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SEDIMENTOLOGY AND FLUVIAL STYLES OF THE UPPERMOST CRETACEOUS CONTINENTAL DEPOSITS OF THE AUSTRAL-MAGALLANES BASIN, PATAGONIA, ARGENTINA

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ABSTRACT

The sedimentary infill of the Austral-Magallanes Basin since the onset of its foreland stage in the Lago Argentino region is dominated by deep-marine and coastal deposits. However, during the Late Cretaceous the basin accumulated a thick and poorly known continental sedimentary succession, which has received different lithostratigraphic names. The aim of this work is to characterize the here defined Uppermost Cretaceous Continental Deposits (UCCD) from a detailed facies and architectural analysis, as well as the resulting stacking pattern. Seven Facies Associations (FAs) were discriminated in order to define the sedimentary paleoenvironments: FA1, gravelly sheet bodies; FA2, tabular bodies of conglomerates with mud rip-up clasts; FA3, complex tabular sandy bodies; FA4, simple tabular sandy bodies; FA5, tabular bodies of structureless sandstones; FA6, heterolithic deposits; and FA7, fine-grained deposits. Three different fluvial styles were recognized: meandering systems dominated by avulsion and meander abandonment processes (fluvial style a), braided systems (fluvial style b), and meandering systems dominated by overbank flood processes (fluvial style c). The stacking pattern of the FAs allowed to divide the UCCD into two major depositional stages related to the accommodation space vs sediment supply (A/S) ratio. Stage I is characterized by the alternation of fluvial styles a and b, while the Stage II is represented by the alternation of fluvial styles c and b, and the Stage III is characterized entirely by fluvial style c deposits. Although the UCCD are considered as a whole within a framework of low A/S ratio, several high frequency variations were recognized. The Stage I records seven high frequency intervals of which four are characterized by high A/S ratio interrupted by three events of low A/S. While the stage II is represented by six high frequency periods of low A/S ratio and other five high frequency events of high A/S ratio. The Stage II is considered as deposited in a relative higher A/S context in comparison with the Stage I, based on the behavior of the moderate to high sinuosity meander fluvial systems. Finally, the Stage III is represented entirely by a high frequency low A/S ratio event.

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INTRODUCTION

The stratigraphic record of foreland basins is the consequence of an interplay between tectonics, magmatism, climate and relative sea-level changes that occur at active continental margins. As result of these interactions, continental basins are developed stretching out many thousands of kilometers parallel to and hundreds of kilometers perpendicular to orogenic belts (DeCelles, 2012; Horton, 2018). In non-marine settings within foreland basins, tectonic activity create or destroy accommodation space, modify landscape profiles and the amount of sediment supply, meanwhile climate changes affect the fluvial discharge which leads to modify sediment load within the channels (Catuneanu *et al.,* 2009). During periods of crustal shortening and orogenic loading, the rate of subsidence increases and coarse-grained sediments are deposited nearby the orogenic load, whereas fine-grained sedimentation occurs throughout the major part of the basin (DeCelles and Giles, 1996). Recently, stratigraphic researches of these alluvial successions have included the application of sequence stratigraphy (Catuneanu *et al.,* 2009). However, along-strike diachroneity of orogenic processes (Jordan *et al.*, 2001) make correlations difficult because of the lithological similarities of resulting deposits, the diachronic sedimentation and the lack of confident age determinations (Ré and Barredo, 1993a, b).

Studies in the Austral-Magallanes Basin have been carried out for decades including the evolution of sedimentary systems in response to the dynamics and evolution of the foreland stage (Arbe and Hechem, 1984; Biddle *et al.*, 1986; Macellari *et al.*, 1989; Varela *et al.*, 2012a, b; Varela, 2015; Malkowski *et al.*, 2017; Moyano Paz *et al.*, this volume). Nevertheless, this knowledge is incipient in comparison with other sedimentary basins in Argentina. From an economic point of view, the continental deposits of the Upper Cretaceous of the Austral-Magallanes Basin present characteristics of potential reservoir for hydrocarbons as part of the Lower Magallanes oil system (Rodríguez and Miller, 2005), representing an exploratory challenge in the basin.

The Uppermost Cretaceous Continental Deposits (UCCD) form part of the sedimentary infill of the Austral-Magallanes Basin during the foreland basin stage. They are located in the foredeep depocenter of the foreland system and cover the deltaic deposits of the La Anita Formation and are overlain by the marine succession of the Calafate Formation (Moyano Paz *et al.,* this volume; Odino Barreto *et al.,* this volume). The aims of this contribution are i) to describe and analyze the Uppermost Cretaceous Continental Deposits, based on a detailed characterization of this sedimentary infill during the foreland stage of the Austral-Magallanes Basin, ii) to propose a conceptual model of accumulation for these deposits, both north and south of the Lago Argentino, and iii) to propose a sequence stratigraphic framework for these non-marine deposits of the basin.

GEOLOGICAL SETTING

The Austral-Magallanes Basin is located at the southern edge of the South American Plate and presents an areal extension of 230.000 km^2 (Rodríguez and Miller, 2005; Fig. 1). The Río Chico-Dungeness High bounds the eastern edge of the basin, the western limit is represented by the Patagonian-Fuegian Andes, meanwhile at the south it is bounded by the Scotia Plate. The Austral-Magallanes Basin covers part of the Santa Cruz and the Tierra del Fuego argentinian provinces, as well as the Última Esperanza and the Magallanes regions of Chile. The sedimentary infill at the basin depocenter is up to 8.000 m thick, both in outcrop and subsurface. The tectonic evolution is divided in three stages (Biddle *et al.*, 1986; Kraemer *et al.*, 2002; Rodríguez and Miller, 2005). Initially, during the Middle to Late Jurassic a rift stage set up the basin shape and location (Pankhurst *et al.*, 2000); subsequently, a thermal subsidence phase took place during the Berriasian to the Albian (Calderón *et al.*, 2007; Richiano *et al.*, 2012). Finally, the onset of the foreland basin, has begun in the Cenomanian (Fosdick *et al.*, 2011; Varela *et al.*, 2012a; Malkowski *et al.*, 2015) encompassing the Late Cretaceous and the Cenozoic.

The UCCD have been focus of discussion since the middle of last century (Feruglio, 1944) and have been denominated with different lithostratigraphic names according to the geographical location where these deposits were studied (*i.e.* Chorrillo Formation; La Irene member of La Anita Formation, La Irene Formation, Cerro Fortaleza Formation). These continental deposits which overlie the deltaic deposits of the La Anita Formation and are overlain by the shallow marine deposits of the Calafate Formation are here defined as the UCCD (Fig. 2).

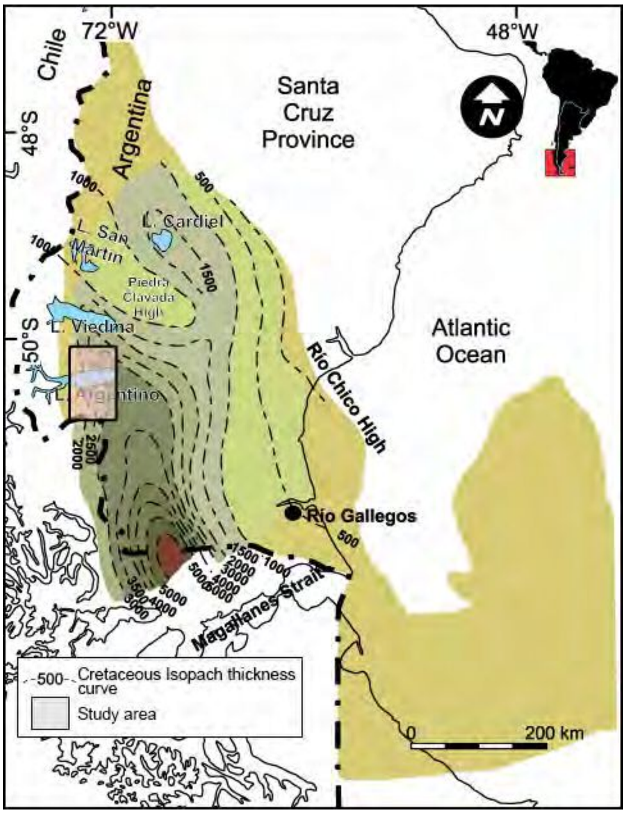

Figure 1. Location map of the Austral-Magallanes Basin. The limits of the basin and maximum thickness of the cretaceous deposits are modified from Marinelli (1998); Varela *et al*. (2019); Moyano Paz *et al*. (this volume). The red box indicates the location of the study area.

