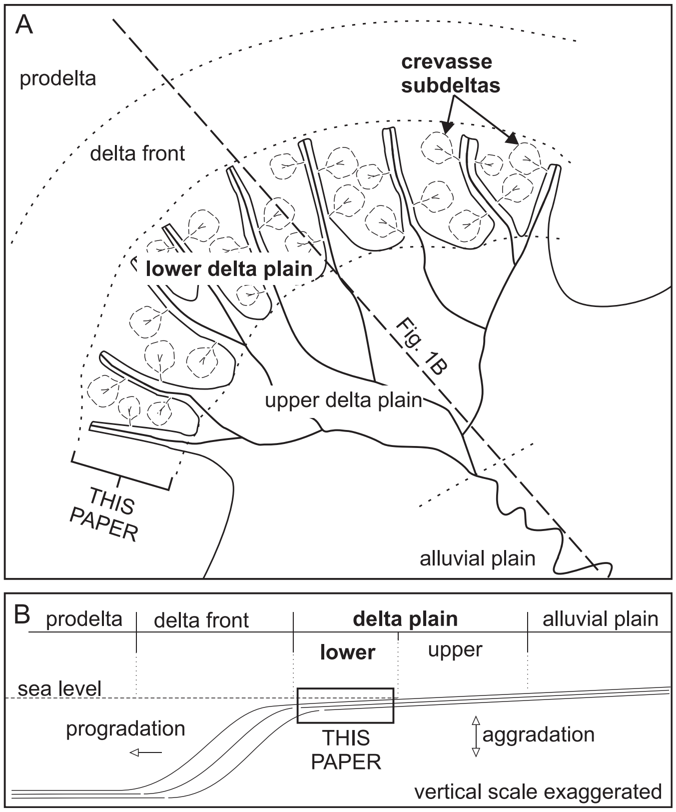

FIG. 1.—**A)** Schematic subdivision of delta environments in map view and **B)** vertical profile differentiating mainly aggradational (delta plain) and progradational (delta front) parts. The delta plain is divided into upper and lower sections, and the depositional processes occurring in the lower delta plain are the main focus of this paper.

crevasse subdelta deposits in ancient systems and 2) what are the roles of tidal processes and variations in river discharge in building the architecture of crevasse subdeltas?

DELTA PLAINS AND CREVASSE SUBDELTAS

Delta plains are extensive lowland areas that comprise active and abandoned channels showing a distributive planform pattern with net sediment transport toward the delta-front area (Coleman and Prior 1982; Reading and Collinson 1996; Bhattacharya 2006, 2010). The delta plain is dominated by interdistributary areas that, although they may be affected by a range of different processes, are usually a lower-energy environment in comparison to distributary channels. The delta plain is commonly subdivided into upper and lower delta plains (Fig. 1), which are separated by the landward limit of marine processes (Coleman and Prior 1982). The upper delta plain is largely fluvial, with some minor tidal influence possible in channel fills, and is characterized by extensive floodplains with possible fresh-water lakes and peat mires. The lower delta plain is usually of mixed energy and process regime since it is still affected by river currents, but also by wave and/or tidal currents, depending on the system. However, wave energy is usually low and restricted to local waves and exceptional storm events because delta plains are typically protected from offshore waves by a beach-barrier shoreline or a dissipative delta-front (Reading and Collinson 1996). In systems with significant tidal range, tidal currents can reach hundreds of kilometers up the distributary channels or develop "blind" tidal channels (Dalrymple and Choi 2007; Goodbred and Saito 2012).

Literature on ancient crevasse-subdelta deposits is almost solely restricted to the Carboniferous of the United Kingdom and Eire (Fielding 1984, 1987; Pulham 1989) and in modern systems limited to the Mississippi Delta (Coleman and Gagliano 1964; Arndorfer 1973; Tye and Kosters 1986; Tye and Coleman 1989; Roberts 1997). Many terms have been proposed to describe these kinds of systems: interdistributary-bay sequences (Elliott 1974; Pulham 1989), crevasse-initiated minor delta systems or complexes (Fielding 1984, 1987), crevasse deltas or crevasse delta systems (Fielding 1984, 1987; Bhattacharya 2006), minor deltas or minor delta systems (Fielding 1984, 1987), crevasse subdeltas (Bhattacharya 2006, 2010), and subdeltas (Coleman and Gagliano 1964; Roberts 1997). Moreover, when these systems flow into fresh-water lakes they are termed lacustrine deltas (Fielding 1984; Tye and Coleman 1989), although not all lacustrine deltas are crevasse-initiated. Here, the term crevasse subdelta is preferred because it highlights the three pertinent features of these systems: 1) they are smaller systems (in area, thinner, and relatively short-lived) compared with the entire delta; 2) they are a subordinate hierarchical feature of the main delta, and 3) they are initiated by crevasse-splay processes.

GEOLOGICAL BACKGROUND

The Neuquén Basin is an important hydrocarbon-producing sedimentary basin (Zambrano and Yrigoyen 1995) located in central-western Argentina and extending into east-central Chile, between 32° S and 40° S latitude (Fig. 2A). It covers more than 137,000 km^2 (Urien and Zambrano 1994) and extends up to 700 km in a north–south direction and up to 400 km from west to east. It is bounded on its northeastern and southern margins by wide cratonic areas, the Sierra Pintada System and the North Patagonian Massif, respectively, and by a magmatic arc on the active western margin of the Gondwanan–South American Plate (Howell et al. 2005). The tectonic history of the Neuquén Basin consists of three different phases (Fig. 3A). Initial subsidence was due to Late Triassic–Early Jurassic extension (syn-rift phase), followed by a post-rift and back-arc basin phase from the Early Jurassic to the Early Cretaceous and a retro-arc foreland basin configuration from the Late Cretaceous to the early Cenozoic (Howell et al. 2005). The Neuquén Basin contains more than 7 km of Late Triassic to early Cenozoic (Fig. 3A) continental and marine siliciclastic, carbonate, and evaporitic rocks affected by several unconformities that reflect intermittent subsidence and episodes of structural inversion (Vergani et al. 1995). The Lower–Middle Jurassic Cuyo Group (Groeber 1946) represents the first major marine depositional episode, which also marks the development of a single depocenter in the basin (Howell et al. 2005). The Cuyo Group (Fig. 3B) comprises pelagic and hemipelagic mudstone with intercalations of sandy turbidites (Los Molles Formation; Burgess et al. 2000; Paim et al. 2008), overlain by shallow-marine deposits (Lajas Formation; Zavala 1996a; Zavala 1996b; McIlroy et al. 1999; McIlroy et al. 2005) and coarse-grained fluvial channels and mudstone-rich floodplain deposits (Challacó Formation; Veiga 1998, 2002).

The Lajas Fm (Weaver 1931), which is the main subject of this paper, has been investigated over an area of about 100 km^2 approximately 40 km south of the town of Zapala (Fig. 2B). Here the Lajas Fm consists of more than 500 m of sandstone, heterolithic (interbedded and/or interlaminated mudstones and sandstones), and mudstone deposits accumulated in different marginal marine settings during the late Aalenian–Bathonian (Zavala 1996a, 1996b; McIlroy et al. 2005). The Lajas Fm is a highly diachronous lithostratigraphic unit that prograded toward the northwest, resulting in a migration and younging of the whole system toward the center of the basin (Zavala and González 2001; Vicente 2006). The deltaic nature of most of the Lajas Formation has been recognized in many studies (Spalletti 1995; Zavala 1996a, 1996b), although the main processes thought to have controlled the style of the delta are still in debate. More recent works considered the Lajas Fm as a tide-dominated system or a tide-dominated delta (McIlroy et al. 1999;

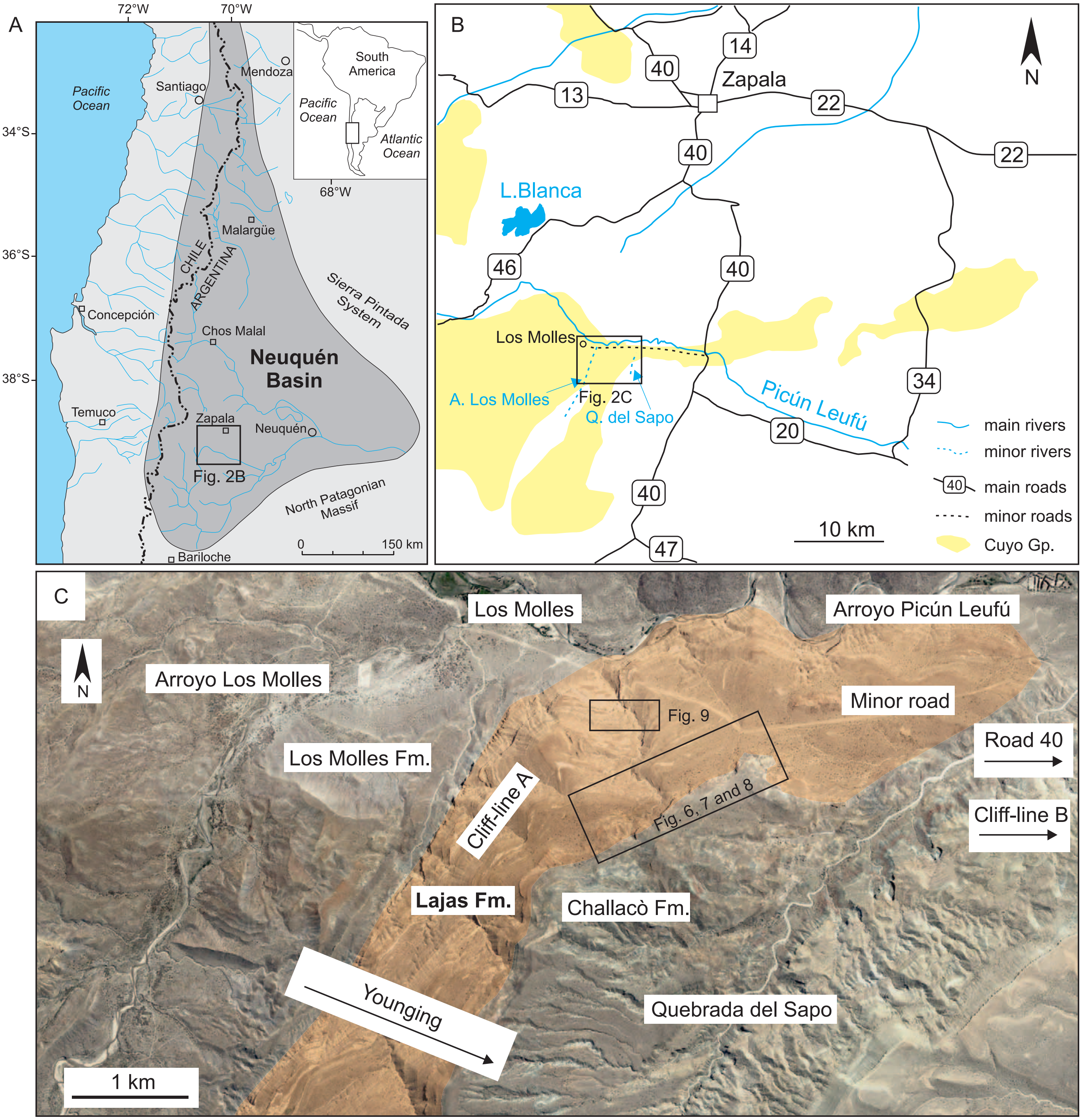

FIG. 2.—**A)** Map of central Argentina–Chile, showing the Neuquén Basin (modified from Howell et al. 2005). **B)** The study area, south of the town of Zapala. Undifferentiated deposits of the Cuyo Group are indicated in yellow. **C)** Satellite image from Google Earth of the study area with the Lajas Fm outcrop indicated in orange.

