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Tectonic control of accommodation space and sediment supply within the Mata Amarilla Formation (lower Upper Cretaceous) Patagonia, Argentina

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ABSTRACT

The Mata Amarilla Formation dates from the early Upper Cretaceous and was deposited during a transition in tectonic regime from the extensional Rocas Verdes Basin to the Austral Foreland Basin. Detailed sedimentological logs and architectural parameters were used to define 13 facies associations. The distribution of facies associations and associated variations in fluvial architecture have enabled large-scale changes in accommodation space/sediment supply ratios (A/S ratio) to be defined for the three component sections of the Mata Amarilla Formation. The lower and upper sections are characterized by a high A/S ratio, whereas the middle section corresponds to a low A/S ratio. In the western part of the study area, small-scale variations in the A/S ratio were recognized in the middle section. The strong west to east trend in evolution of the fluvial systems coincides with the direction of propagation of the Patagonian fold and thrust belt, which is located to the west of the study area. Intervals of high A/S ratio (i.e. lower and upper sections) are interpreted to have developed during periods of increased loading by the fold and thrust belt caused by tectonic uplift. In contrast, intervals of low A/S ratio (i.e. middle section) were developed during periods of tectonic quiescence. This article suggests that the large-scale variations in A/S ratios are related to different rates of migration and growth of the Patagonian fold and thrust belt, whereas the small-scale variation occurred in response to specific periods of thrusting and folding in the Patagonian fold and thrust belt (i.e. local loads). This field example of the effects of different scales of variation in A/S ratios across the Austral Foreland Basin could be used to recognize similar tectonically forced variations in stratigraphic architecture in other foreland basins throughout the world, as well as to understand the response of fluvial systems to such changes.

Keywords Architectural stacking patterns, Austral Foreland Basin, fluvial sedimentology, Late Cretaceous, Patagonian fold and thrust belt, tectonic control.

INTRODUCTION

Sedimentological analysis often aims to quantify the extrinsic factors (tectonics, eustasy and climate) that controlled the deposition of a sedimentary succession (e.g. Van Wagoner, 1995, 1998; Yoshida *et al.*, 1998; Yoshida, 2000). It is well-established that relative sea-level fluctuations control the architecture of numerous marine and marginal marine sedimentary successions but, in continental basins, climate can produce similar architectural changes (Blum &

Törnqvist, 2000). Identifying changes in the ratio of accommodation space to sediment supply (A/S ratio) is an effective method for understanding the variations in sedimentary successions in non-marine environments and to consider the extrinsic factors that control these changes (Wright & Marriott, 1993; Shanley & McCabe, 1994; Martinsen *et al.*, 1999; Howell & Flint, 2003; Huerta *et al.*, 2011). Changes in geometry, dimensions, density and distribution of channelized units (for example, from low-density simple ribbons to high-density sheet-like bodies) have been modelled in laboratory experiments and observed in field data (Bridge & Leeder, 1979; Leeder, 1993; Wright & Marriott, 1993; Shanley & McCabe, 1994). A low A/S ratio favours lateral channel migration and the development of sheet-like deposits with high width/thickness (w/t) ratios (Wright & Marriott, 1993; Shanley & McCabe, 1994; Friend, 1983; Huerta *et al.*, 2011); in contrast, a high A/S ratio favours the development of simple ribbon-shaped channels with low w/t ratios and more complete preservation of out of channel deposits (Friend, 1983; Wright & Marriott, 1993; Shanley & McCabe, 1994; Huerta *et al.*, 2011).

The aims of this contribution are to characterize and analyse the Mata Amarilla Formation through detailed sedimentological observations and analysis of architectural elements in order to interpret the influence of allocyclic factors (source area tectonism, basin subsidence, eustasy and climate). The early Late Cretaceous Mata Amarilla Formation is a key element in the understanding of the transition from the rift/thermal subsidence stages to the foreland stage of the Austral Basin (Varela *et al.*, 2012a). The Mata Amarilla thus shows changes in the architectural arrangement and distribution of sedimentary environments that may have been influenced by the growth of the proto-Andes and the evolution of the Patagonian fold and thrust belt.

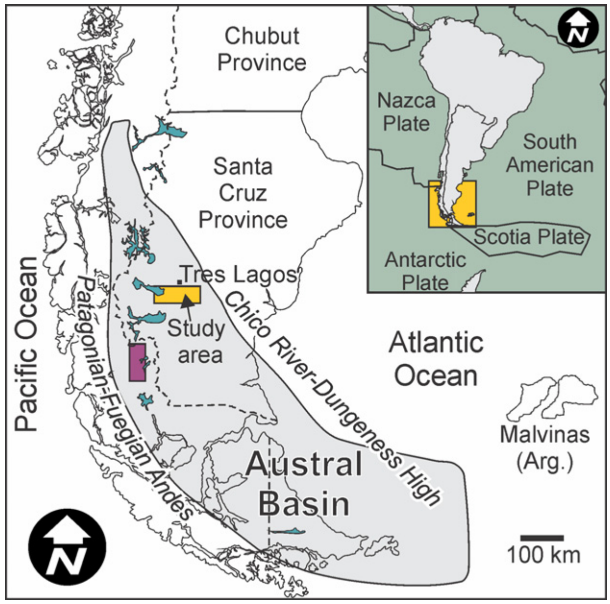


Fig. 1. Geological setting of the Austral Basin and location of the study area (yellow rectangle). The region of the Torres del Paine National Park and Última Esperanza District in Chile, where the basin is known as the Rocas Verdes and Magallanes basins, is also located (purple rectangle).