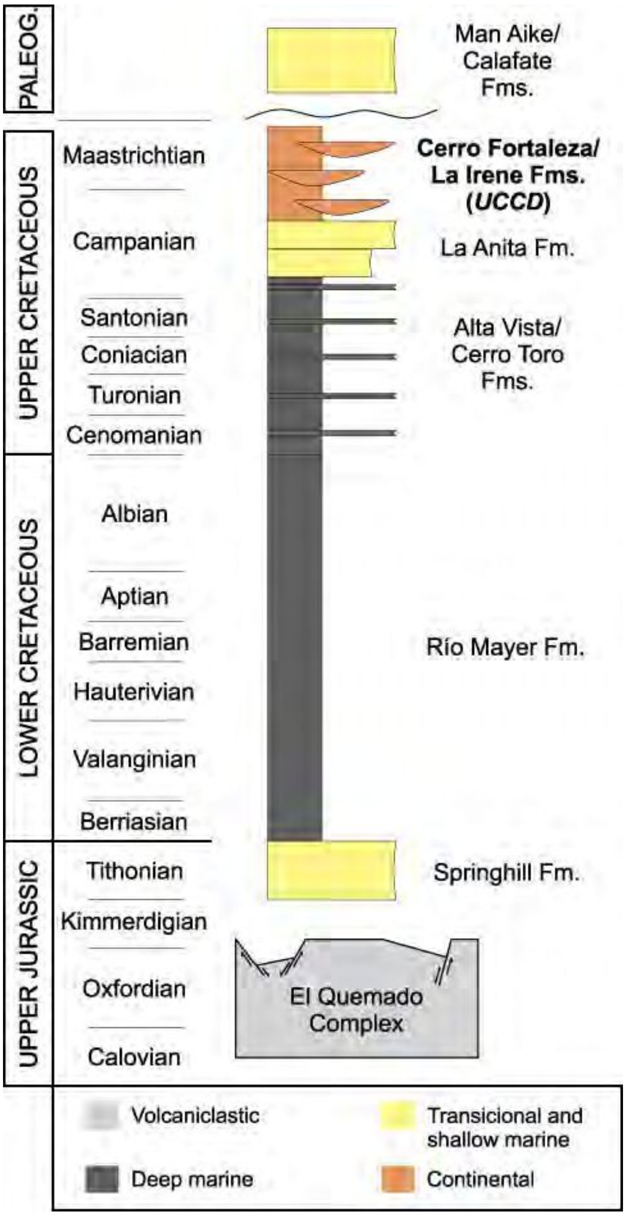

Figure 2. Synthetic stratigraphic column of the Austral-Magallanes Basin (AMB) in the Lago Argentino region (modified from Ghiglione *et al*., 2014; Sickmann *et al*., 2018; Moyano Paz *et al*., this volume).

The studied succession is 200 m thick and consists of yellowish conglomerates, pebbly sandstones and coarse-grained sandstones interbedded with greenish, greyish and purple massive and laminated mudstones. The UCCD are characterized by an alternation of coarse-grained and fine-grained deposits in sets of tens of meters. Recently, Sickmann *et al*. (2018) restricted these deposits to the Campanian-Maastrichtian through detrital zircons maximum ages. These deposits have been interpreted in some regional and stratigraphic studies as accumulated in a braided fluvial environment (Arbe and Hechem, 1984; Macellari *et al*., 1989). However, detailed sedimentological studies are needed in order to constrain stratigraphic variations within this succession.

STUDY AREA AND METHODS

The study area is located in the Lago Argentino region, at the southwest of the Santa Cruz province, Argentina (Figs. 1, 3). Nine detailed sedimentological logs were performed in the localities of the Irene farm (EI1, EI2, EIN), the La Porfía farm (LP1, LP2, LP3), the Calafate hill (CC), the El Tropilla field (CET) and the Anita farm (EA; Figs. 3, 4).

Nineteen sedimentary facies were defined on the basis of sedimentological features such as, grain size, mechanical and biological sedimentary structures, sorting features and vegetal remains (Table 1). Recurrent groups of facies allowed the definition of 7 facies

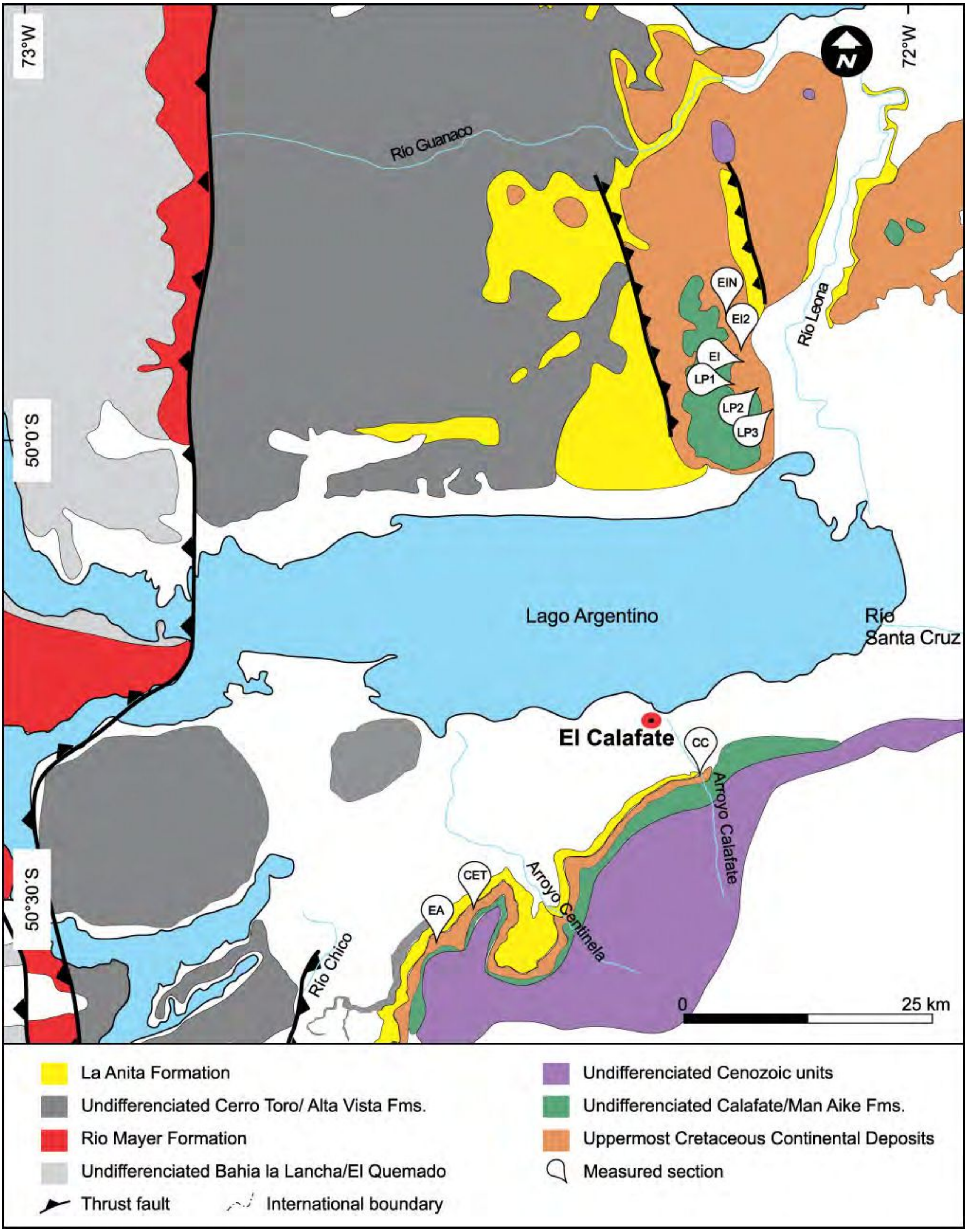

Figure 3. Geological maps of the Lago Argentino region showing the distribution of the lithostratigraphic units of the Austral-Magallanes Basin and the location of the measured sections (modified from Kraemer and Riccardi, 1997; Ghiglione *et al*., 2014; Moyano Paz *et al*., this volume). Measured section names: EIN = Estancia Irene Norte; EI2 = Estancia Irene 2; EI1 = Estancia Irene; LP1 = La Porfía 1; LP2 = La Porfía 2; LP3 = La Porfía 3; CC = Cerro Calafate; CET = Campo el Trompilla; EA = Estancia Anita.

associations (FAs). Geometrical data, lateral facies variations, bounding surfaces and dimensions of the sedimentary bodies were measured and described in order to determine different depositional architectures (e.g. Friend *et al.*, 1979; Bridge, 1993; Gibling, 2006). The thickness (T) and width (W) of the different channelized bodies have been measured using measuring-tape or GPS for outcrop-scale bodies and corrected for the obliquity of paleocurrents with respect to the orientations of the outcrop belt. External shape of fluvial channels was described following the W/T criteria of Gibling (2006). Paleocurrent directions were measured in planar and trough cross-bedding structures and in imbricated clasts using a Brunton® compass, which in turn were corrected for magnetic declination. Corrected paleocurrent data was treated statiscally with the Stereonet® program and differentiated according to FAs.