Brandsaeter et al. 2005; McIlroy et al. 2005; Morgans-Bell and McIlroy 2005; McIlroy 2007; Martinius and Van den Berg 2011). At the time of Lajas deposition the South American Plate was located in a position similar to the present-day configuration (Iglesia Llanos et al. 2006; Iglesia Llanos 2012). The paleoclimate of the area has been interpreted by several palynological studies as warm and mainly arid, but with variable humidity (Quattrocchio et al. 2001; Martinez et al. 2002; Garcia et al. 2006; Stukins et al. 2013), and evidence for wildfires has been reported (Marynowski et al. 2011).

METHODS AND DATASET

The stratigraphy of the Lajas Fm has been investigated along two main cliff-line exposures near the village of Los Molles (Fig. 2C). Cliff line A is

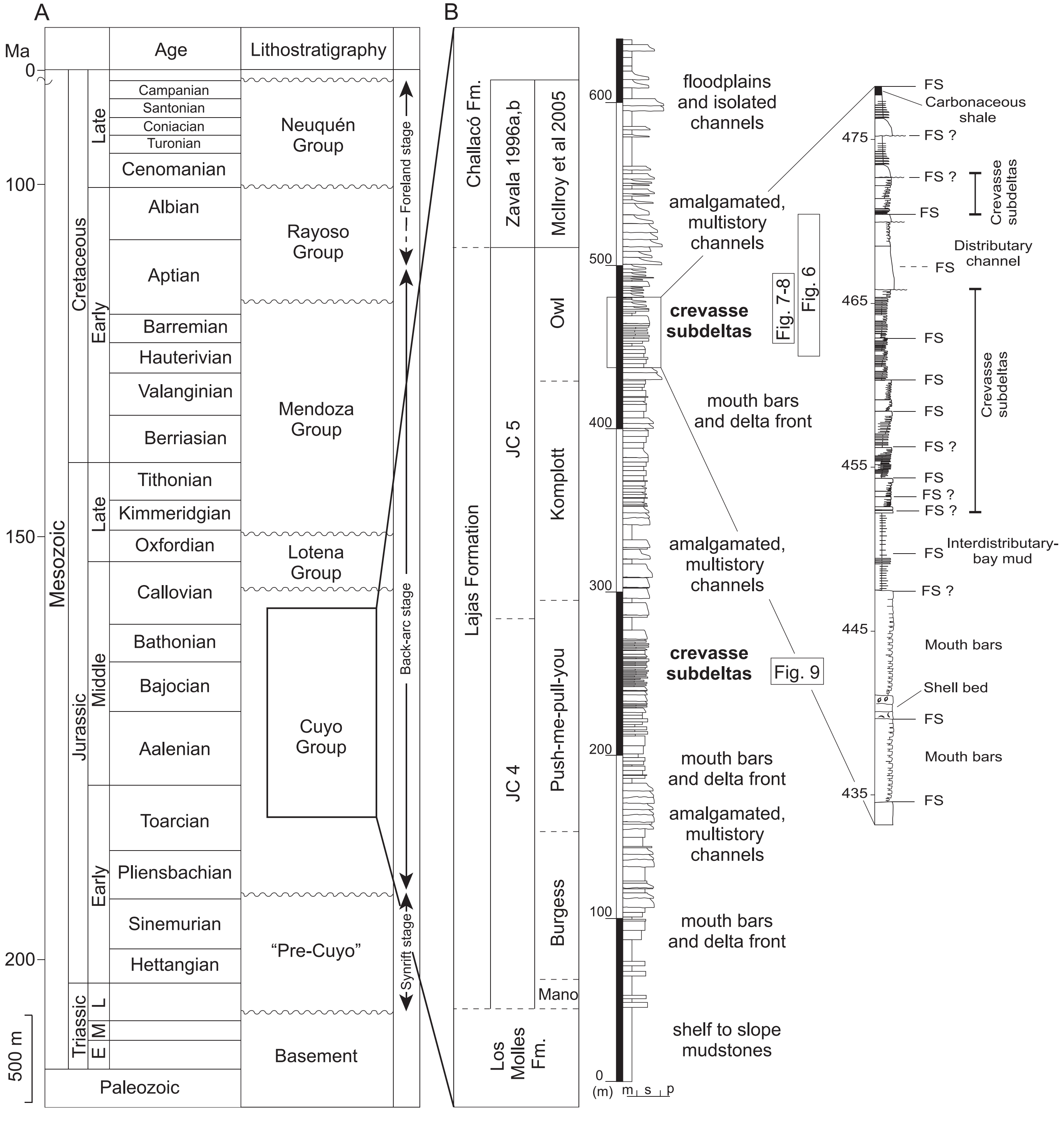

FIG. 3.—**A)** Stratigraphy of the Neuquén Basin with main lithostratigraphic units and tectonic history (modified from Vergani et al. 1995). **B)** Detail of the Cuyo Group with a broad paleoenvironmental interpretation; the two intervals showing lower-delta-plain deposits and crevasse subdeltas are in bold font type. The stratigraphic subdivisions on the left of the column are from Zavala (1996a, 1996b) and McIlroy et al. (2005).

SSW–NNE oriented and provides continuous exposure for about 8 km and cliff line B is E–W oriented and extends for approximately 10 km. Both cliff lines are oriented at an oblique angle to the regional paleoflow, which is broadly toward the NW, but ranges from W to NE. Numerous canyon exposures provide three-dimensional constraints. This paper focuses on deposits of two stratigraphic intervals 30–50 m thick in the middle and upper sections of the Lajas Fm in which deposits of crevasse subdeltas have been recognized (see Fig. 3B). Although the investigation was carried out along both cliff lines, the data presented herein are mainly from the northern part of cliff line A (Fig. 2C). Methods used included the collection of detailed measured stratigraphic sections, integrated with interpreted photopanels in order to capture architecture,

TABLE 1.—*Lower-delta-plain facies associations in the Lajas Formation.*

	Facies Associations	Photos	Thicknesses, Sizes, Geometries, and Trends	Lithology, Grainsize, Sorting, Facies, and Structures	Biogenic Features	Associated With	Interpretation
FA 1	Large-Scale, Erosionally Based, Lenticular Sandstone Units	Fig. 4A	Up to 5 m thick, laterally extensive for hundreds of meters, lenticular, upward fining, with basal and internal erosional surfaces	Yellow, orange, or brown, quartz-rich, fine- to coarse-grained, moderately to well sorted sandstones with mudstone clasts, carbonaceous drapes, silicified wood, carbonaceous and plant debris and rare pebbles, commonly structureless and trough cross-stratified or showing also planar-tabular cross-stratification, horizontal lamination, ripple cross-lamination, trough-like scour and fill, water-escape structures, and soft-sediment deformation	*Planolites* BI 0–1	Erosionally overlies FA 2–7	Distributary channels dominated by unidirectional river currents and with very little tidal influence
		/	1-2 m thick, laterally extensive up to a few tens of meters, tabular, upward-fining and upward-thinning (beds)	Same as above, but coarser-grained sandstones are interbedded with finer-grained sandstones or siltstones at cm to dm scale and show low-angle cross-stratification			Bank-attached, side-bars within distributary channels dominated by unidirectional river currents
FA 2	Small-Scale, Erosionally Based, Lenticular Sandstone Units	Fig. 4B	Up to 2 m thick, laterally extensive up to tens of meters, lenticular and upward fining, with concave-up erosional bases	Yellow, green, or brown, fine- to coarse-grained, muddy, poorly sorted sandstones containing mudstone clasts, sparse granules, silicified wood, carbonaceous and plant debris and rare mudstone drapes. Typically structureless and showing trough cross-stratification, but also planar-tabular cross-stratification and trough-like scour and fill	*Dactyloidites ottoi* BI 0–1	Erosionally overlies FA 4–5	Crevasse channels dominated by unidirectional river currents and with minor tidal influence
FA 3	Tabular Sandstone Units	Fig. 4E	0.1 to 0.4 m thick, laterally continuous up to tens of meters and tabular	Green to brown, poorly sorted, muddy, fine- to coarse-grained sandstones with rare granules, commonly structureless or with planar-tabular cross-stratification, ripple and horizontal cross-lamination	BI 0	Erosionally overlies FA 7 and is overlain by FA 7 or by FA 4–5	Crevasse-splays
FA 4	Small-Scale, Upward-Coarsening Sandstone Units	Fig. 4A, C, E, 9	Up to 1.2 m thick, laterally extensive up to tens of meters, upward coarsening and thickening (beds)	Green to brown, poorly sorted, muddy, fine- to coarse-grained, erosionally based sandstones with sparse pebbles, mudstone clasts, sandy rip-up clasts, silicified wood, carbonaceous and plant debris showing planar-tabular cross-stratification or structureless and interbedded with yellow, clean, well sorted, fine- to medium-grained sandstones with mudstone drapes, bidirectional current ripples, and rare wave ripples	*Dactyloidites ottoi*, *Palaeophycus*, *Planolites*, and *Thalassinoides*, oyster shells with *Gastrochaenolites* borings BI 0–2	Overlies and passes laterally into FA 5. It is usually erosionally overlain by FA 2	Proximal part of crevasse mouth bars dominated by river currents and influenced by tides
FA 5	Small-Scale, Upward-Coarsening Sandy Heterolithic Units	Fig. 4A, B, C, D, E, 9	Up 1.3 m thick, laterally extensive up to tens of meters, upward coarsening and thickening (beds)	Green to brown, poorly sorted, muddy, fine- to medium-grained, erosionally based sandstones with sparse pebbles, mudstone clasts, silicified wood, carbonaceous and plant debris showing planar-tabular cross-stratification, ripple cross-lamination or structureless and interbedded with yellow, clean, well sorted, fine-grained sandstones with mudstone drapes, bidirectional current ripples, and rare wave ripples and with structureless fine- to coarse-grained siltstones	*Dactyloidites ottoi*, *Palaeophycus*, *Planolites*, and *Thalassinoides*, oyster shells with *Gastrochaenolites* borings BI 0–3	Overlies and passes laterally into FA 6. It is usually overlain by and passes into FA 4 or may be erosionally overlain by FA 2	Medial part of crevasse mouth bars dominated by river currents with tidal influence and minor suspension fallout
FA 6	Small-Scale, Upward-Coarsening, Muddy Heterolithic Units	Fig.4A, D, F, G, 9	Up to 0.9 m thick, laterally extensive up to tens of meters, upward coarsening and thickening (beds)	Green to brown, poorly sorted, muddy, fine to medium-grained, erosionally based sandstones usually structureless or mottled, with mudstone clasts and current ripples interbedded with yellow, clean, well sorted fine-grained sandstones with bidirectional current ripples and mudstone drapes and with fine- to coarse-grained siltstones	Undistinguishable trace fossils BI 3–5	Overlies and passes laterally to FA 7. It is usually overlain by and passes into FA 5	Distal part of crevasse mouth bars controlled by river and tidal currents and suspension fallout
FA 7	Massive Mudstones with Sandy Laminae and Thin Shell Beds	Fig. 4E, F	0.5 to 2 m thick, laterally extensive up to hundreds of meters, tabular	Blue to gray mudstones commonly structureless with sandy laminae	Oysters that may show *Gastrochaenolites* borings BI 5–6	It is usually overlain by and laterally passes into FA 6 or may be erosionally overlain by FA 3	Interdistributary bay mud. Mainly controlled by suspension fallout with rare river- and -tidal- derived currents