GEOLOGICAL SETTING

The Austral Basin is located at the south-western end of the South American plate (Fig. 1) where it crops out at the southern end of Argentina and Chile. The Austral Basin is known in Chile as the Rocas Verdes Basin and Magallanes Basin (Figs 1 and 2). Its shape is elongated north–south and it widens to the south; the eastern edge is demarcated by the Chico River–Dungeness High (Fig. 1). The western edge is tectonic in origin, formed by uplift of the Patagonian–Fueguian Andes, while the southern boundary is a transform fault that separates the South American plate from the Scotia plate (Fig. 1). The evolution of the Austral Basin in the study area (Fig. 1) differs from the evolution of the linked Rocas Verdes – Magallanes Basin further to the south (Fig. 1), in that the former was not subject to sea-floor spreading (Fig. 2). The Rocas Verdes Basin is a Late Jurassic–Early Cretaceous backarc basin characterized by rifting and sea-floor spreading along the western margin of the Patagonian–Fuegian Andes (Dalziel *et al.*, 1974; Dalziel, 1981; Biddle *et al.*, 1986; Calderón *et al.*, 2007). A change from regional extension to compression occurred during the mid-Cretaceous and produced a retroarc fold–thrust belt and linked foreland basin, known in Chile as the Magallanes Basin (Biddle *et al.*, 1986; Wilson, 1991; Fildani *et al.*, 2003; Fildani & Hessler, 2005; Fosdick *et al.*, 2011; Varela *et al.*, 2012a). The Austral Basin in the study area underwent three main tectonic stages in its history (Biddle *et al.*, 1986; Arbe, 1989, 2002; Robbiano *et al.*, 1996; Kraemer *et al.*, 2002; Peroni *et al.*, 2002; Rodríguez & Miller, 2005; Varela *et al.*, 2012a): (i) a rift stage; (ii) a