FACIES ASSOCIATIONS

Facies Association 1 (FA1): Gravelly sheet bodies

Description: FA1 consists of conglomerates and pebbly-sandstones with coarse-grained sandstone matrix. It comprises tabular bodies with erosive base and fining-upward trends. Maximum dimensions are up to 20 m thick and 250 m wide. The W/T is 12.5 (narrow sheet channels *sensu* Gibling, 2006; Fig. 5a). The erosive bases commonly show lags of structureless conglomerates (Gm), the top of these bodies are planar and frequently shows current ripples (Sr). Internally, these bodies consist of vertically and laterally amalgamated stories bounded by erosional bases and irregular tops (Fig. 5b). Stories consist of gently inclined lenticular bodies up to 0.2 m thick and 0.8 m wide with abundant mud rip-up clasts and wood fragments toward their bases (Fig 5b). The conglomerate to sandstone sedimentary infill of these stories records trough, tangential and planar cross-bedding (Gt, Gp, SGt and SGp); the thicknesses of sets and cosets is up to 0.5 m and 2 m, respectively. Both sets and cosets show irregular bases that frequently contain mud rip-up clasts and wood fragments. Paleocurrent directions measured in cross-beds (n=131) indicate an average direction toward the south east (N166°). Facies Association 1 was recognized in all studied localities excepting LP3.

Interpretation: Based on the erosive nature of the base, the coarse grain-size of the stories and the lack of lateral-accretion surfaces, FA1 deposits are interpreted as sandy-gravel bed-load multistory fluvial sheet channels, infilled by migration and accretion of three-dimensional dunes and bar. Bars can be simple (formed by sets) or compound (formed by cosets) and both suggest downstream direction of accretion (Bridge, 2003; DA downstream accretion bars *sensu* Miall, 1996; 2006), migrating mainly toward the southeast. Because these bars are not attached to a channel margin, no lateral accretion component was recorded. FA1 reflects deposition of gravel and sand in diluted conditions from multiple channels within a main braided channel belt (Bridge *et al.*, 2000).

Facies Association 2 (FA2): Tabular conglomerate bodies with mud rip-up clasts

Description: FA2 consists of tabular bodies with erosive sharp bases (Fig. 6) and sharp tops with thicknesses ranging between 1 to 10 m and a lateral continuity ranging between 100 to 1000 meters. Internally, these bodies consists of an intercalation of conglomerates entirely composed of mudstones rip-up clasts (Gmrc) interbedded with structureless and planar cross-bedded pebbly-sandstones towards the top (SGm and SGp; Fig. 6b,c). Conglomerates with horizontal stratification (Gh) are also common. This facies alternation conforms packages 0.1 - 0.2 m thick. FA2 was recognized only in the north of Lago Argentino, generally under or overlying the deposits of FA1 or the fine grained deposits (FA7 - flood plain, see below). Paleocurrent measurements in SGp facies indicate an average flow direction southeastward (N145°). This facies association has been recognized in LP1 and EIN localities.

Interpretation: FA2 represents the initial migration of bidimensional bars during flood stages in which the muddy sediments are transported as silt- to sand-sized grains (Bridge, 2003). The migration of these bars occurs within braided channels of FA1. The onset of these bars migration and mud rip-up transport reflect the action of an erosive agent but not intense enough to break-up this clasts (Spalletti and Mazzoni, 1975; Limarino and Sessarego, 1986). During the final stage or after these flood events, flow loses energy and act as dilute subcritical currents forming lower-stage plane beds (Gh; Bridge, 2003).

Figure 4. Detail of the sedimentary logs measured in the UCCD exposures. The upper datum corresponds to a regional flooding surface which marks the base of the Calafate Formation. For location of these sections see Fig. 3.

Facies Codes	Lithology	Sedimentary structures	Sorting	Bed/set thickness (cm)	Vegetal remains	Interpretation
Fm	Mudstones	Structureless, subangular blocky structures	Well sorting	10 – 100	Rooting and coaly fragments	Settling from suspension
Fl	Mudstones and siltstones to very fine-grained sandstones	Planar bedding	Well to moderate sorting	5 – 30	Absent	Settling from suspension
Htf	Very fine-grained sandstones and mudstones	Planar bedding	Poor sorting	100 – 200	Plant debris	Alternation of tractive currents and settling of suspended fine-grained sediments
Htl	Mudstones and very fine-grained sandstones	Horizontal lamination to planar cross-lamination	Poor sorting	50 – 100	Plant debris, rooting	Alternation of settling of suspended fine-grained sediment and tractive currents
Wm	Fine- to coarse-grained wackes	Structureless, wedge-shaped peds	Poor sorting	60 – 150	Carbonaceous fragments	Rapid deceleration of a hyperconcentrated flow (high-sedimentation rate) or biogenic activity
Sm	Fine- to coarse-grained sandstones, fine- to coarse-grained siltstones	Structureless, fining upward or wedge-shaped peds	Moderate sorting	60 – 150	Plant debris, carbonaceous fragments, rooting	Rapid deceleration of a hyperconcentrated flow (high-sedimentation rate)
Sr	Medium- to coarse-grained sandstones	Ripples with sinous ridges	Moderate sorting	5 – 10	Absent	Downstream migration of three-dimensional ripples
Sl	Fine- to very coarse-grained sandstones	Planar cross-lamination	Poor sorting	10 – 15	Absent	Downstream migration of bidimensional ripples
Sh	Medium- to coarse-grained sandstones	Horizontal lamination	Moderate sorting	10 – 50	Absent	Tractive deposition during critical flow (upper flow regime)
Sp	Medium- to coarse-grained sandstones	Planar cross-stratification	Well sorting	10 – 80	Absent	Downstream migration of bidimensional dunes
St	Medium- to very coarse-grained sandstones	Trough and tangential cross-stratification	Well sorting	3 – 45	Absent	Downstream migration of three-dimensional dunes
SGm	Coarse- to very coarse-grained pebbly sandstones	Structureless, rarely fining upward, mud rip-up clasts	Moderate sorting	20 – 75	Wood fragments	High-sedimentation rate, dense current deposition, channel fill and central and/or head of bars
SGp	Medium- to coarse-grained pebbly sandstones	Planar cross-stratification	Moderate sorting	10 – 30	Absent	Downstream migration of bidimensional dunes
SGt	Medium- to coarse-grained pebbly sandstones	Trough and tangential cross-stratification	Moderate sorting	15 – 50	Absent	Downstream migration of three-dimensional dunes
Gmrc	Mud rip-up clast conglomerate	Subhorizontal bedding	Poor sorting	5 – 10	Absent	Initial barform migration during flooding events
Gm	Clast supported fine- to medium-grained conglomerate	Structureless, mud rip-up clasts	Moderate sorting	20 – 25	Wood fragments	Channel lag deposits, central and/or head of bars
Gh	Clast-supported fine- to medium-grained conglomerate	Horizontal bedding, fining upward	Moderate sorting	60 – 200	Absent	Lower flow regime flat bedding, head of bars or non-channelized shallow currents
Gp	Clast-supported fine- to medium-grained conglomerate	Planar cross-stratification	Moderate sorting	15 – 30	Absent	Downstream migration of transverse bars
Gt	Clast-supported fine- to medium-grained conglomerate	Trough and tangential cross-stratification	Moderate sorting	12 – 60	Absent	Downstream migration of three-dimensional bars

Table 1. Codes, description and interpretation of the 19 sedimentary facies defined in the UCCD.

Facies Association 3 (FA3): Complex tabular sandy bodies

Description: FA3 is composed of structureless conglomerates (Gm), pebbly-sandstones with trough and tangential cross-bedded structures (SGt), and trough and planar cross-bedded sandstones (St and Sp). This FA shows tabular to lenticular bodies with erosive bases, ranging from 4 to 10 m thick and 20 to 250 m of lateral continuity (Fig. 7a). The W/T is 5 to 25 (broad ribbons to narrow sheets *sensu* Gibling, 2006). Internally, the tabular bodies are composed of vertical and lateral stacked simple ribbon bodies, or stories, which show high-angle (10° – 12)° large inclined surfaces and are bounded by medium-scale erosional bases (Fig 7a). These stories show tens of meters of lateral continuity and are composed of structureless conglomerates (up to 0.3 m thick) towards the base with abundant mud rip-up clasts and trunk fragments followed by fining-upward cosets (0.5 – 1 m thick) with cross-bedded structures bounded by small-scale erosional surfaces (Fig. 7b). At the top, FA3 deposits show cut and fill structures in which the facies St shows paleocurrent data near orthogonal respect to the channelized bodies axis (Fig. 7a,c). Paleocurrents of FA3 indicate a paleoflow mainly toward the southeast (N164°) but they also show south and west-northwest directions (Fig. 4). FA3 was recorded in the north and south of the Lago Argentino, in CET, EA and CC sections and around Irene farm localities.