main stratigraphic surfaces, and lateral and vertical facies variations. More than 50 GPS located sections were logged in detail at 1:50 and 1:25 scale. Facies and facies associations (Table 1) were interpreted in terms of depositional processes and environments of deposition, based on grain size, sorting, sedimentary structures, and presence and character of body and trace fossils.

FACIES ASSOCIATIONS

This paper focuses on the sedimentary facies recognized and interpreted as deposits of the lower delta plain of a large delta system, based on their process sedimentology and stratigraphic context and are grouped into seven facies associations (FA 1 to FA 7; see Table 1). Bioturbation is generally low but highly variable in intensity and is considered in terms of Bioturbation Index (BI; Taylor and Goldring 1993; MacEachern 2010). The related fluvial, upper-delta-plain, delta-front, and prodelta deposits of the main deltaic system, plus shelf and paleovalley deposits, were also studied but are not included herein.

FA 1: Large-Scale, Erosionally Based, Lenticular Sandstone Units

Description.—FA 1 consists of sandstone-prone units, up to 5 m thick (Fig. 4A) and laterally extensive at least for hundreds of meters, with erosional bases and upward-fining profiles. This facies association thickens southward and eastward (both directions are up-dip) up to 12 meters. Sandstones are fine- to coarse-grained and moderately to well sorted and are structureless or cross-stratified. Cross-set thicknesses range from centimeter-scale ripple cross-lamination to decimeter-scale planar-tabular and trough cross-stratification and usually decrease in scale upwards. Paleocurrents are strongly unimodal, broadly toward N or NE. Silicified logs up to 1 m long are found together with plant and carbonaceous debris and rare mudstone clasts. Logs are in some cases still oriented with their long axes in the direction of paleoflow of the channels. Drapes to cross-beds are occasionally present and are composed of terrestrial organic and carbonaceous particles, and are mostly restricted to the bottomsets or cross-set boundaries, but they rarely show rhythmic patterns. Marine body fossils are absent and trace fossils are scarce, consisting of *Planolites* and rare nondistinctive burrows. A subordinate type of FA 1 consists of tabular sandstones 1 to 2 m thick or heterolithic deposits with sharp erosional bases and upward-fining trend. The facies is laterally continuous for tens of meters and passes into main FA 1. Sandstones are organized in layers up to 0.4 m thick that may be interbedded with finer-grained sandstones or siltstones at a centimeter to decimeter scale. Thickness of the sandstones beds decreases upward (upward thinning). The master surfaces typically show low-angle cross-stratification, perpendicular to the orientation of the other cross-stratification.

Interpretation.—Lenticular, sand-prone, erosionally based units with upward-fining profiles are interpreted as distributary-channel fills. The upward-fining trend, together with the upward tendency of decreasing thickness of cross-sets, are symptomatic of upward-waning current velocity which occurs as the channel is gradually filled (Collinson and Lewin 1983; Miall 1996). Sandstones or heterolithic units with low-angle cross-stratification and upward-fining and upward-thinning trends are interpreted as bank-attached side bars rather than point bars because of their limited lateral extent (up to tens of meters). This architecture is consistent with the general case that distributary channels are usually straighter than their fluvial meandering counterparts (Payenberg et al. 2003) and that their deposits have a lower width/thickness ratio (Fielding 1985; Payenberg et al. 2003). The unidirectionality of sedimentary structures suggests river dominance, but rare rhythmic carbonaceous drapes are interpreted as indicating tidally modulated bedforms (Martinius and Gowland 2011) that form in the fluvial to marine transition zone (Dashtgard et al. 2012) and not in purely tidal settings. However, the majority of carbonaceous drapes usually lack rhythmicity consistent with tidal processes (Kvale 2012; Longhitano et al. 2012); thus a tidal origin cannot be inferred (Martinius and Gowland 2011). The presence of silicified logs and carbonaceous and plant debris indicates sediment input from emergent vegetated areas. The trace-fossil assemblage does not constrain paleoenvironmental conditions because *Planolites* can be found in any setting and any salinity (Gérard and Bromley 2008). However, because of the absence of distinctly marine trace fossils or body fossils and the dominance of river current processes, a freshwater environment with possible sporadic brackish-water conditions is inferred.

FA 2: Small-Scale, Erosionally Based, Lenticular Sandstone Units

Description.—Facies association 2 consists of lenticular, erosionally based sandstones up to 2 m thick (Fig. 4B) and laterally extensive up to a few tens of meters. FA 2 is composed of fine- to coarse-grained sandstones, which are usually poorly sorted and relatively muddy and contain rare granules, abundant mudstone clasts, and rare continuous mudstone drapes 1–2 mm thick. FA 2 is usually structureless or trough-cross-stratified with occasional trough-like scours up to 0.5 m deep filled with cross-bedded sandstone. Paleocurrents are commonly unimodal and are oriented at a high angle to the main ones from FA 1. Trace-fossil content is generally low (BI 0–1), consisting of *Dactyloidites ottoi*, which is usually concentrated in distinctive layers. Sparse pieces of silicified wood up to 0.30 m long, and carbonaceous and organic debris, are found.

Interpretation.—FA 2 is interpreted as the fills of minor channels of the distributive system, specifically crevasse channels. FA2 is distinct from FA1 in sedimentary facies and architecture in a number of ways. The channels are considerably smaller (~ 1–2 m thick versus 5 m thick) and consist of less well-sorted sandstone. The lower degree of sorting is attributed to the shorter length of transport, the local erosion of muddy distributary banks, and the higher variation in discharge leading to preservation of a mud matrix in the sandstones of crevasse-channel fills. Trough cross-bedding, trough-like scours, and abundant mudstone clasts indicate relatively high energy and erosive capacity. Paleocurrents show a unidirectional prevalence, indicating river dominance. Scarcity of mudstone drapes and absence of bidirectionality suggest only weak tidal action, but higher than in FA 1. The *Dactyloidites ottoi* trace fossil is associated with reduced salinity and episodic sedimentation (Agirrezabala and de Gibert 2004).

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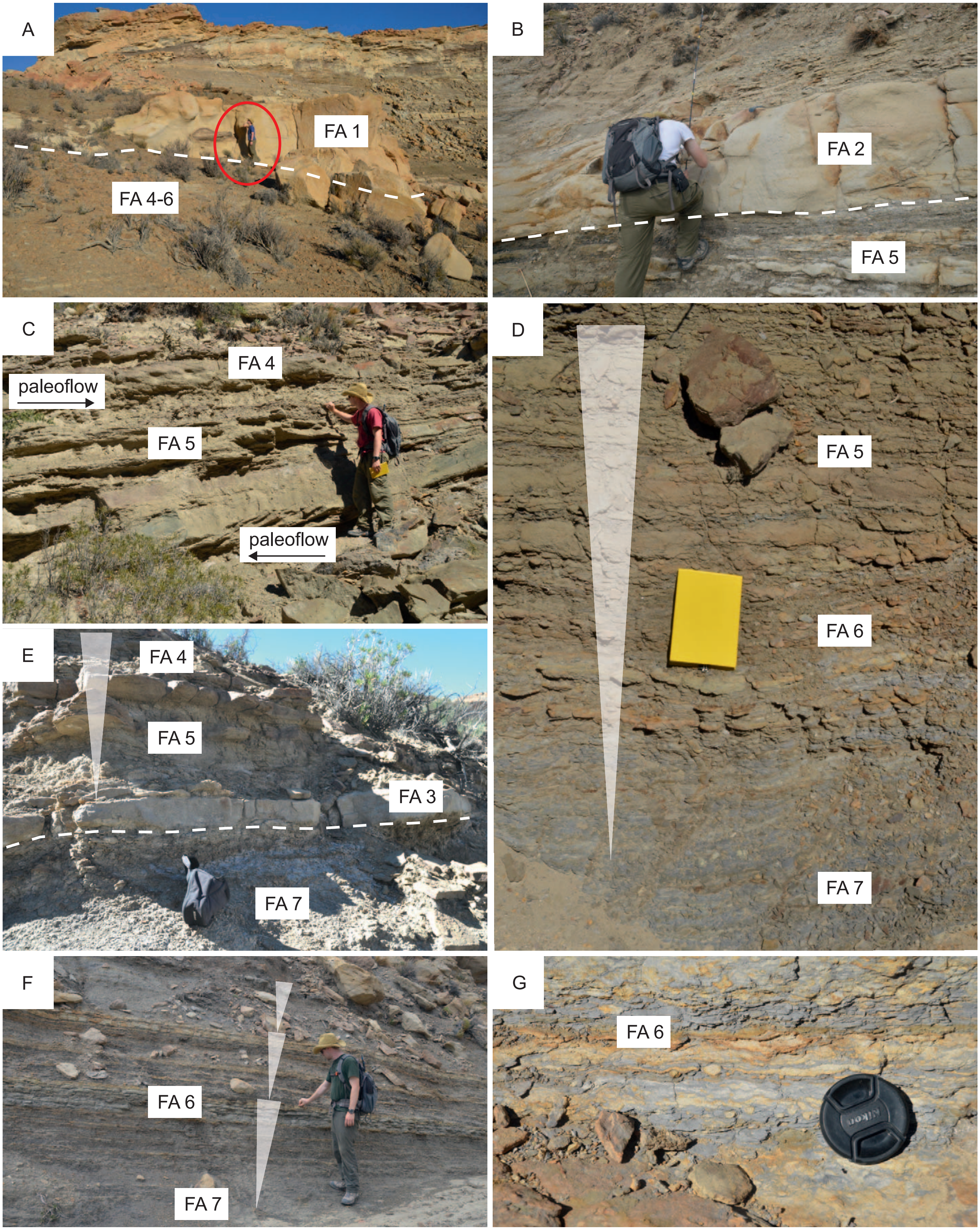
FIG. 4.—Representative photographs of facies associations: **A)** distributary channel deposits (FA 1) cutting into crevasse mouth bars (FA 4–6). Person is approximately 1.75 m tall. **B)** Crevasse channel (FA 2), ~ 1 m thick, cutting into crevasse mouth bar facies (FA 5). Person is approximately 1.75 m tall, and marked spacing on the logging pole is 0.10 m. **C)** Proximal to medial crevasse mouth bars (FA 4–5). Arrows indicate paleocurrents (note that the apparent bidirectionality is a result of different orientation of individual crevasse subdeltas and is not a tidal indicator). Person is approximately 1.75 m tall. **D)** Almost complete succession of a crevasse mouth bar showing a gradual coarsening-upward trend from FA 7 to FA 5. Notebook is approximately 0.20 m long. **E)** Initial crevasse splay (FA 3) overlying massive mudstone (FA 7) and overlain by crevasse mouth bar deposits (FA 4–5). Camera case is approximately 0.20 m long. **F)** Distal part of crevasse mouth bar (FA 6) overlying crevasse prodelta deposits (FA 7). Person is approximately 1.75 m tall. **G)** Detail of mottled facies of FA 6. Lens cap is 52 mm in diameter.