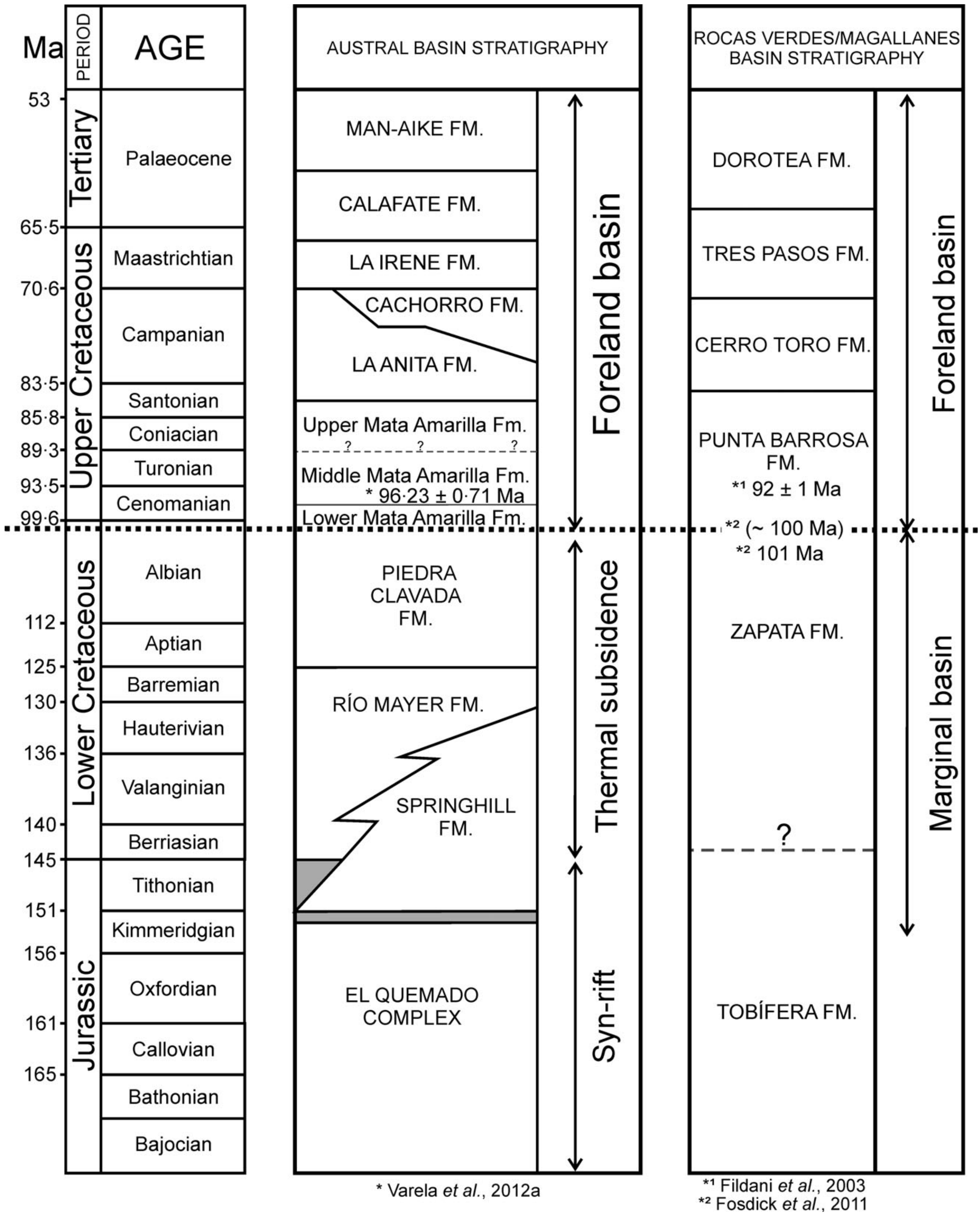


Fig. 2. Stratigraphic scheme of the Cretaceous of the Austral Basin compared to the Rocas Verdes – Magallanes Basin (Fig. 1), modified from Varela *et al.* (2012a). Stratigraphy and data on the Rocas Verdes – Magallanes Basin taken from Fildani *et al.* (2003), Fildani & Hessler (2005), Hubbard *et al.* (2008), Romans *et al.* (2011) and Fosdick *et al.* (2011). Dashed line marks the regional change from an extensional to a compressional tectonic regime.

thermal subsidence stage; and (iii) a foreland stage (Fig. 2). The rift and thermal subsidence stages of the Austral Basin mainly coincide with deposition of the Rocas Verdes basin fill, whereas the foreland stage of the Austral Basin is simultaneous with the evolution of the Magallanes Basin (Fildani *et al.*, 2003; Fildani & Hessler, 2005; Hubbard *et al.*, 2008; Romans *et al.*, 2011; Fosdick *et al.*, 2011; Varela *et al.*, 2012a) (Fig. 2).

Rift stage

The rifting stage is related to the break-up of Gondwana (Pankhurst *et al.*, 2000). Diachronism is recognized between the Early–Middle Jurassic volcanism of the Deseado Massif in eastern Patagonia (Marifil and Chon Aike formations) and the Middle Jurassic–earliest Cretaceous volcanism of the Andean Cordillera (El Quemado, Ibañez and Tobífera formations; Fig. 2) (Pankhurst *et al.*, 2000). In this initial stage, grabens and half-grabens were developed and filled with volcaniclastic and volcanic rocks intercalated with epiclastic sediments (Biddle *et al.*, 1986).

Thermal subsidence stage

Subsequently, thermal subsidence resulted in deposition of the transgressive quartzose sandstones of the Springhill Formation (Biddle *et al.*, 1986; Arbe, 1989, 2002; Rodríguez & Miller, 2005) (Fig. 2). The Springhill Formation broadly overlaps the margins of the initial half-graben, and is overlain by a thick deep-marine succession, characterized by alternating black mudstones and marls of the Río Mayer Formation, which extends to the Albian (Richiano *et al.*, 2012, 2013). Towards the end of this stage (early Aptian–Albian), a large passive-margin delta system, the Piedra Clavada Formation, developed in the northern and eastern sectors of the basin (Poiré *et al.*, 2004; Richiano *et al.*, 2012) (Fig. 2).

Foreland stage

The regional change from extension to compression took place in the mid-Cretaceous, as a result of the convergence of an arc and/or a craton to the South American continent, thus causing obduction of the ophiolite, which constituted the sea floor of the Rocas Verdes Basin, over the cratonic continental margin (Dalziel, 1981; Ramos, 1989). It has not been possible to determine the exact timing of obduction, but the compression associated with the early stages of the orogeny caused the development of a retro-arc fold and thrust belt along the Patagonian–Fuegian Andes (Ramos *et al.*, 1982; Biddle *et al.*, 1986; Wilson, 1991; Fildani *et al.*, 2003; Fildani & Hessler, 2005). This Patagonian fold and thrust belt is associated along its eastern margin with a foreland basin (Austral – Magallanes Basin; Fig. 1). This compressional regime extended from the Upper Cretaceous to the Neogene (Ramos *et al.*, 1982; Biddle *et al.*, 1986; Wilson, 1991; Spalletti & Franzese, 2007; Fosdick *et al.*, 2011). The onset of the shortening phase in the northern sector of the Austral Basin took place *ca* 100 Ma and is recorded within sediments of the Mata Amarilla Formation (Varela, 2011; Varela *et al.*, 2012a, 2013). In Chile, on the other hand, in the region of the Torres del Paine National Park and in the Última Esperanza District (Fig. 1), the compressional phase of the Magallanes Basin occurs in the transition from the shelfal, shallow-marine Zapata Formation to the deep-marine Punta Barrosa Formation (Wilson, 1991; Fildani *et al.*, 2003; Fildani & Hessler, 2005; Fig. 2). The transition was dated by means of detrital zircons, and the age was estimated by Fildani *et al.* (2003) as being no older than 92 ± 1 Ma. Recently, Fosdick *et al.* (2011) obtained new zircon U-Pb ages from an interbedded volcanic ash in the Zapata–Punta Barrosa transition, suggesting an age of 101 ± 1 Ma. These revised ages indicate that the deformation at 51°30′S began at *ca* 100 Ma (Fosdick *et al.*, 2011) and the ensuing development of the foreland basin occurred simultaneously throughout the basin (Fig. 2).

Mata Amarilla Formation

The Mata Amarilla Formation marks the beginning of the foreland basin stage (Varela, 2011; Varela *et al.*, 2012a). The Mata Amarilla Formation overlies the deltaic Piedra Clavada Formation and underlies the shoreface deposits of the La Anita Formation (Fig. 2). It was deposited during the lower Upper Cretaceous and ranges from upper Albian–lower Cenomanian to Santonian in age (Varela, 2011; Varela *et al.*, 2012a; Fig. 2). Recently, Varela *et al.* (2012a) obtained a precise zircon U-Pb age from a tuff in the middle section of the Mata Amarilla Formation, which yielded an age of $96{\cdot}23 \pm 0{\cdot}71$ Ma (middle Cenomanian).