Interpretation: Based of the erosive nature of the base, the wide dispersion of paleocurrents direction, the presence of bars attached to channels margins and the vertical and lateral association with floodplain elements of FAs 4, 5, 6 and 7, Facies Association 3 is interpreted as sandy-gravelly loaded fluvial channels infill. These channels were filled by simple and compound bars with lateral accretion components (Fig. 7a), which are developed within convex margins of meandering channels (Bridge, 2003; Page *et al.*, 2003). Fining-upwards trends within these deposits suggest a gradual decrease of the current energy.

Facies Association 4 (FA4): Simple lenticular sandy bodies

Description: FA4 comprises lenticular bodies composed of sandstones and pebbly-sandstones with erosional bases. These bodies are up to 1.5 m thick and the width ranges between 8 and 10 m, the W/T ratio is 5 – 6 (broad ribbons channels *sensu* Gibling, 2006; Fig. 8a–b). The tops of these bodies are sharp and flat but are frequently truncated by the highly erosional bases of FA1. The infill of these bodies is single-story and is dominated by trough cross-bedded sandstones and pebbly-sandstones (St and SGt), with frequent mud rip-up clasts (Fig. 8c). Planar cross-lamination is also common (Spl). In a case, a single-story body composed of massive to laminated sandstones (Sm and Sh) was recorded. Cross-beds are oriented mainly toward the east and south-east (Fig. 4), with an average measured direction of N148°. FA4 was recorded in LP1, EI2 and EIN sections and it is associated with FA3.

Interpretation: FA4 is interpreted as produced by rapid deceleration of tractive shallow small-scale channelized currents in flood plains (Bridge, 2003). Through overbank during high discharge events, crevasse channels theoretically cut levees in orthogonal to oblique relationship with the main channel, flowing to low relief areas (Mjøs *et al.*, 1993*;* Plint and Browne, 1994; Veiga *et al*., 2008; Miall, 2010). The finer grain-size in comparison with main channels (FA3), the fining-upward trends and the more eastward paleocurrent direction in relation with the ones measured for FA3 supports this interpretation.

Facies Association 5 (FA5): Tabular bodies of structureless sandstones

Description: FA5 consists of tabular sandbodies up to 1 m thick and 20 to 200 m wide. These bodies have sharp bases and subtle convex-up tops (Fig. 9a). The architecture of these bodies is simple and single-story, dominated by structureless sandstones that grade upward into planar laminated sandstones (Sm and Sh; Fig. 9) with abundant vegetal remains at their bases. Fining-upward trends from coarse- to fine-grained sandstones were observed within FA5. This FA is vertically related with fine-grained deposits of FA7 and simple lenticular sand bodies of FA4. FA5 was recognized in the localities north of Lago Argentino.

Interpretation: Because of the structureless aspect, FA5 is interpreted as rapid deceleration of shallow,

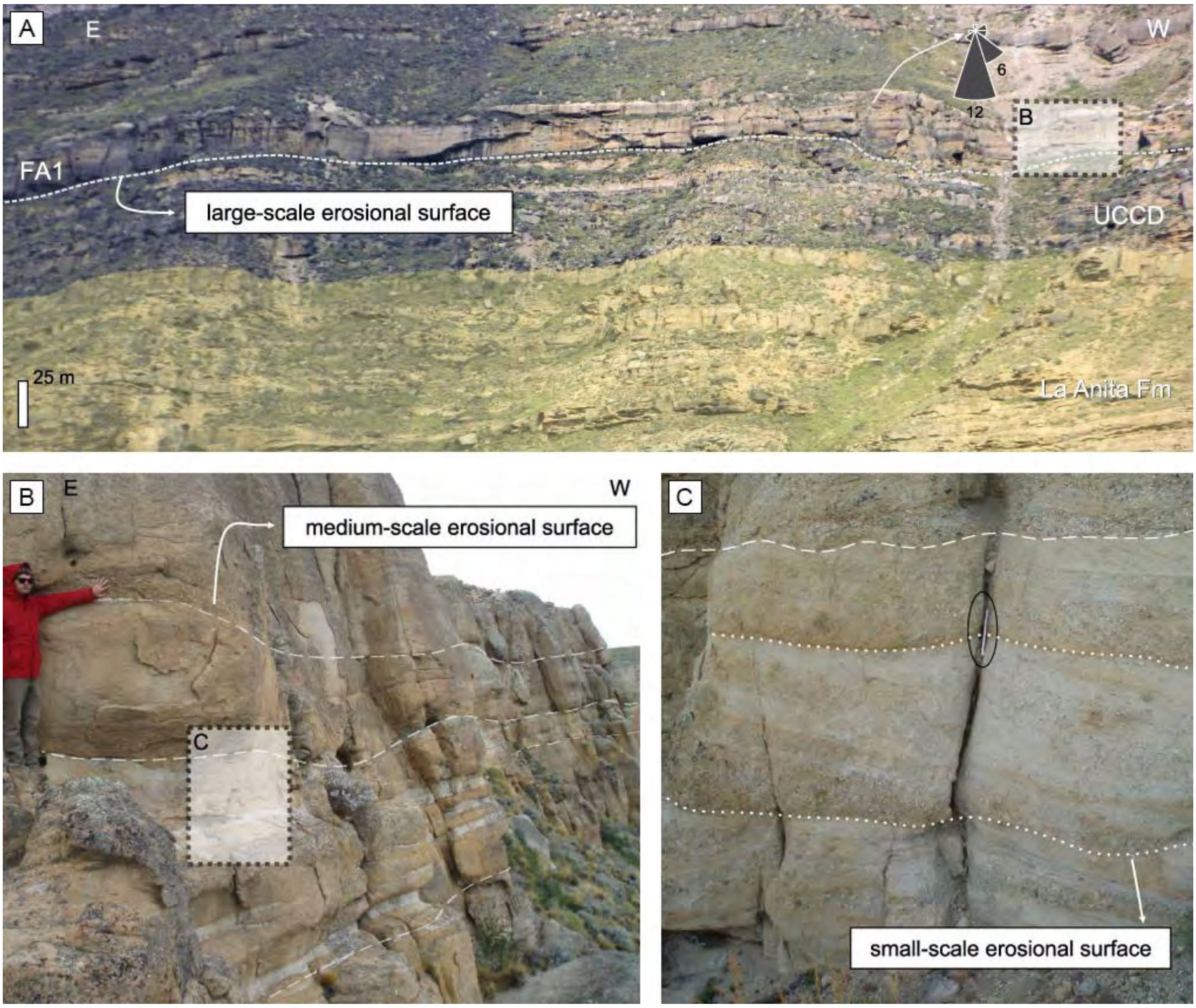

Figure 5. Outcrop photographs of Facies Association 1 (FA1). **a)** Overview of the erosional based tabular, gravelly sheet bodies. **b)** Medium-scale bodies with vertical and lateral amalgamation, erosional bases and convex-up tops (person for scale is 1.8 m high). **c)** Pebbly sandstones compound cosets with trough cross-bedding (pencil for scale is 0.12 m long).

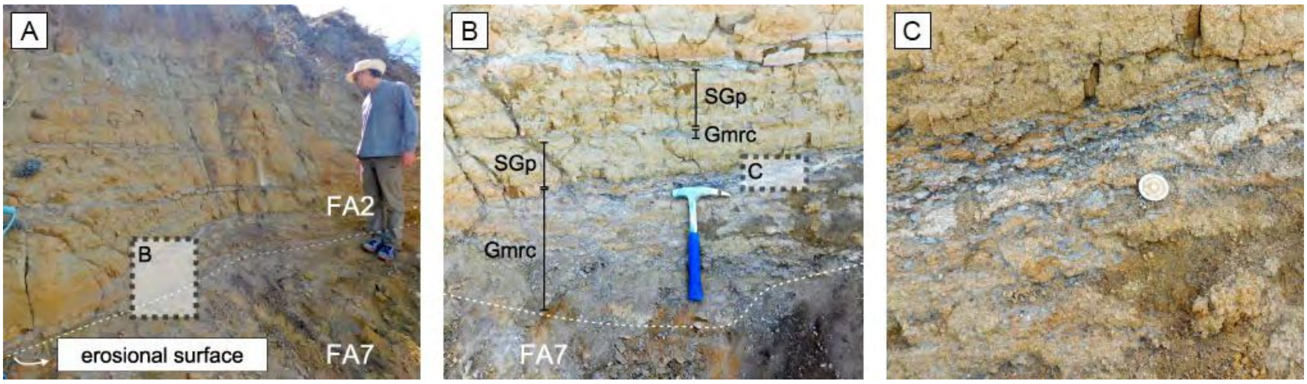

Figure 6. Overview of Facies Association 2 (FA2). **a)** tabular bodies of conglomerates with mud rip-up clasts (person for scale is 1.8 m high). **b)** Interbedding of planar cross-bedded pebbly-sandstones (SGp) and mud rip-up clasts conglomerates (Gmrc). **c)** Detail view of mud rip-up clasts.