A
FA 1
FA 4-6
B
FA 2
FA 5
C
FA 4
paleoflow
FA 5
paleoflow
D
FA 5
FA 6
FA 7
E
FA 4
FA 5
FA 3
FA 7
F
FA 6
FA 7
G
FA 6

FA 3: Tabular Sandstone Units

Description.—Facies association 3 consists of tabular sandstone bodies up to 0.40 m thick that extend for only a few tens of meters (Fig. 4E). These bodies have sharp, slightly erosional bases and consist of one to several decimeter-scale beds. FA 3 has a variable vertical profile with no clear upward thickening or thinning trend. The main sedimentary facies consist of structureless, poorly sorted, muddy, fine- to coarse-grained sandstones with sparse granules. Rare planar-tabular cross-stratification or ripple and horizontal cross-lamination are observed, and some sparse plant and carbonaceous debris is present, but no body or trace fossils.

Interpretation.—These tabular, sharp-based, and laterally discontinuous sandstones are interpreted as crevasse-splay deposits. They can consist of a single or several associated splays, but the lack of any clear trends, unlike in FA 4–6, suggests sporadic deposition. The structureless, poorly sorted, and mud-rich nature of the deposits is interpreted as due to local substrate entrainment and rapid deposition, but traction currents are sometimes recorded by planar-tabular cross-stratification or ripple cross-lamination.

FA 4: Small-Scale, Upward-Coarsening Sandstone Units

Description.—Facies association 4 consists of fine- to coarse-grained sandstones, up to 1.20 m thick, with high matrix mud content (poorly sorted) and rare, sparse pebbles that are laterally extensive up to tens of meters. Decimeter-scale beds show planar-tabular cross-stratification or are structureless (Fig. 4C) with slightly erosional bases and mudstone clasts. A less common facies consists of clean, well-sorted, fine-grained sandstone beds up to 0.20 m thick, containing abundant 1–2-mm-thick mudstone drapes, asymmetric ripples showing opposed paleocurrents (Fig. 5), and rare symmetric ripples. FA 4 shows an upward-coarsening trend and an upward-thickening trend of the erosionally based beds. Trace fossils consist of *Dactyloidites ottoi*, *Paleophycus*, *Planolites*, and *Thalassinoides*, and their concentration is variable (BI 0–2). Body fossils consist of rare oyster shells with *Gastrochaenolites* borings. Sparse pieces of silicified wood and carbonaceous and organic debris are found.

Interpretation.—The upward-coarsening trend and dominance of unidirectional sedimentary structures is typical of prograding mouth bars, but the vertical scale of the facies association suggests a small-scale system compared to a major delta (major mouth bars are typically 5–6 meters and maximum 10 meters thick; Fig. 3); thus FA 4 is interpreted as the proximal part of a crevasse mouth bar and supports the establishment of a small delta system rather than single splays of FA 3. Sandstones are poorly sorted and contain mud, suggesting rapid deposition and high water turbidity. The prevalence of planar-tabular cross-stratification rather than trough cross-stratification suggests a lower current velocity compared with FA 2, although the energy was high enough for the substrate to be entrained, as shown by the erosional bases of beds and the presence of mudstone clasts and mud-rich matrix. This reduction of flow velocity may be associated with the transition from channelized and confined (FA 2) to unconfined settings that typically occurs at the transition from channel to mouth bar (Wright 1977; Olariu and Bhattacharya 2006). The erosionally based beds with abundant mudstone clasts are interpreted as the deposits of river floods during high river discharge. The clean sandstones with mudstone drapes, rhythmicity, and bimodality of asymmetric ripples are interpreted to have been transported during the late stages of river floods and reworked by tidal currents during interflood periods at low river stages. Weak wave action is indicated by the presence of symmetric ripples. Presence of oysters, *Gastrochaenolites* borings, *Paleophycus*, and *Thalassinoides* indicate that brackish-water conditions were established occasionally in this area, probably during periods of low river discharge.

FA 5: Small-Scale, Upward-Coarsening, Sandy Heterolithic Units

Description.—Facies association 5 consists of up 1.30 m thick, laterally extensive up to tens of meters, heterolithic, but predominantly sandy deposits (Fig. 4B–E). The sandy portion is composed of fine- to medium-grained, poorly sorted, muddy, sandstone with rare granules. The muddy part consists of beds of structureless siltstone 0.01–0.10 m thick. Sandstone layers are up to 0.40 m thick, showing an upward-thickening trend; they usually have a weakly erosional base rich in mudstone clasts. These sandstones are commonly structureless, but they may show planar-tabular cross-stratification and ripple cross-lamination. A second facies consists of clean, well-sorted, fine-grained sandstones up to 0.20 m thick with abundant rhythmical mudstone drapes, bidirectional current ripples (Fig. 5), and rare symmetric ripples and are regularly interbedded with the main FA 5 deposits. Trace fossils consist of rare *Dactyloidites ottoi*, *Paleophycus*, *Planolites*, and *Thalassinoides* (BI 0–3). Body fossils consist of rare oyster shells with *Gastrochaenolites* borings. Sparse pieces of silicified logs and carbonaceous and organic debris are found.

Interpretation.—These sandstone-rich heterolithic packages with upward-coarsening and upward-thickening trends are interpreted as the medial portion of crevasse mouth bars. The poorly sorted, muddy sandstones suggest rapid deposition and turbid water. The regularly spaced beds with erosional bases and abundant mudstone clasts are interpreted as the deposits of river floods (high river stage), and the clean sandstones are interpreted as interflood deposits (low river stage). Rhythmic mudstone drapes and ripple-scale bidirectionality in the interflood deposits indicate tidal processes, and a weak wave action is indicated by symmetric ripples. As for FA 4, the presence of trace fossils, oysters, and borings suggest temporarily brackish-water conditions.

FA 6: Small-Scale, Upward-Coarsening, Muddy Heterolithic Units

Description.—Facies association 6 consists of up to 0.90 m thick, laterally extensive up to tens of meters, mud-rich heterolithic deposits with upward-coarsening and upward-thickening trends (Fig. 4F). The mudstone portion consists of structureless, usually mottled (Fig. 4G), fine- to coarse-grained siltstones with vertical and horizontal, small, indistinguishable trace fossils (BI 3–5). The sandy portion is composed of fine- to medium-grained, poorly sorted, muddy, sandstone beds 0.02 to 0.20 m thick, erosionally based, structureless, and rich in mudstone clasts or clean, well-sorted, fine-grained sandstones with abundant mudstone drapes and bidirectional asymmetric ripples, but the interbedding is not as easily distinguishable as for FA 5.

Interpretation.—Mudstone-rich heterolithic packages are interpreted as distal parts of crevasse mouth bars. The thickness of river-flood beds is less than in the medial and proximal portions, and the sands are finer and significantly less abundant than mudstone. The fine grain size and low sandstone content is thought to reflect transport to this distal part of the system. The effect of tides is recorded by reworking of sandstones, bidirectional current ripples, and mudstone drapes. The higher bioturbation index is indicative of relatively long periods of brackish-water conditions and lower sedimentation rates than the proximal parts. Salinity is interpreted as relatively high during low river stage because of the high bioturbation index, but probably almost freshwater conditions were still present during high river stage.