The Mata Amarilla Formation consists of three sections: the lower, middle and upper (Varela, 2011; Varela *et al.*, 2011, 2012a, 2013), defined by dark colouration and a large proportion of fine-grained sediments in the upper and lower sections (Fig. 3), while the middle section shows a whitish colouration due to a preponderance of sandy sediments (Fig. 3). The lower section of the Mata Amarilla Formation is characterized by mudstones with subordinate fine to medium-grained sandstones in the west (fluvial facies), while to the east it consists of a fining-upward succession of mudstones, heterolithic sediments (containing flaser, lenticular and wavy bedding) and sandstones with herringbone cross-bedding attributed to littoral environments (Varela, 2011; Varela *et al.*, 2011, 2012b, 2013; Griffin & Varela, 2012). The middle section is characterized by conglomerates to coarse-grained sandstones with subordinate mudstones in the west, while to the east it consists of medium to coarse-grained sandstones with subordinate mudstones (Varela, 2011; Varela *et al.*, 2012a, 2013). Finally, the upper section also is characterized by mudstones with subordinate fine to medium-grained sandstones (Varela, 2011; Varela *et al.*, 2012a, 2013).

METHODOLOGY

The study area is located in the south-west of Santa Cruz province, Patagonia, Argentina (Figs 1 and 4), and it coincides with a west–east transect line located to the south and to the east of Lake Viedma (Fig. 4). Eight localities have been studied (Fig. 4), where detailed sedimentary logging was undertaken. On the basis of facies analysis, 13 facies associations were distinguished (Table 1 and Fig. 5). Also, geometrical data, lateral facies variations, bounding surfaces and dimensions of the rock bodies were obtained to determine different depositional architectures (e.g. Friend *et al.*, 1979; Veiga *et al.*, 2008) (Table 1 and Fig. 5). The thickness and length of the different depositional architectures have been corrected for the obliquity of palaeocurrents with respect to the orientation of the outcrop belt.

For the measurement of palaeocurrents, both unidirectional and bidirectional, a *Brunton*® compass (Brunton, Boulder, CO, USA) was used, and the criteria of DeCelles *et al.* (1983) and Bossi (2007) were followed. Palaeocurrents of the lower, middle and upper sections of the Mata Amarilla Formation were measured in planar cross-bedding, trough cross-bedding, imbricated clasts and herringbone cross-bedding. All of the palaeocurrent data were corrected for magnetic declination according to the date on which they were surveyed. Then, the corrected data were treated statistically with the *Stereonet*® program. The data were differentiated according to facies associations.

For individual outcrop localities, the vertical and lateral arrangement of different facies associations is described. The detailed description and interpretation of the facies associations, and their spatial arrangement to define fluvial architecture, were crucial in the definition of the conceptual model of accumulation and in analysis of the factors that controlled their deposition.

FACIES ASSOCIATIONS

Thirteen facies associations (FA) from the Mata Amarilla Formation were identified. A detailed description of each facies association with lateral facies variations, geometrical data, bounding surfaces and scales of the rock bodies (i.e. depositional architecture) is presented below in order

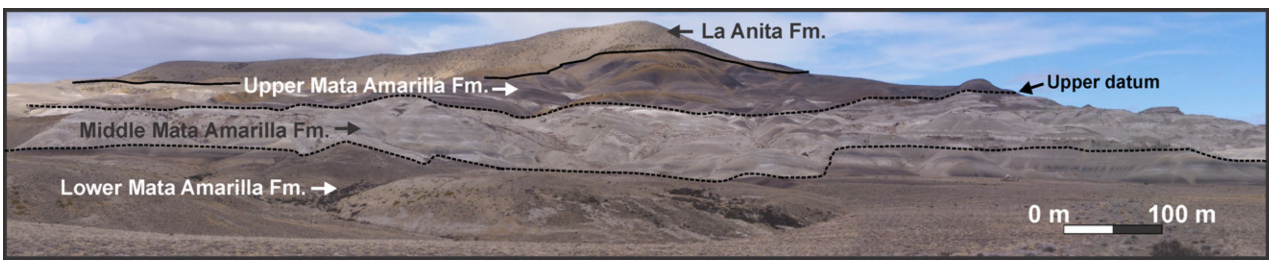


Fig. 3. Panoramic photograph of the Mata Amarilla Formation at La Blanca Farm (LB; Fig. 4). The lower and upper sections (dark-coloured) are predominantly fine-grained, and correspond to distal fluvial and coastal environments containing histosols, histosols with acid sulphate properties and vertisols. The middle section of the Mata Amarilla Formation (light-coloured) has a higher proportion of sandstones, and is characterized by high-sinuosity and low-sinuosity meandering fluvial systems, in which inceptisols and vertisols are developed. At the top of the hill are the outcrops of the La Anita Formation (brown).