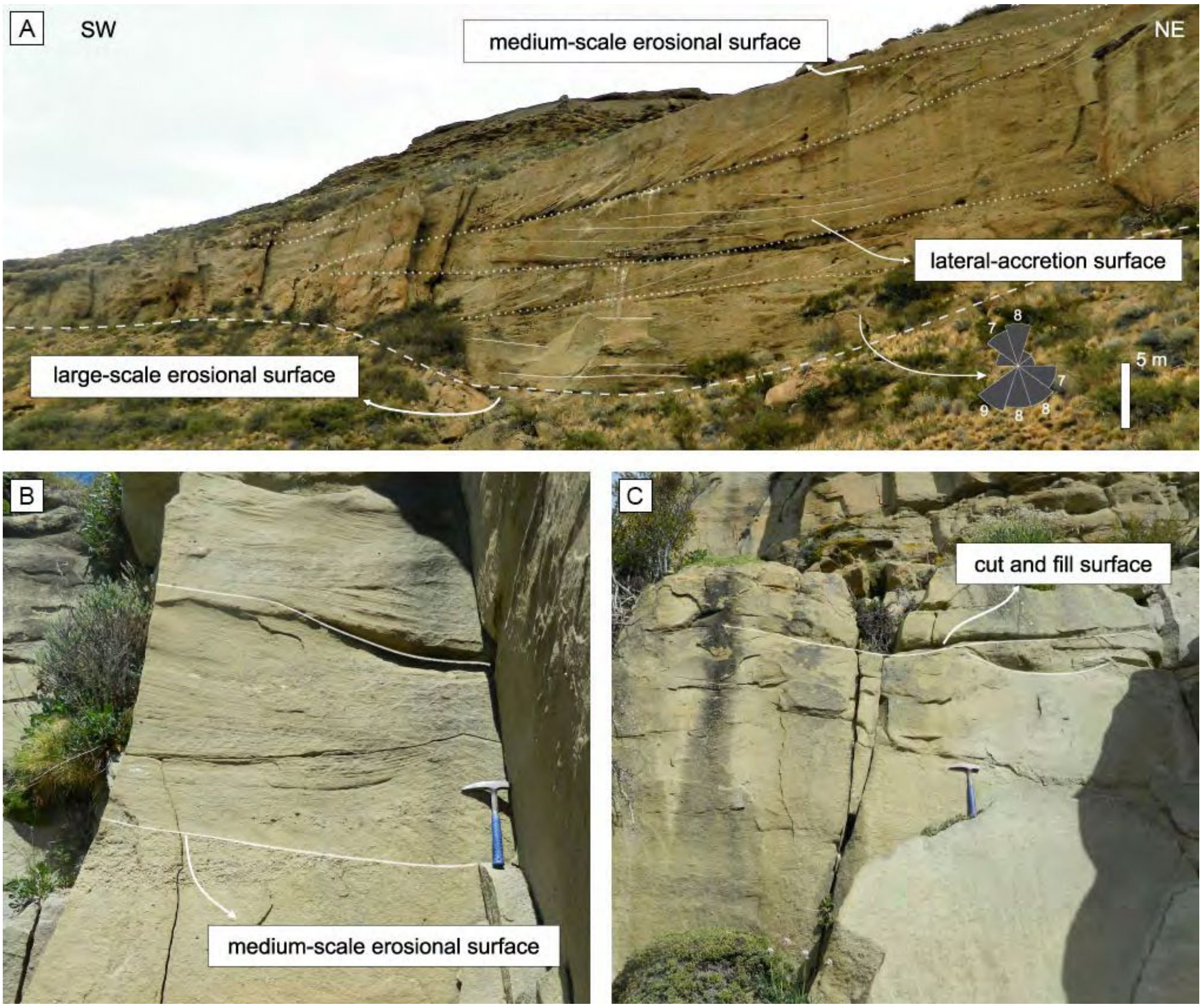

Figure 7. Representative outcrop photos of Facies Association 3 (FA3). **a)** Detail of a complex tabular sandy bodies with their bounding surfaces and paleocurrent directions. **b)** Cosets of pebbly-sandstones with cross-bedding, bounded by small-scale erosional surfaces (hammer for scale is 0.35 m long). **c)** Cut and fill surface with orthogonal relationship of paleocurrents in relation to the underlying set (hammer for scale is 0.35 m long).

non-channelized tractive currents (Bridge, 2003). Their convex-up geometry suggest these deposits can be interpreted as crevasse-splays, formed by episodic overbank of channels during flood events (Miall, 1996).

Facies Association 6 (FA6): Heterolithic deposits

Description: FA6 is composed of flaser and wavy laminated, green- and black-colored heterolithic facies (Htf and Htl) disposed in tabular bodies 1 to 5 m thick (Fig. 10a-b). Bases and tops are sharp (Fig. 10a), but tops are frequently truncated by coarser deposits of FA1 and FA3. This FA shows both fining- and coarsening-upward trends, produced by variations in the sand proportion. Leaves and wood fragments are common and well preserved, as well as the rhizoliths. These bodies are commonly associated with fine-grained deposits of FA7 and they were recognized in the localities south of Lago Argentino.

Interpretation: FA6 is interpreted as water-logged floodplains or the infill of abandoned meanders (oxbow lakes deposits; Bridge, 2006). The process of abandonment of a meanders starts with decreasing