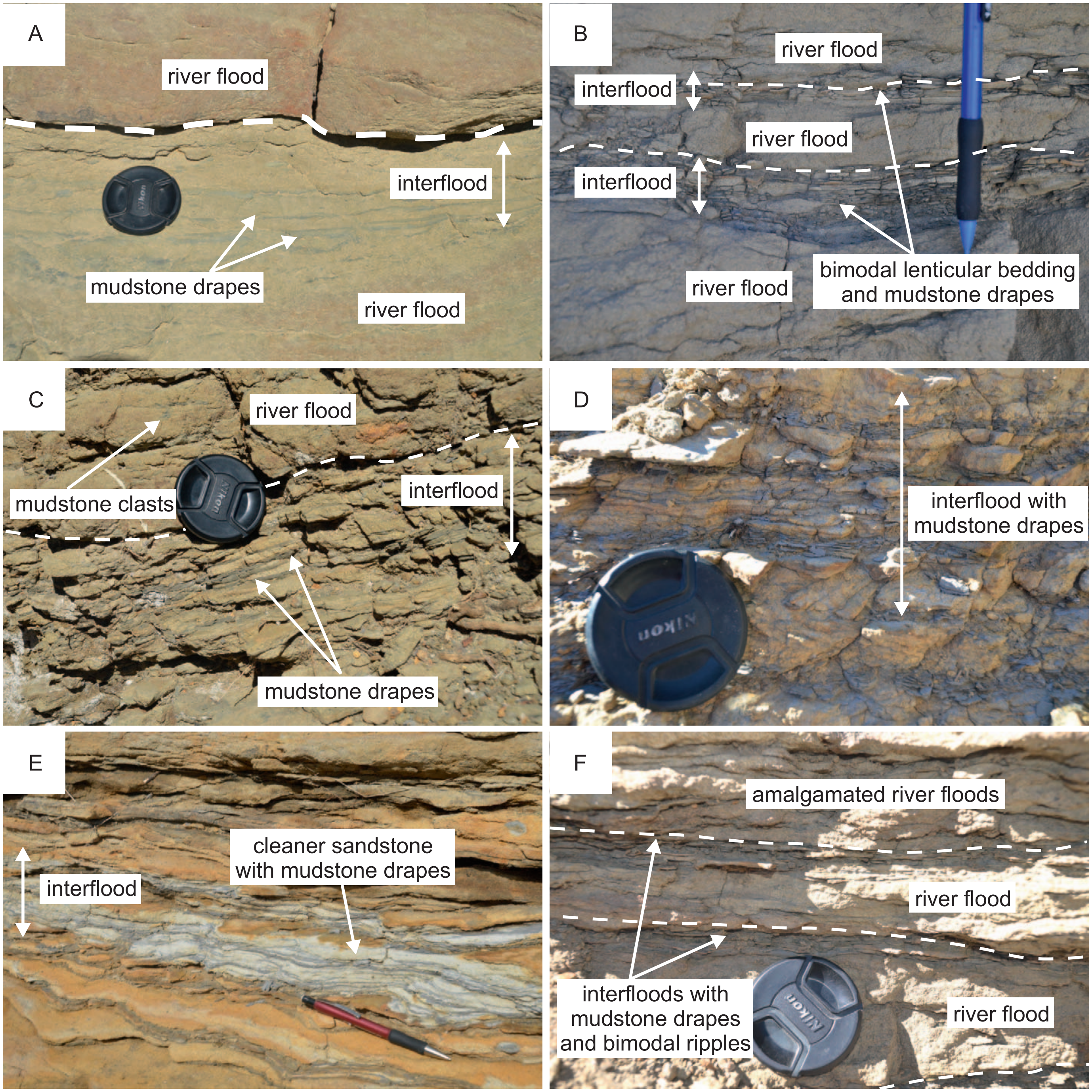


FIG. 5.—Representative photographs of tidal facies in interflood of FA 4–6, showing rhythmically distributed mudstone drapes and bidirectional current ripples. Note that river flood deposits usually lack tidal indicators. Lens cap is 52 mm in diameter, and pencil is about 0.10 m long.

FA 7: Massive Mudstones with Sandy Laminae and Thin Shell Beds

Description.—Facies association 7 consists of 0.50 to 2 m thick, laterally extensive up to hundreds of meters, tabular, blue to gray mudstones with grain size ranging from clay to fine-grained silt and lacking any internal structures (Fig. 4F). Sandstone and coarse siltstone layers from a few millimeters to 0.10 m thick may be present along with shell-beds, 0.10 to 0.30 m thick, composed mainly of oysters that show *Gastrochaenolites* borings.

Interpretation.—FA 7 is interpreted as interdistributary-bay mudstone deposits rather than open-shelf offshore mudstones because of the stratigraphic position, the lateral facies associations with FA 1 to FA 6, and the lack of open marine indicators, such as pelagic fauna or carbonates. FA 7, deposited mainly from suspension fallout away from the main distributary channels and in the distal part of the crevasse subdelta system. Thin sandstone beds and coarse siltstone beds are related to rare, episodic depositional events marking exceptional river discharges. The lack of lamination is probably due to complete or almost complete

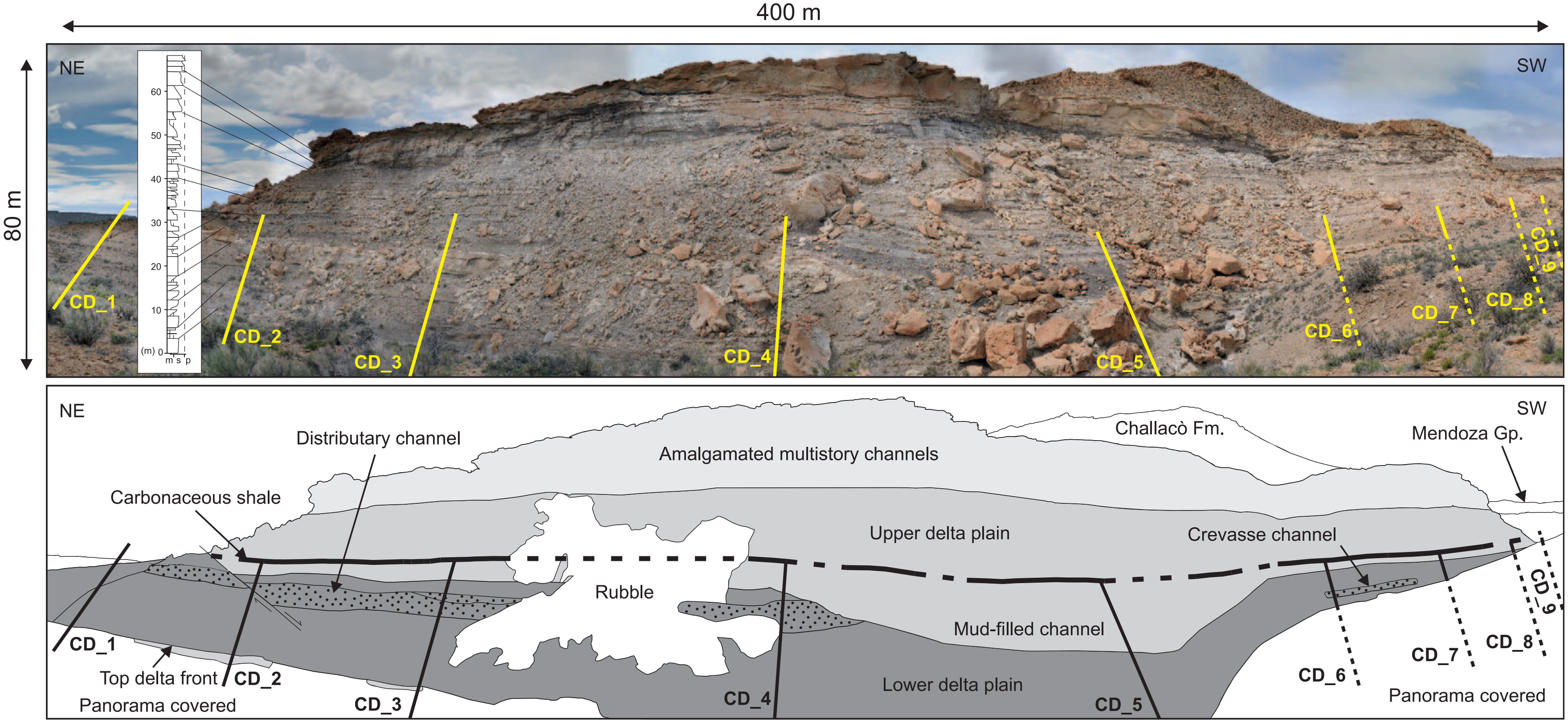


FIG. 6.—**A)** Bajada de los Molles outcrop and **B)** interpretation showing the upper part of the Lajas stratigraphy and the position of the measured sections. See location and stratigraphic context in Figures 2C and 3B.

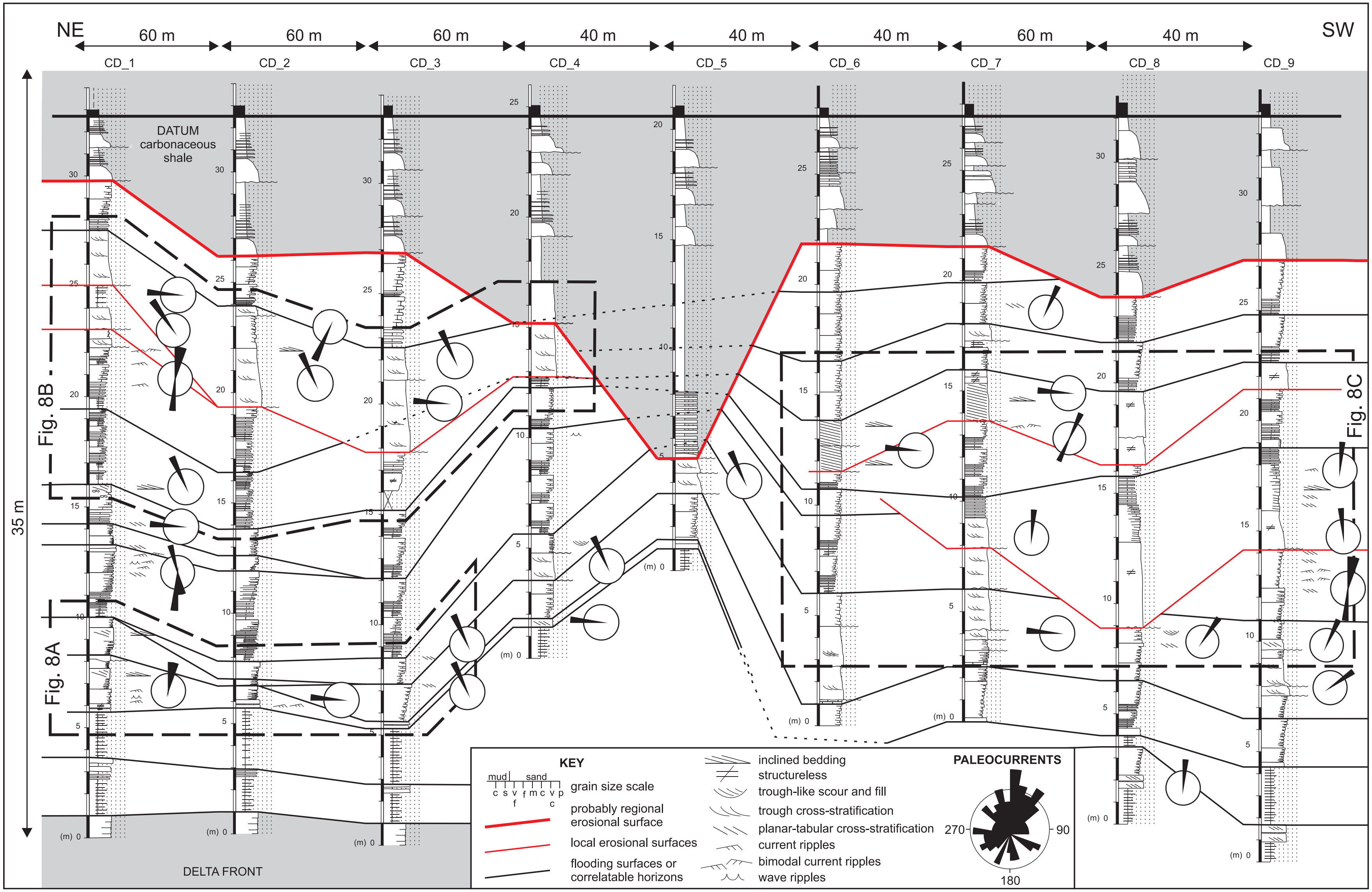
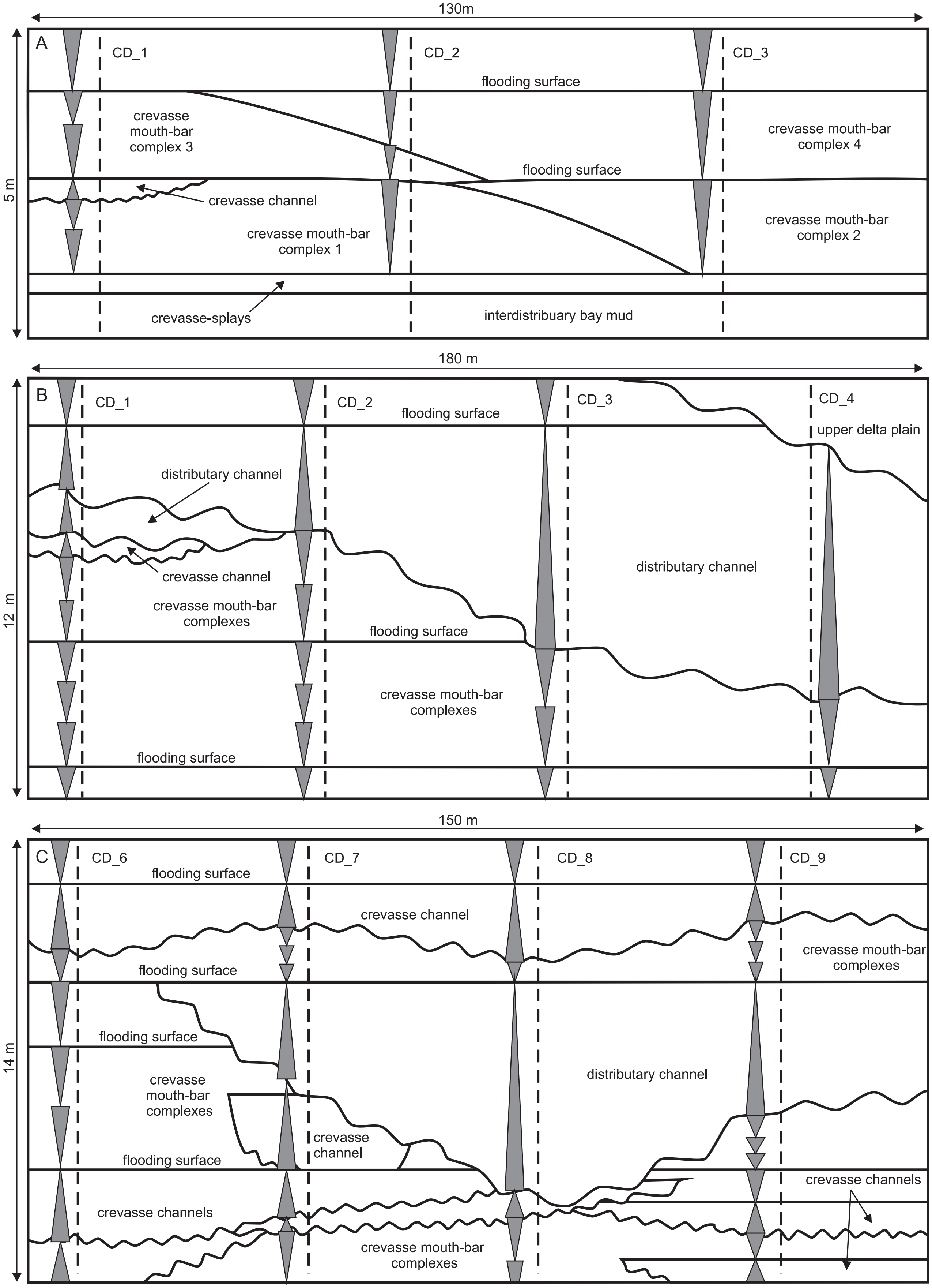