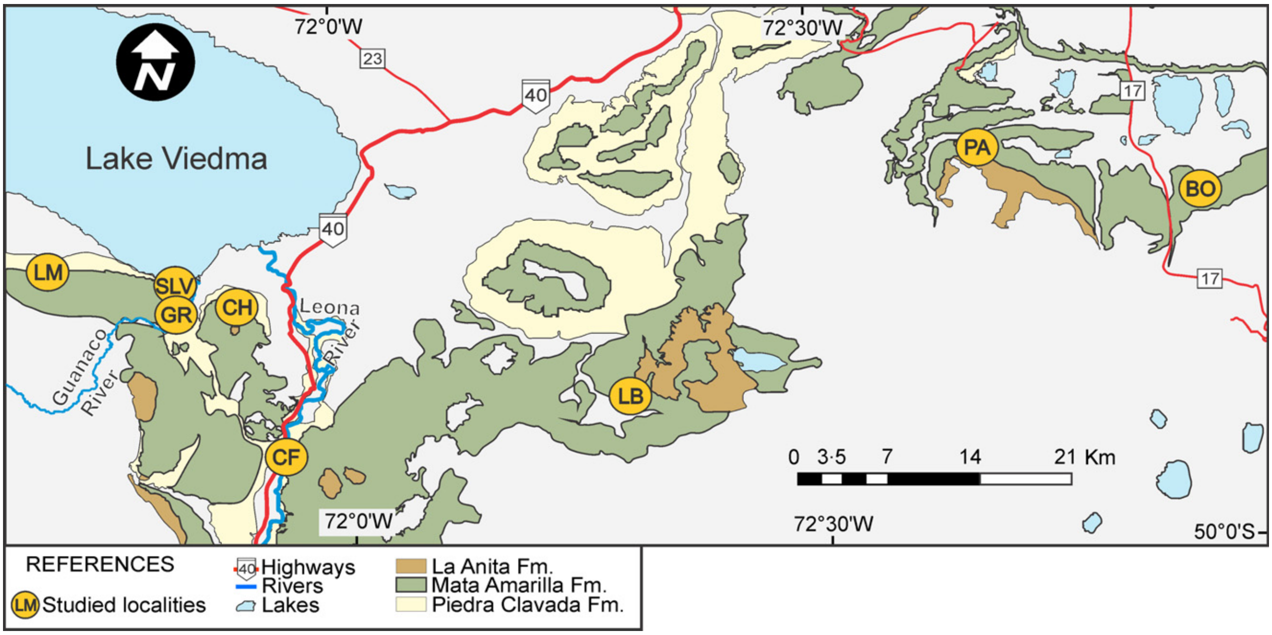


Fig. 4. Geological map of the study area showing outcrop distribution for the stratigraphic units of the Austral Basin (Fig. 2) (after Varela, 2011). Localities: LM, La Marina Outpost; SLV, South of Lake Viedma; GR, Guanaco River; CH, Hornos Hill; CF, Fortaleza Hill; LB, La Blanca Farm (Fig. 3); PA, Pari Aike Farm; and BO, Bajada de los Orientales Farm.

to interpret the different sedimentary palaeoenvironments.

Facies Association 1: Gravelly sheet bodies

Description

This facies association (FA1) consists of bodies ranging from conglomerates to coarse-grained sandstones, which are moderately to poorly sorted, with erosional lower boundaries. They comprise tabular bodies which are 5 m thick on average; at outcrop scale, they have a lateral continuity ranging from 250 m to several kilometres. Internally, they are composed of lenticular amalgamated medium-scale sets and cosets (60 cm thick on average) of large-scale tangential cross-bedding, low-angle planar cross-bedding and, less frequently, trough cross-bedding (Fig. 6A and B). These sets are composed of whitish conglomerates, which are generally pebbly matrix-supported and contain clasts that are well-rounded. The grain size reaches 15 cm, and typically ranges from 5 to 10 cm. Some sets show a fining-upward trend, with concentrations of larger clasts and mud intraclasts at the base, grading upwards to coarse-grained sandstones (Fig. 6A and B). Facies association 1 deposits are composed of volcanic lithic fragments, accompanied by metamorphic basement clasts (Fig. 6C) and are classified as lithic orthoconglomerates (*sensu* Scasso & Limarino, 1997). This facies association is characteristic of the middle section of the Mata Amarilla Formation at the La Marina Outpost (LM) locality, situated in the western part of the study area (Fig. 4). Facies association 1 is usually interbedded with FA8 (see below; Table 1 and Fig. 5).

Interpretation

This facies association (FA1) is interpreted as fluvial channel-belt deposits, where the bedload material was mainly transported as longitudinal downstream accretion bars (Miall, 1996; Bridge, 2003). The three-dimensional nature of these outcrops indicates that FA1 deposits are composed of amalgamated bars (i.e. compound bars; cf. Bridge, 2003; Fig. 6). The fluvial system is interpreted to have been braided with a gravelly bedload. Facies association 1 is usually interbedded with FA8, although these two laterally adjacent FAs are not genetically related (i.e. coeval).

Facies Association 2: Sandy sheet bodies

Description

This facies association (FA2) is characterized by whitish medium to coarse-grained sandstones with trough cross-bedding, and less abundant

Table 1. Summary of facies associations identified in the Mata Amarilla Formation. See text for details.