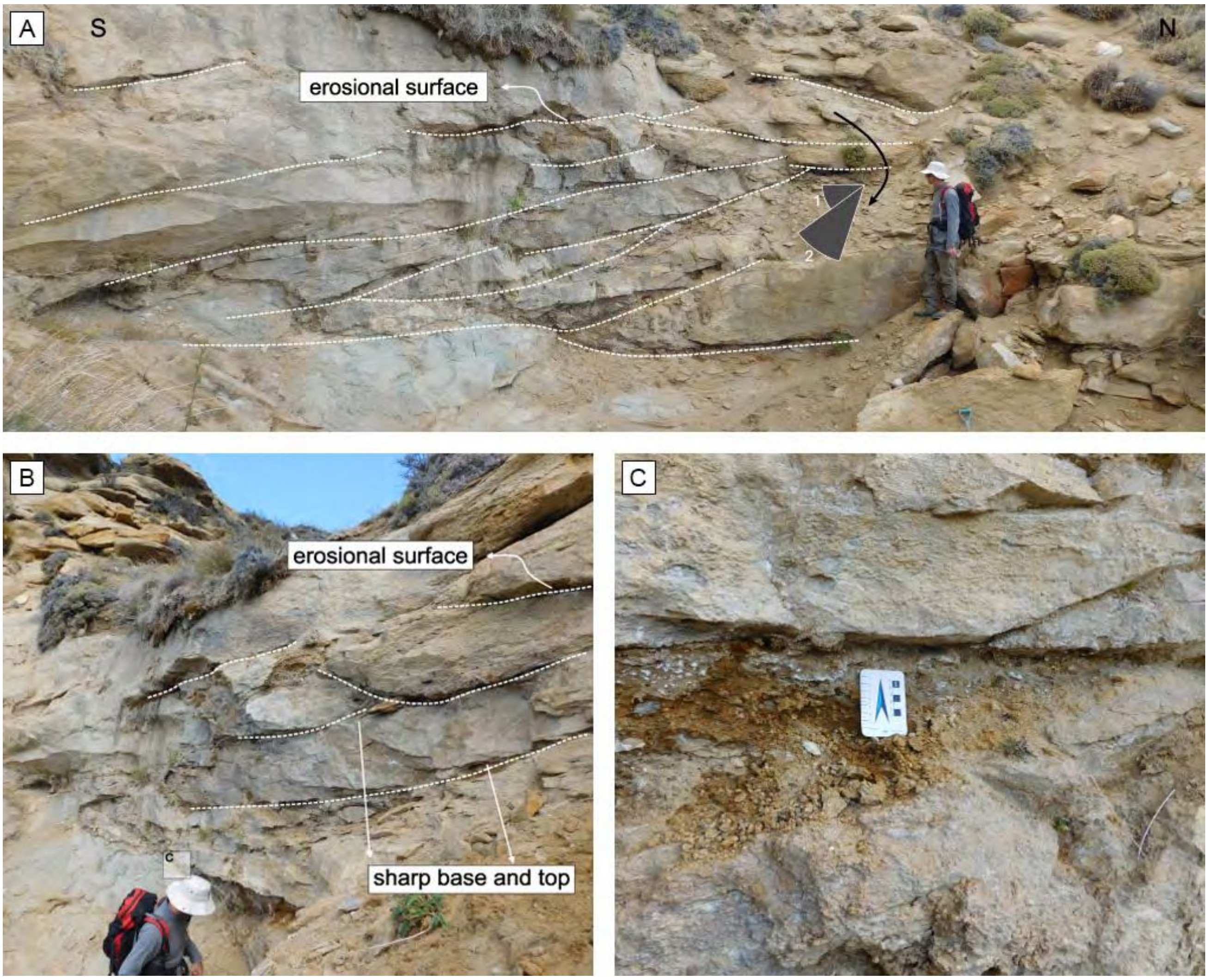

Figure 8. Outcrop photos of Facies Association 4 (FA4). **a)** Overview of simple lenticular sandy bodies with vertical amalgamation (person for scale is 1.8 m high). **b)** Detail of Fig. 8a showing sharp and flat tops and erosional bases of the channels (person for scale is 1.8 m high). **c)** Mud rip-up clasts between the channels.

Figure 9. Outcrop photograph of Facies Association 5 (FA5) showing a lenticular body with sharp base and gently convex-up top (person for scale is 1.8 m high).

Figure 10. a) Photograph of heterolithic deposits of Facies Association 6 (FA6); **b)** Detail showing the variation in sand proportions (coin diameter is 2.3 cm).

flow, reflected in the accumulation of a thick succession characterized by low regime structures (*i.e.* flaser and wavy laminations; *sensu* Bridge, 2006). Completed abandonment and consequent generation of the oxbow lake, the sedimentation is restricted to fine-grained sediment that reach the lake as a consequent overbank of the main channel product of high discharge episodes (Miall, 2010). The well preservation of leave fragments, together with the presence of gley colors indicates a water-logged environment. Moreover, the presence of rhizoliths indicate terrestrial, low-energy conditions with soil development (Retallack, 2001).

Facies Association 7 (FA7): Fine-grained deposits

Description: FA7 consist of gray structureless wackes (Wm) that grade upward into green, gray or reddish structureless mudstones (Fm) and, less commonly, laminated mudstones or siltstones (Fl; Fig. 11). This FA consists of tabular bodies up to 20 m thick and few hundreds of meters of lateral continuity. Frequently, the top of these deposits is truncated by fluvial channels of FA1 and FA3. Internally, facies are disposed in horizontal tabular layers ~0.5 m thick that show sharp to transitional and generally ondulated contacts with fining-upward trends (Fig. 11a). FA7 deposits are characterized by showing pedogenic features recognizable in the field such as blocky and subangular peds, rhizoliths, slickensides, argillic cutans, and Fe/Mn nodules, as well as, leaves and vegetable fragments (Fig. 11b-d). Compositionally, these fine-grained deposits are dominated by expansive clays including smectite and interstratified illite-smectite. FA7 has been recognized in all studied localities.

Interpretation: FA7 is interpreted as the product of settling in fluvial flood plains (Bridge, 2006). Gley colors and the presence of Fe/Mn nodules indicate reductive conditions in paleosols located in low zones of a paleorelief (possibly water-logged; Retallack, 2001). The smectite type clay-minerals are responsible of the generation of slickensides that show evidence of alternation of wet and dry periods (Retallack, 2001). The vertical clay translocations (clay illuviation) in wet environments with dry seasons is reflected in the development of clay-cutans. Pedogenic features indicate soil development. The tabular layers with sharp to transitional, typically ondulated, contacts are interpreted as soil horizons limits. Because of these characteristics, deposits of FA7 are interpreted as cumulative paleosols (Bown and Kraus, 1981, 1987; Smith, 1990), formed in a long period of time (Kraus and Aslan, 1993; Retallack, 2001). The pedofeatures of these paleosols al-

Figure 11. Outcrop photographs of Facies Association 7 (FA7). **a)** Tabular geometries of FA7, showing sharp to transitional and ondulated bed contacts (person for scale is 1.7 m high); **b)** detail of fine-grained deposit bounded on the top by pebbly-sandstones of Facies Association 1; **c)** detail of blocky structure of Facies Association 7; **d)** detail of peds with rhizoliths and slickensides (coin diameter is 2.3 cm).

low us to compare with modern-Vertisols (Soil Sourvey Staff, 1998).

DISCUSSION

Fluvial styles of the UCCD

The analysis of ancient fluvial deposits represents an important disadvantage in comparison with the analysis of present-day fluvial systems. This is especially evident for parameterizing the relationship between channels and bars, or to describe channels sinuosity considering the curvature of the meanders (Brice, 1964; Leopold and Wolman, 1957; Rust, 1978). However, in the last few years these parameters have been the focus of study for ancient deposits (Foix *et al*., 2012; Ghinassi *et al*., 2016). Over the years, many authors have analyzed the transport mechanisms (sediment in suspension vs. bedload), as a key factor in the morphology of the channels (Schumm, 1972; Orton and Reading, 1993; Bridge, 2003). Hence, it is understood that meandering rivers transport a greater amount of sediment in suspension in comparison with braided rivers; although gravelly meandering rivers and silty braided rivers can also exist due to other factors influencing the river pattern such as discharge regime, slope or gradient of the terrain and the erodibility of the bed (Schumm, 1981).

The stratigraphic architecture of these continental deposits allows distinguishing three different fluvial styles: a, b and c (Fig. 12). Fluvial style a corresponds to mix-loaded, sinuous multistory fluvial channel deposits (FA3) which are associated with thicker and finer-grained successions. The latter are dominated by pedogenized floodplain strata (FA7), which alter-

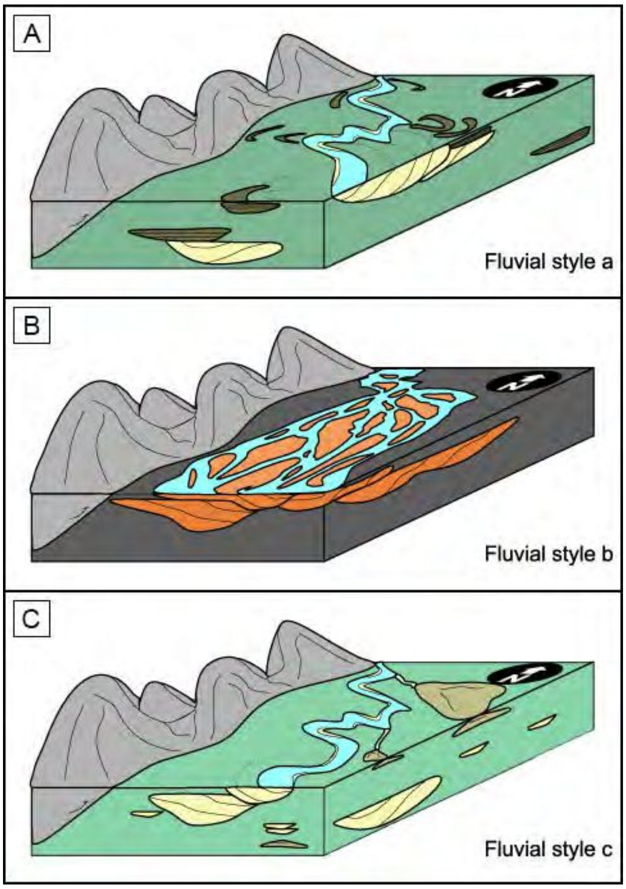

Figure 12. Conceptual models of accumulation in sedimentary paleoenvironments. **a)** Moderate to high sinuosity meandering systems with oxbow lakes deposits (fluvial style a). **b)** Braided system (fluvial style b). **c)** Moderate to high-sinuosity meandering systems with crevasse channels and crevasse splays (fluvial style c).

nate with water-logged floodplain/oxbow lakes deposits that shows finning- and coarsening-upwards trends and abundant phytodetrites and rhizoliths (FA6). This configuration represents meandering fluvial systems characterized by avulsion and meander abandonment (Fig. 12a). Fluvial style a suggests deposition in a relatively distal position respect to the source area (Rust, 1977; Klausen *et al*., 2014).