FIG. 7.—Correlation panel of the upper part of the Bajada de los Molles with nine measured sections and associated sedimentary structures and paleocurrents. See locations of logs in Figure 6. The studied lower-delta-plain stratigraphic interval is well constrained by delta-front deposits (underneath) and upper-delta-plain deposits (above). A laterally continuous carbonaceous shale (datum) and several other key horizons provide correlatable surfaces, which are shown with black lines.


130m
A
CD_1
CD_2
CD_3
flooding surface
crevasse mouth-bar complex 3
crevasse mouth-bar complex 4
flooding surface
crevasse channel
crevasse mouth-bar complex 1
crevasse mouth-bar complex 2
crevasse-splays
interdistributary bay mud
5 m
180 m
B
CD_1
CD_2
CD_3
CD_4
flooding surface
upper delta plain
distributary channel
crevasse channel
distributary channel
crevasse mouth-bar complexes
flooding surface
crevasse mouth-bar complexes
flooding surface
12 m
150 m
C
CD_6
CD_7
CD_8
CD_9
flooding surface
crevasse channel
crevasse mouth-bar complexes
flooding surface
flooding surface
distributary channel
crevasse mouth-bar complexes
crevasse channel
flooding surface
crevasse channels
crevasse channels
crevasse mouth-bar complexes
14 m

bioturbation (BI 5–6), which, together with oysters and *Gastrochaenolites* borings, suggest persistent brackish-water conditions.

ARCHITECTURE

The facies associations described above overlie several packages of decameter-scale mouth bars and delta-front deposits and are overlain by several tens of meters of upper-delta-plain deposits including carbonaceous shales, which provide a context consistent with a lower-delta-plain setting (Fig. 6). Distributary-channel fills (FA 1) erosionally overlie interdistributary-bay deposits (FA 2–7; Fig. 4A, 6, 7, 8B, C) and crevasse channel deposits (FA 2) are erosional into proximal and medial crevasse mouth bar deposits (FA 4–5; Fig. 4B, 8A, B, C). Crevasse-splay deposits (FA 3) usually erosionally overlie interdistributary-bay mud deposits (FA 7; Fig. 4E, 8A) and are overlain by FA 4–5 (Fig. 4E) or again by FA 7. Proximal crevasse mouth bar deposits (FA 4) overlie and pass laterally into medial crevasse mouth bar deposits (FA 5) through distal crevasse mouth bar deposits (FA 6) (Fig. 9) and into interdistributary-bay mud deposits (FA 7) over tens of meters in lateral distance. Crevasse mouth-bar deposits (FA 4–6) form packages up to 2 m thick showing upward-coarsening and upward-thickening trends and clinothems with relatively high-angle (up to ~ 15–20°) asymptotic foresets (Fig. 9). Mouth bars with similar angles are described in marine deltas (Catuneanu 2006; Fielding 2010; Abouessa et al. 2012) and lacustrine deltas (Coleman and Prior 1982; Schomacker et al. 2010) and are possibly associated with river load with a density in the same range as the density of the water of the receiving basin (Mulder et al. 2003). Foreset dips are oriented parallel to cross-stratification paleoflow, indicating forward accretion and progradation. These facies associations comprise crevasse mouth bars that are up to a few tens of meters long and organized into crevasse mouth bar complexes laterally extensive for a few hundreds of meters (Fig. 7, 8 9). Each crevasse mouth bar is separated from the adjacent one by a surface which may also be marked by a slight change in angle of the clinothems and a change in facies (Fig. 9). This organization of crevasse mouth bars and mouth-bar complexes is typical of modern river-dominated deltas (Wellner et al. 2005), but it has rarely been described in the ancient record (Enge et al. 2010). Vertical successions show a partial overlapping of the same (e.g., FA 5 above FA 5) or a contiguous facies association (FA 4 above FA 5; Figs. 7, 8). The typical stacking pattern shows one to three subvertically stacked crevasse mouth bars and this is interpreted as due to autocyclic processes of the crevasse subdelta system. The total thicknesses of these composite packages range from 2 to 4 m (Fig. 7, 8A, B, C), which may correspond to the paleo–water depth in the interdistributary bays plus local compaction-driven subsidence.

DISCUSSION

Depositional Model and Interaction of River and Tidal Processes

The facies associations and their spatial and relative temporal relationships described herein fit the key attributes of crevasse-subdelta depositional models, similar to the ones proposed by several authors (Elliott 1974; Fielding 1984, 1987; Tye and Coleman 1989). Crevasse subdeltas form in the lower delta plain of major deltas, in the backwater zone, and seaward of the bayline (Posamentier et al. 1988; Blum et al. 2013). Paleocurrents have a predominant north orientation in the Lajas distributary channel deposits but show a wide range in the crevasse-subdelta deposits (Fig. 7). This spread is interpreted as due to different sediment source points, high angles of crevasse channels to distributary channels, and interaction of flows and deposits of multiple synchronous systems. The high angles of flow direction indicated from the paleocurrent data can also be inferred from the geomorphology of modern systems, such as the Wax Lake Delta or the Mississippi (Coleman and Gagliano 1964; Wellner et al. 2005). The relatively small scale of cross-sets and sizes of the packages (up to ~ 2 m thick) indicate a shallow-water environment with limited accommodation, and the paleo–water depth is estimated as a few meters (Allen 1984; Leclair and Bridge 2001). Based on the size of the major distributary channels, the main delta system was of relatively small size, maybe comparable to or slightly larger than the Wax Lake delta (Wellner et al. 2005) or to the systems described in the Turonian Ferron sandstone (Bhattacharya and Tye 2004; Li and Bhattacharya 2014). The observed trace-fossil assemblage supports this interpretation, in that most of the ichnotaxa recognized (*Gastrochaenolites*, *Dactyloidites ottoi*, *Paleophycus*, and *Thalassinoides*) are indicative of shallow-water conditions (Agirrezabala and de Gibert 2004; Gérard and Bromley 2008). The diversity of the trace-fossil assemblage is generally low, but with a highly variable bioturbation index, which is typical of stressed environments with changing salinity (MacEachern et al. 2005; Carmona et al. 2008; Carmona et al. 2009; MacEachern 2010; Dashtgard 2011). Salinity levels were at least brackish in the interdistributary areas, as indicated by *Gastrochaenolites* borings, *Paleophycus*, and *Thalassinoides* (Gérard and Bromley 2008) and by the presence of oysters. Although water depth was shallow, there is no evidence of subaerial exposure, such as paleosols, rooted horizons or coals, as described in other ancient crevasse-subdelta examples (Elliott 1974; Fielding 1987).

The Lajas crevasse subdeltas show typical characteristics of river-dominated deposits, such as mainly unidirectional paleocurrents, signs of variation in river discharge (high and low river stages), and upward coarsening and thickening trends, suggesting progradational bodies. Tidal effects are represented by the rhythmical mudstone drapes and bidirectional current ripples (Fig. 5), associated with trace fossils, indicating brackish-water conditions, and wave action, indicated by rare symmetrical ripples. However, the distribution of these features, interbedded with deposits of clearly fluvial affinity, indicates that tidal effects are recorded in these deposits only during interflood periods, at low river stage, and wave action was extremely low. Nevertheless, subsequent river floods can erode large parts of the previous interflood deposit, particularly in the proximal area of the crevasse subdelta, where river flood deposits are amalgamated and interflood deposits are not always clear. Tidally influenced deposits are best developed in the medial part of the crevasse mouth bar, and decrease landward and seaward (Fig. 10). In the distal part of the system, presence of mud and abundant bioturbation suggest deposition mainly by suspension fallout and longer periods with absence of currents in which organisms were able to rework large parts of the substrate.