Facies association	Lithology	Sedimentary structures	Geometry	Dimensions	Bounding surfaces	Interpretation
FA1 Gravelly sheet bodies	Conglomerates to very coarse-grained sandstones	Large-scale tangential cross-bedding, low-angle planar and trough cross-bedding	Tabular at outcrop scale	5 m thick; more than 250 m wide	Base: horizontal and erosional. Top: sharp and horizontal	Braided fluvial system
FA2 Sandy sheet bodies	Coarse to medium-grained sandstones. Rip-up clast conglomerates	Large-scale inclined strata. Medium-scale trough cross-bedding and planar cross-bedding; soft-sediment deformation	Tabular at outcrop scale. Lenticular storeys	1 to 8 m thick; more than 250 m wide	Base: horizontal and erosional. Top: sharp and horizontal	High-sinuosity meandering fluvial system
FA3 Large-scale complex ribbon bodies	Coarse to fine-grained sandstones. Rip-up clast conglomerates	Trough and planar cross-bedding. Current ripples and cross-lamination. Mud intraclasts	Lenticular	2 to 6 m thick; up to 25 m wide	Base: concave-up and erosional. Top: horizontal. Interfingered with fine-grained deposits	Low-sinuosity meandering fluvial system with aggradation
FA4 Large-scale simple ribbon bodies	Medium-grained sandstones	Mainly massive. Trough and planar cross-bedding. Mud intraclasts	Lenticular	1 to 2 m thick; 8 to 15 m wide	Base: concave-up and erosional. Top: horizontal	Small distributary channels
FA5 Small-scale simple ribbon bodies	Medium to fine-grained sandstones. Rip-up mudclasts	Massive, small-scale trough cross-bedding, horizontal lamination and current ripples. Mud intraclasts. Bioturbation and rhizoliths	Lenticular	0·4 to 1·2 m thick; up to 8 m wide	Base: concave-up and erosional. Top: horizontal	Crevasse channels
FA6 Tabular mud stones and fine-grained sandstones	Fine to very fine-grained sandstones and mudstones in a coarsening upward succession	Massive, horizontal to inclined lamination, current ripples and cross-lamination. Rhizoliths, mottles, cutans and slickensides	Tabular	Coarsening upward sequences 0·5 to 5 m thick	Base: transitional from fine-grained sediments. Top: horizontal and sharp	Levée, crevasse splays

Table 1. (Continued)

Facies association	Lithology	Sedimentary structures	Geometry	Dimensions	Bounding surfaces	Interpretation
FA7 Lobe-shaped bodies	Medium to fine-grained sandstones	Massive, low-angle cross-bedding and current ripples	Lenticular	0·1 to 1·2 m thick; 5 to 15 m wide	Base: sharp and horizontal. Top: sharp, convex-up	Crevasse splays
FA8 Fine-grained deposits	Mudstones	Massive, rhizoliths, mottles, cutans, nodules, concretions and slickensides. Horizontal lamination	Tabular	Centimetres to tens of metres thick	Base and top: horizontal, sharp to transitional	Floodplains, coastal plains
FA9 Heterolithic deposits with continental fossils	Heterolithic intervals	Horizontal, wavy, lenticular and flaser lamination	Tabular	Centimetres to tens of metres thick	Base and top: horizontal, sharp to transitional	Lacustrine sedimentation
FA10 Sandstones with herringbone cross-bedding	Medium to fine-grained sandstones	Herringbone cross-bedding, mud drapes. Bioturbation	Tabular	3 to 6 m thick; more than 50 m wide	Base and top: horizontal, sharp to transitional	Estuarine bars
FA11 Coarsening-upward succession with high-angle planar cross-bedding	Coarse-grained to pebbly sandstones in a coarsening upward succession	Medium-scale high-angle planar cross-bedding. Mud intraclasts and fossil trunks. Bioturbation	Tabular to lenticular	5 to 10 m thick; up to 200 m wide	Base and top: horizontal, sharp to transitional	Bayhead delta mouth bar
FA12 Diamictites with small-scale gravel-filled channel-shaped bodies	Conglomerates to fine-grained sandstones	Massive. Large mud intraclast, vegetable remains and fossil trunks	Tabular and small-scale lenticular	Diamictites: 0·1 to 10 m thick. Channels: 0·2 m thick and 0·6 m wide	Diamictites: (base and top) horizontal, sharp to transitional. Channels: (base) concave-up and erosional: (top) horizontal	Prodelta
FA13 Heterolithic deposits with marine fossils	Heterolithic intervals	Horizontal and cross-lamination, wavy, lenticular and flaser lamination. Bioturbation	Tabular	Centimetres to tens of metres thick	Base and top: horizontal, sharp to transitional	Estuarine bay deposits