The fluvial style b is dominated by gravelly sheet multistory fluvial channel deposits (FA1) and tabular bodies of conglomerates with mud rip-up clasts (FA2). This configuration represents the infill of fluvial channel complexes with strongly erosional bases, with development of basal lags and downstream accretion bars that are not attached to channels border (Ghinassi *et al*., 2016). Internally, the bodies show finning-upward trends and minor-scale 2D and 3D dunes migration. This fluvial style reflects deposition in braided fluvial systems dominated by downstream accretion bar migration and erosive processes with scarce to null preservation of their floodplains (Fig. 12b). Deposition under this configuration is considered as relatively proximal respect to the source area of the system (Rust, 1977; Klausen *et al.,* 2014).

Finally, fluvial style c comprises sinuous fluvial channels (FA3) and floodplain, including crevasse channels (FA4), crevasse-splay deposits (FA5) and pedogenized overbank strata (FA7). Channel infills are characterized by multistory belts with large-scale erosive bases and presence of lateral accretion bars with internal finning-upward trends. FA3 channelized bodies are interrupted by three floodplain elements that suggest periodicity of overbank processes during high discharge events (*i.e.* flood event). Fluvial style c represents meandering fluvial systems (Fig. 12c). This fluvial style is differentiated from fluvial style a, because it is dominated by flood events reflected in its floodplains elements. As mentioned before, meandering rivers are associated with mix-load transport. Bedload is deposited inside the channels, while the fine-grained sediments are accumulated at the margins and as overflows during flood episodes (Bluck, 1971; Gustavson, 1978; Forbes, 1983).

Stacking pattern and hierarchical arrangements

The vertical stacking of the seven FAs recognized in the UCCD is represented in the Figure 13. The correlation of sedimentary logs and the spatial distribution of FAs allowed to divide the UCCD into three different depositional stages (Fig. 13). These stages are bounded by major hierarchy erosional surfaces (Fig. 13). Internally, each stage shows different type and proportion of the three fluvial styles previously described (Fig. 12). Moreover, within each stage minor scale erosional surfaces were recorded (Fig. 13). The internal stratigraphic architecture of each depositional stage is explained below.

Stage I: This stage was recorded in the three studied localities south of the Lago Argentino (EA, CeT and CC; Figs. 3, 4, 13). This stage overlies the delta plain deposits of the La Anita Formation through a major hierarchy erosional surface and is overlied by the depositional Stage II through a major hierarchy erosional surface (Fig. 13). The basal erosional surface, is well marked towards the southwest in EA locality and became a paraconformity towards the east (CET and CC localities). Above this erosional surface, depositional Stage I begins with water-logged floodplain/oxbow lake heterolithic deposits of the FA6 that transitionally grade upward to fine-grained flood plain deposits with pedogenic features of FA7. FAs 6 and 7 reflects sedimentation in proximal and distal portions of floodplains respectively. These two FAs correspond to architectural elements of fluvial style a (a_1; Fig. 13). The latter is interrupted in CET section by a minor hierarchy erosional surface followed by sand- and gravel-rich fluvial channel, defined as architectural element of fluvial style b (b_1; Fig. 13). These two architectural elements (a_1 and b_1) are overlyied by architectural element a_2 deposits, which consist of fine-grained floodplain deposits (FA7) with isolated meandering fluvial channel of FA3 (Fig. 13). A new minor hierarchy erosion surface incises into the uppermost interval of the fine-grained deposits of a_2 and it is filled by multi-story braided deposits of the FA1. These deposits correspond to the architectural elements b_2 (Fig. 13). The preservation of fine-grained deposits between each story of braided deposits suggests a process of avulsion and reoccupation of the same area (Fig. 13). Based on the thickness, basal erosional surface and lateral correlation in outcrop the architectural element b_2 probably could be interpreted as a compound paleovalley fill (Holbrook, 2001; Fig. 13). Fluvial style b_2 deposits are covered by fine-grained flood plain and oxbow lake deposits of FAs 6 and 7 which are associated to meandering fluvial channel deposits of the FA3; corresponding to architectural elements of fluvial style a_3 (Fig. 13). A new minor hierarchy erosion surface, bounds the by sand- and gravel-rich deposits of FA1 which conforms the architectural element of fluvial style b_3 (Fig. 13).This could also respond to another compound paleovalley fill. The uppermost interval of the Stage I is characterized by water-logged floodplain /oxbow lakes and fine-grained deposits of FA 6 and 7, which are associated to architectural elements of fluvial style a_5 (Fig. 13).

Stage II: This stage was recorded in the northern localities and also in the CC section (Figs. 3, 4, 13). This depositional stage is located stratigraphically above the depositional Stage I and it is covered by the depositional Stage III, in both cases bounded through major hierarchy erosional surfaces. This stage is differentiated from depositional stage I because it presents architectural elements of fluvial style c and it not present architectural elements of fluvial style a (Figs. 12 and 13). The lowermost interval of this stage was recorded in the EI2 and the CC and it is characterized by the presence of sandy-gravel sheet braided channel deposits of the FA1 which were included in the architectural elements of fluvial style b_4 (Fig. 13). Stage II is dominated by fine-grained deposits (FA7) which are interbedded with amalgamated small-scale channels (FA4) and crevasse-splay deposits (FA5) which corresponds to architectural elements of fluvial style c ($c_1 - c_5$; Fig. 13). The architectural elements of fluvial style c are truncated by minor hierarchy erosional surfaces which are filled by sand-gravelly sheet bodies of FA1 and FA2, defined as architectural elements of fluvial style b ($b_5 - b_9$; Fig. 13). These sheet bodies show aggradational trends (Fig. 13). The presence of conglomerate, composed of mudstones rip-up clasts of FA2, could indicate higher recurrence of flood events or proximity to the source area of the fluvial system toward the top of this stage.

Stage III: The depositional Stage III was recognized in all northern localities and also in the CC section (Figs. 3, 4, 12). It covers the depositional Stage II through a major hierarchy erosional surface and it is overlain by a regional unconformity product of the subsequent marine transgression responsible for the deposition of the Calafate Formation (Odino Barreto *et al.*, this volume). The onset of the depositional Stage III is characterized by multi-story meandering fluvial channel, which are included in the architectural elements of fluvial style c_6 (Figs. 7a, 13). The multi-story, multi-lateral infill of this stage suggests the infill of a compound valley. Floodplain elements are poorly represented in this stage, fine-grained and crevasse-splay deposits were only recorded on the uppermost interval in the EI2 section (Fig. 13).

A/S ratio variations

The combination of control factors such as discharge conditions, the slope of the valley, the accommodation space (A), the sediment supply (S) and the transported grain size results in complex modifications of fluvial systems (Schumm, 1981; Bridge, 1985, 2003; Brierley and Hickin, 1991). The alternation between braided and meandering channel deposits, together