Understanding of Ancient Upward-Coarsening Deposits in Tidal Environments

The existence of tide-influenced crevasse subdeltas adds to the debate on the origin and processes responsible for upward fining *versus* upward coarsening trends and forward *versus* lateral accretion in modern and ancient tidal bars. Tidal bars in modern tide-dominated delta and estuarine settings are described as having typical fining-upward grain-size profiles because of the upward decrease of flow velocity in the channels and because of the lateral migration of the barforms (Dalrymple et al. 1992; Dalrymple and Rhodes 1995; Dalrymple and Choi 2007; Dalrymple 2010; Dalrymple et al. 2012; Longhitano et al. 2012; Olariu et al. 2012a;

←
FIG. 8.—Architecture and lateral and vertical variability of crevasse subdeltas and associated distributary-channel fills. See positions of 8A, B, and C in Figure 7. Triangles indicate upward-coarsening and upward-fining trends, which are also visible in the logs of Figure 7.

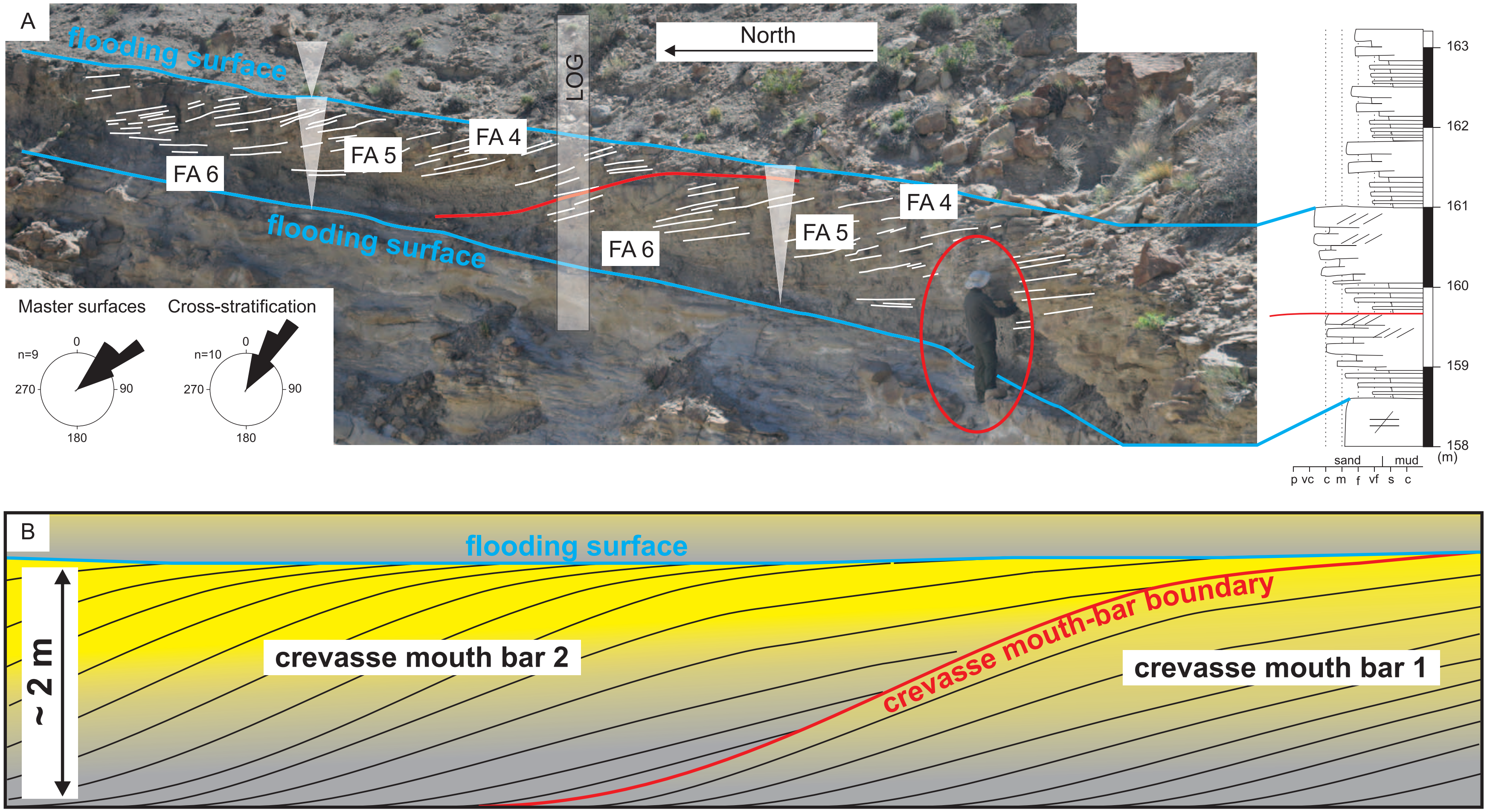


FIG. 9.—**A)** Outcrop of 2-m-thick crevasse mouth bars with clinothems and asymptotic toes showing forward accretion. The angle of dip of the clinothems is up to ~ 15–20 degrees. Person for scale is approximately 1.70 m tall. **B)** Interpretation of two offset-stacked crevasse mouth bars in a crevasse-mouth-bar complex.

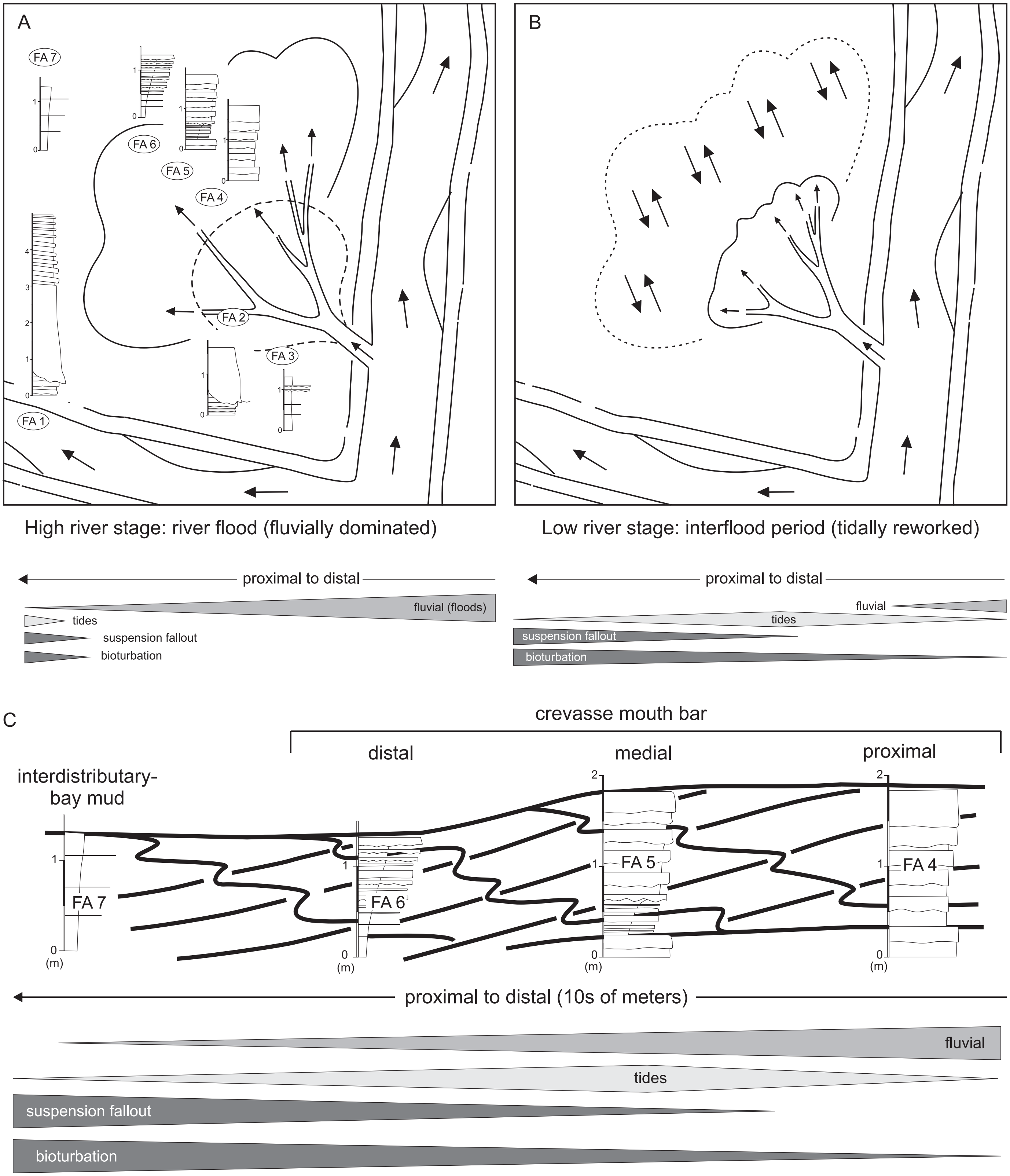


FIG. 10.—Conceptual depositional model for crevasse subdeltas with associated stratigraphic logs of each facies association and variations of tidal, fluvial, suspension fallout, and bioturbation processes for **A)** high river stage and **B)** low river stage. **C)** Proximal-to-distal trends from FA 4 to FA 7 and the relative dominance of different processes to convey the interaction of fluvial current, tidal reworking, bioturbation, and suspension fallout.