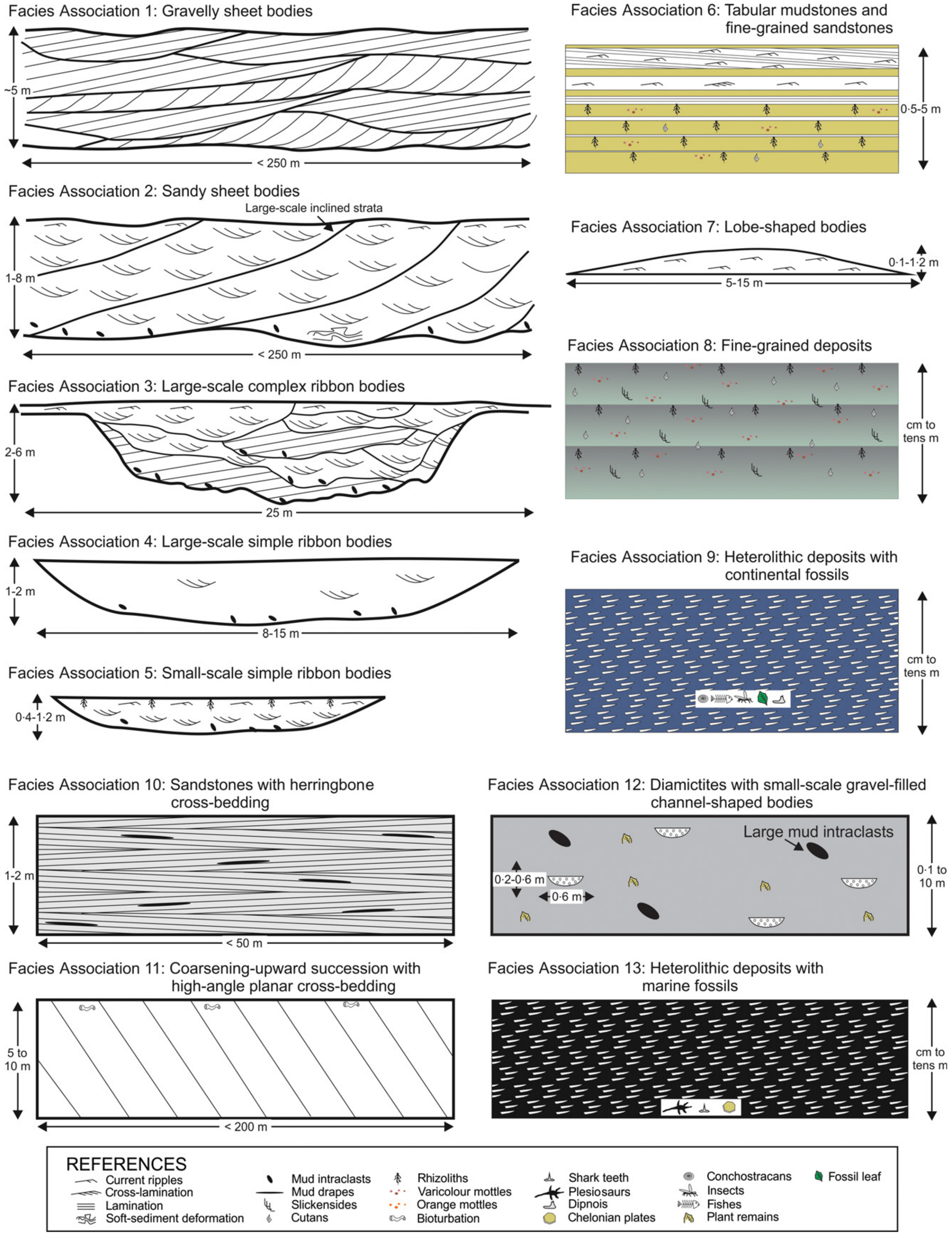


Fig. 5. Graphical summary of dimensions and geometries of units of facies associations identified in the Mata Amarilla Formation in the study area (Table 1). See text for details.