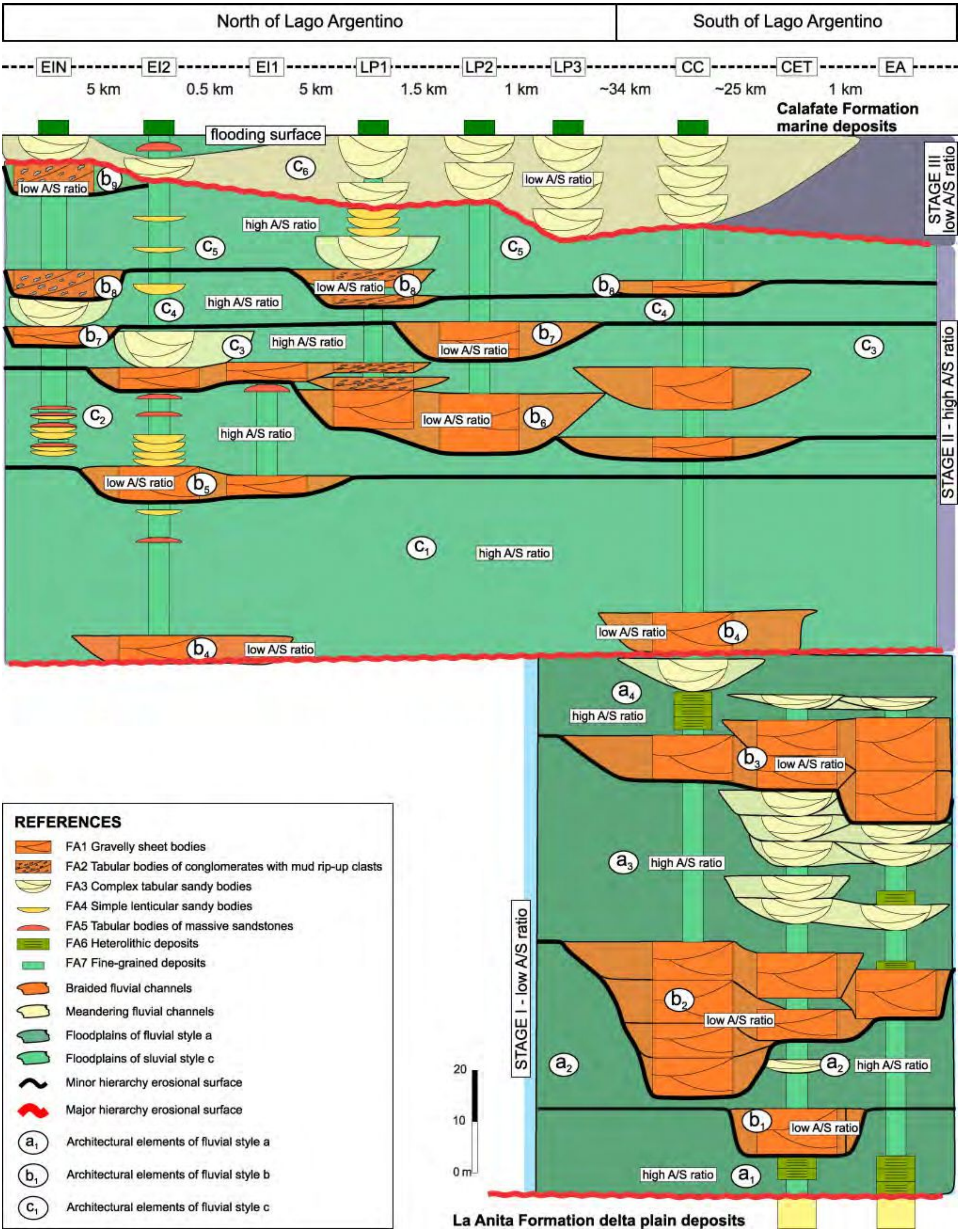

Figure 13. Correlation panel showing spatial distribution of Facies Associations (FAs) both North and South of Lago Argentino and the three depositional stages recognized for the UCCD. The flooding surface of the base of the Calafate Formation was used as correlation datum.

with the floodplains development with different characteristics according to the locality, can be analyzed through A/S ratio variations in time and space. For nonmarine deposits, the establishment of any relationship with a coeval shoreline strata is difficult or even impossible. For this reason, traditional system tracts nomenclatures result inappropriate (Catuneanu, 2006, 2017). Independently of the sea level variations, nonmarine stratigraphic units are defined in terms of changes of accommodation vs. sediment supply (A/S) ratio (*i.e.*, Olsen *et al.*, 1995; Martinsen *et al.*, 1999; Plint *et al.,* 2001; Varela, 2015; Catuneanu, 2017).

The UCCD, at the northern and southern margins of the Lago Argentino, are interpreted as a non-marine lowstand wedge (Legarreta and Uliana, 1991, 1998; Wright and Marriott, 1993; Shanley and McCabe, 1994; Veiga et al., 2008; Jensen and Pedersen, 2010; Varela, 2015). This lowstand wedge overlies the highstand deposits of the deltaic system of the upper unit of the La Anita Formation by a major hierarchy erosional surface and it is covered by the transgressive shallow-marine deposits of the Calafate Formation (Odino Barreto *et al.*, this volume).

The UCCD shows internally different hierarchy cycles of both high and low accommodation vs. sediment supply ratio (A/S). The three stages defined for de UCCD represent the low-frequency cycles. Stage I represent a low frequency low A/S ratio interval due to the high proportion of channel deposits (Fig. 13). The Stage II reflects a low frequency higher A/S ratio than Stage I because of the higher preservation of floodplain deposits. Finally, depositional Stage III represent low frequency low A/S ratio interval because of high amalgamation of channel deposits.

Internally, each depositional stage shows higher frequency A/S ratio intervals represented in the different architectural elements of the different fluvial styles (Fig. 13). Architectural elements of fluvial style a represent high frequency high A/S ratio periods with high preservation rate of overbank fine-grained floodplain deposits with pedogenic features. By contrary, architectural elements of fluvial style b suggests high frequency low A/S ratio intervals in which the deposition and preservation of coarse-grained sediments is greater than those of fine-grain suggesting null to zero preservation (Fig. 13).The Stage I is represented by four architectural elements of meandering fluvial style (a_1 to a_4; Fig. 13), that are interrupted by the installation of three architectural elements of braided fluvial style (b_1 to b_3; Fig. 13), evidencing high frequency variations in the A/S ratio. The Stage II is also characterized internally by high frequency variations in A/S ratio related to the vertical alternation of coarse-grained braided fluvial styles (b_4 to b_9) and high-sinuosity meandering fluvial styles (c_1 to c_5; Fig. 13). Architectural elements of braided fluvial style b represent high frequency low A/S ratio intervals, whereas architectural elements of meandering fluvial style c represent high frequency high A/S ratio periods (Fig. 13). Finally, the depositional Stage III of the UCCD is characterized entirely by deposits of architectural elements of fluvial style c_6. Although deposits of fluvial style c are associated with high A/S ratio time intervals, the scarce to null proportion of fine-grained deposits and the development multi-story amalgamated channel (Fig. 12) is associated to the infill of a compound valley developed in a low A/S ratio time interval.

Considering the UCCD succession, it should be noted that the Stage II reflects higher A/S ratio than the Stage I. This upward increase of accommodation space, in detriment of sediment supply, is probably related with an increase of subsidence rate associated with tectonic uplift in the adjacent mountain belt (Heller *et al.*, 1988; Fosdick *et al.,* 2011). The strong amalgamation of channel bodies in the depositional Stage III indicates that this stage shows the lowest A/S ratio of the UCCD. The major hierarchy erosional surfaces located at the base of each depositional stage are interpreted as sequence boundaries (SBs). These SBs could be related to tectonic quiescence periods (Heller *et al.*, 1988; Leeder, 1993; Varela, 2015). On the other hand, high frequency variations within each stages can be a response of both climatic and/or tectonic controls that probably have influence in the stratigraphic architecture of these deposits and their internal boundaries. However, there is not a clear field evidence relation with a coeval shoreline (*i.e.* the La Anita Formation shoreline, Moyano Paz *et al.,* this volume) which could allow an accurate and detailed sequence stratigraphic model (Martinsen *et al.*, 1999).

CONCLUSIONS

The Upper Cretaceous Continental Deposits of the Austral-Magallanes Basin were studied at nine localities of the southwestern sector of Santa Cruz province. The facies, architectural and stacking pattern analysis of these deposits allowed us to reach the following main conclusions.

Three different paleoenvironmental fluvial styles were defined for the UCCD: fluvial style a is interpreted as moderate to high sinuosity meandering fluvial systems dominated by avulsion and meander abandonment processes; fluvial style b represents braided fluvial systems; and, fluvial style c records moderate to high sinuosity meandering fluvial system deposits dominated by overbank flood. Paleocurrent analysis evidences an average southeastward flow direction for the three fluvial styles.

The studied succession was divided into three major depositional stages according to the vertical stacking of FAs. Stage I, which is characterized by the alternation of fluvial styles a and b, was only recorded in the southern margin of Lago Argentino. Stage II represented by an alternation of fluvial style b and c and it was recorded in both north and southern localities. Depositional Stage III is represented entirely by amalgamated bodies of fluvial style c.

The UCCD shows internally different hierarchy cycles of both high and low accommodation vs. sediment supply ratio (A/S). In this regard, low-frequency cycles of A/S ratios were called Stages (I to III), while high-frequency cycles were identified with fluvial styles (a, b, c). Stages I and III represents low frequency low A/S ratio interval due to the high proportion of channel deposits (Fig. 13). The Stage II reflects low frequency higher A/S ratio than Stage I because of the higher preservation of floodplain deposits. Considering the high-frequency variations in the A/S ratio, which were recognized in stages I and II, the low A/S ratio periods are interpreted from architectural elements of braided fluvial styles b, in which channels are amalgamated and floodplains processes relegated, while high A/S ratio periods are interpreted from architectural elements of meandering fluvial styles a and c.

Stages I and II record an upward rise of the base level of the system, due to the evidence of avulsion and abandonment of channels in the Stage I, and the aggradation and preservation of overbank deposits in the Stage II. Depositional Stage III shows the lowest A/S ratio and this could be related with a rise of the base level, before the marine transgression of the Calafate Formation. Because of the position of the UCCD in relation with the active orogenic front, tectonic activity is considered as the main factor controlling these low-frequency cycles.

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