TABLE 2.—*A summary of key features of upward-coarsening and upward-fining types of deposits to show the discrepancy between modern fining-upward, lateral-accreting tidal bars and interpreted ancient coarsening-upward, forward-accreting tidal bars. The table also shows a comparison between major distributary and crevasse channels in the Lajas. Compiled from different sources (see text).*

Type	Setting	Thickness	Trends	Facies	Geometries And Sedimentary Structures
Crevasse mouth bars	Bays and lakes of river-dominated delta plains	Typically 1–2 m	Upward coarsening and thickening of beds	Poorly sorted and muddy sandstones or heterolithic	Clinothems, forward accretion, coarser- and finer-grained bed couplets, tidal rhythmites, and drapes more common in the interflood and distal deposits
Mouth bars	River-dominated delta fronts	Several m to maximum of approximately 10 m	Upward coarsening and thickening of beds	Sandstones or heterolithic	Similar to crevasse mouth-bars, but different in facies and scale
Single and compound tidal dunes	Tide-dominated shelves	Reported up to 15 m	Upward coarsening	Clean, well-sorted sandstones with scarce mud content	Reactivation surfaces common, forward accretion, unimodal or bimodal cross-stratification
Tidal ridges	Tide-dominated shelves	Up to 50 m thick	Upward coarsening	Clean, well-sorted sands with scarce mud content	Reactivation surfaces common, lateral accretion, unimodal or bimodal cross-stratification
Tidal bars (modern)	Tide-dominated estuaries and deltas	Several m to a few tens of m	Upward fining	Sands or heterolithic	Reactivation surfaces common, lateral accretion, fluid muds common and strongly bimodal cross stratification
Tidal bars (ancient)	Tide-dominated deltas (interpreted)	Several m to a few tens of m	Upward coarsening	Sandstones or heterolithic	Often reported as forward accreting and coarser- and finer-grained bed couplets sometimes reported
Crevasse channels	Bays and lakes of river-dominated delta plains	Up to 2 m thick	Upward fining	Poorly sorted and muddy sandstones or heterolithic	Lenticular, structureless, or trough and planar-tabular cross-stratified and usually unimodal
Major distributary channels	Deltas	Up to 5 m thick in the lower delta plain and up to 12 m thick in the upper delta plain and alluvial plain	Upward fining	Sandstones or heterolithic	Similar to crevasse mouth bars, but different in facies and scale

Olariu et al. 2012b). Sandier-upward trends in tidal bars are possible when associated with an upward decrease in fluid-mud layers, but this is not reflected in a real upward coarsening of sand grain size (Dalrymple and Choi 2007). Nevertheless, many studies on the deposits of ancient tide-influenced systems have interpreted upward-coarsening and forward-accreting facies associations as tidal bars (Mutti et al. 1985; Mellere 1994; Willis and Gabel 2001; Tänavsuu-Milkeviciene and Plink-Björklund 2009; Legler et al. 2013). Recent studies have questioned the interpretations of such upward-coarsening and forward-accreting deposits as tidal bars (Dalrymple and Choi 2007; Longhitano et al. 2012; Olariu et al. 2012a), and some of these deposits (Mutti et al. 1985) have later been reinterpreted as compound dunes (Olariu et al. 2012a). Other possible explanations for the upward-coarsening trend in interpreted ancient tidal bars have been suggested through the effect of reworking by storms in the delta-front area (Goodbred and Saito 2012), and through the proximity to the river mouth and the consequent interaction with fluvial processes and high rates of sediment delivered, both in bay-head-delta systems (Fenies and Tastet 1998) and at the delta fronts of major deltas (Willis 2005). However, given the characteristics of the Lajas crevasse-delta deposits, it could be that some of these small-scale, coarsening-upward and forward-accreting successions described in the rock record could be crevasse mouth bars with a subordinate tidal influence that overprinted the original fluvial dominance of the deposits. Tide-influenced crevasse mouth bars can be distinguished from other coarsening-upward facies on the basis of the stratigraphic context, as they would be confined to a lower-delta-plain setting with expected lateral association with river-dominated distributary channels. Thicknesses rarely exceed two meters in a single crevasse mouth bar and parasequences are up to 3–4 meters thick, while major mouth bars are typically several meters thick and can form parasequences up to 20 meters thick, as visible in the Lajas Fm (Fig. 3) or in other examples (Ahmed et al. 2014). Crevasse-subdelta mouth bars in the Lajas Fm also show high muddy matrix content and poor sorting compared to the main mouth bars (Table 2). This is ascribed to the high turbidity of the shallow bays and erosional entrainment of muddy substrate. Although the crevasse mouth bar deposits of the Lajas Fm are mud-rich, there are common medium- to coarse-grained sandstones, whereas the cleaner main mouth bar deposits largely comprise fine- to medium-grained sandstones. The sand size of the crevasse subdelta reflects the position in the system where the breach of the levee occurred, which may be tens of kilometers landward from the mouth of the river and, because mean grain size is commonly down-dip decreasing in deltas, have coarser sediments than the coeval mouth bars. Tidal dunes are typically very well sorted with low mud content (Olariu et al. 2012a; Reynaud and Dalrymple 2012) because of continuous reworking by tidal currents and low turbidity concentrations, and they would mark transgressive intervals in shallow-marine successions (Reynaud and Dalrymple 2012). Dunes, which may be organized in compound dunes, show forward accretion and form larger-scale, laterally migrating tidal ridges. Single and compound tidal dunes, tidal ridges, and tidal bars may show more strongly bimodal paleo-orientation compared with crevasse mouth bars and major mouth bars while the latter two can show systematic fluctuations of river discharge, as described herein for crevasse mouth bars.

Crevasse Subdeltas in Modern Systems: Implications for the Lajas Formation and the Paleogeography of the Neuquén Basin

Crevasse subdeltas have been widely studied in the modern Mississippi River delta system (Coleman and Gagliano 1964; Arndorfer 1973; Tye and Kosters 1986; Tye and Coleman 1989; Roberts 1997), are known in the Atchafalaya and Wax Lake deltas (Roberts 1998; Wellner et al. 2005) in the Gulf of Mexico, and are reported in the Danube Delta in the Black Sea (Bhattacharya 2006). Investigation of present-day systems allowed us to recognize crevasse subdeltas in interdistributary-bays of other deltas, such as the Po (Adriatic Sea, Italy), Volga (Caspian Sea, Russia), Ural (Caspian Sea, Kazakhstan), Selenga (Lake Baikal, Russia), and Huang

TABLE 3.—*List of modern major deltas showing crevasse-subdelta systems and with indication of mean tidal range for each of them. Compiled from different sources (see text).*

River Delta	Country	Setting	Tidal Range
Mississippi	Louisiana (USA)	Gulf of Mexico	Microtidal (0.40 m)
Atchafalaya	Louisiana (USA)	Gulf of Mexico	Microtidal (0.40 m)
Wax Lake	Louisiana (USA)	Gulf of Mexico	Microtidal (0.40 m)
Volga	Russia	Caspian Sea	Microtidal (~ 0.00 m)
Ural	Kazakhstan	Caspian Sea	Microtidal (~ 0.00 m)
Danube	Romania	Black Sea	Microtidal (0.10 m)
Po	Italy	Adriatic Sea	Microtidal (0.70 m)
Huang He (Yellow)	China	Bohai Sea	Microtidal (0.60–0.80 m)
Selenga	Russia	Lake Baikal	Microtidal (~ 0.00 m)

He (Yellow River, Bohai Sea, China). All these modern delta systems are classified as river-dominated (Galloway 1975; Orton and Reading 1993; Bhattacharya 2006) and lie in semi-enclosed (Adriatic Sea, Gulf of Mexico, Bohai Sea, Black Sea) or enclosed (Caspian) seas or lakes (Baikal) where marine processes are suppressed (Table 3). Mean tidal range is less than 0.10 m in the Black Sea (Giosan et al. 2005), 0.70 m in the Po area (Fain et al. 2007), 0.40 m in the Gulf of Mexico (Mikhailov and Mikhailova 2010; Shaw and Mohrig 2014), and 0.60–0.80 m at the mouth of the Huang He (Bi et al. 2010). It is close to zero in the Caspian Sea and Lake Baikal. Minor effects of tides on sedimentation are reported in the Wax Lake (Wellner et al. 2005; Shaw et al. 2013; Shaw and Mohrig 2014), Atchafalaya (Roberts 1998), Mississippi (Scruton 1956; Arndorfer 1973; Mikhailov and Mikhailova 2010), and Po (Falcieri et al. 2014), and the Huang He example shows crevasse subdeltas coexisting with tidal channels and tidal flats (Xue 1993; Yin et al. 1999; Hui and Haijun 2004). Present-day tide-dominated deltas such as the Fly (Harris et al. 1993; Baker et al. 1995; Dalrymple et al. 2003), Ganges–Brahmaputra (Kuehl et al. 2005), and Chang Jiang (Yangtze; Hori et al. 2001), or mixed-energy fluvial–tidal deltas such as the Fraser (Dashtgard et al. 2012) or the Mahakam (Storms et al. 2005; Salahuddin and Lambiase 2013) do not show active crevasse subdeltas, probably because crevassing is inibited by the presence of tidal currents in distributary channels and because of more effective sediment redistribution processes in the bays. It appears therefore that crevasse-subdelta systems form preferentially in relatively sheltered settings where input from the rivers is predominant and marine processes are minor. This inference contrasts with previous interpretations of the Lajas Fm as a tide-dominated system where tides were interpreted to have been enhanced by a structurally controlled embayment (McIlroy et al. 2005; McIlroy 2007). The presence of interdistributary and crevasse-subdelta deposits interpreted herein suggests that the major delta must have been, at least for the two stratigraphic intervals described, largely river-dominated, following the arguments above. The tidal facies described in interdistributary-bays and particularly in interflood deposits forming at low river stages, are possibly explainable using the Mississippi, Atchafalaya, or Wax Lake or a slightly more tide-influenced delta as an analog. This interpretation would fit with Jurassic paleogeographic studies that indicate the Neuquén Basin was a semi-enclosed sea with limited connections to the Pacific Ocean, and comparable in size to the Caspian, Black, Bohai, and Adriatic seas during deposition of the Lajas Fm (Vergani et al. 1995; Howell et al. 2005; Vicente 2005, 2006).

CONCLUSIONS

This study highlights the importance of crevasse subdeltas as an important component of ancient river-dominated lower-delta-plain successions. The crevasse-subdelta deposits show many similarities with major deltas, including clinothems that are similar in geometry, but much smaller in scale. Variations in river discharge (low river stage to high river stage), that may be related to seasonality, result in flood–interflood couplets in the deposits. At low river stage in crevasse subdeltas, tides are able to rework part of the sediment of the previous river flood deposit, but do not transport additional sediment into the bay, having therefore a role subordinate to that of river currents during the construction of crevasse subdeltas. At the facies scale, the primary role of tides is to remove mud matrix from the sands, thus improving grain sorting and potential reservoir quality of sandstones, but tidal activity also produces mud drapes during slack water, which can act as baffles, reducing both horizontal and vertical permeability locally.

More fundamentally this paper questions the characteristics in the stratigraphic record of tide-dominated deltas and their depositional features. We suggest that some coarsening-upward and forward-accreting "tidal bars" interpreted from the rock record may be instead deposits of tide-influenced crevasse subdeltas, thus implying a river-dominated, tide-influenced delta rather than a tide-dominated system, with consequent differences in large-scale geometries.

Moreover, crevasse subdeltas in the modern appear to be restricted to the delta plains of river-dominated major delta systems that flow into semi-enclosed or enclosed seas and lakes where tidal range is usually microtidal and wave activity is low, and a similar interpretation is proposed for the Neuquén Basin, during the deposition of the Lajas Fm This observation forms an important principle in improved prediction of facies distributions and sediment dispersal patterns in deltaic settings.

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