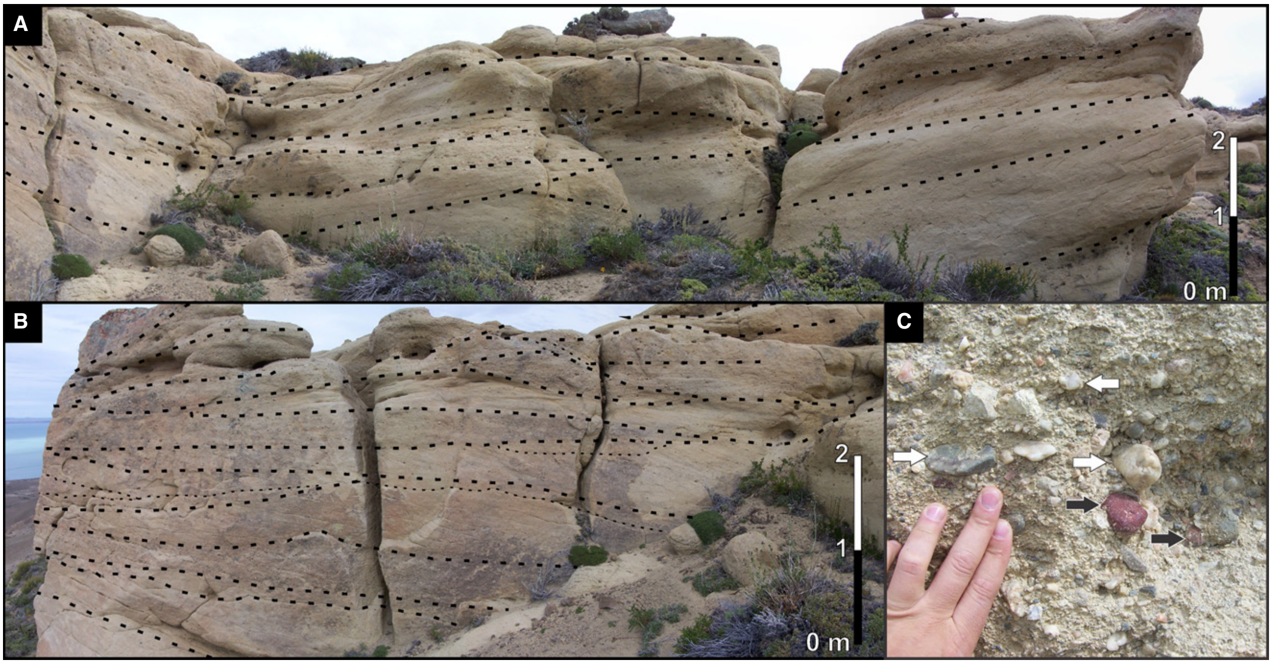
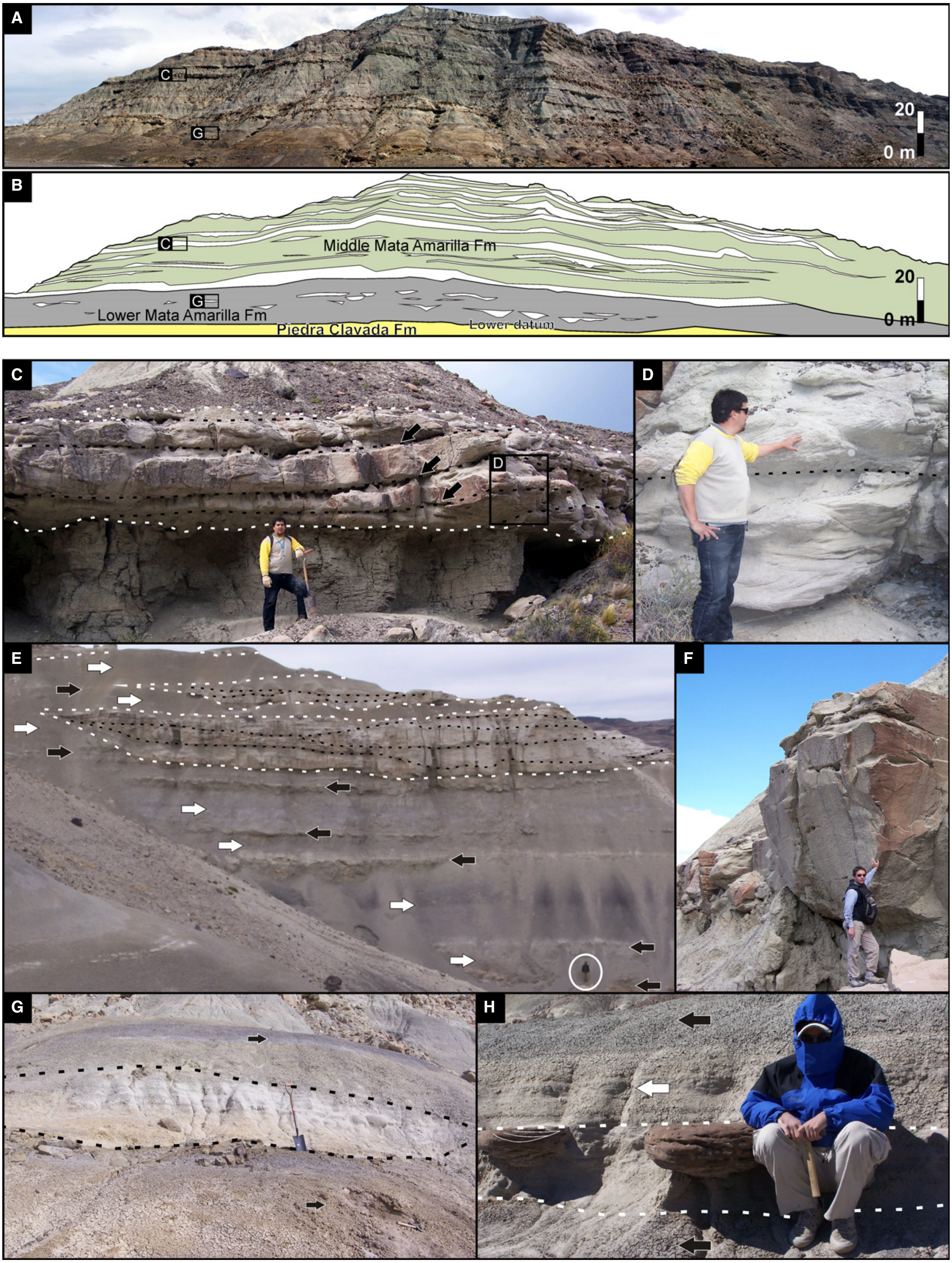


Fig. 6. Photographs of FA1 (gravelly sheet bodies) at the La Marina Outpost (LM) locality with cross-set boundaries annotated: (A) parallel to the mean palaeocurrent; (B) perpendicular to the mean palaeocurrent. (C) Detail of FA1 showing volcanic lithic clasts (black arrows) and metamorphic clasts (white arrows).

planar cross-bedding with mud intraclasts. Towards their bases, bodies of FA2 contain mud clasts up to 8 cm in diameter, and generally between 2 cm and 5 cm. This facies association has a tabular geometry at outcrop scale and occurs in bodies with erosional lower boundaries with a width to thickness ratio >30 (*sensu* Friend *et al.*, 1979; Fig. 7A to D). The typical body thickness is 1 to 8 m and true width >250 m (Fig. 7A and B). Internally, bodies of FA2 contain large-scale inclined surfaces (*sensu* Bridge, 1993), dipping at angles between 10° and 20°, which bound 50 cm thick cosets (Fig. 7C). These surfaces are inclined perpendicular to palaeoflow as measured from trough cross-bedding and planar cross-bedding (Fig. 7D). The clast composition is mostly lithic with abundant volcanic lithic fragments. These sandy sheet bodies erosionally overlie fine-grained deposits of FA8 and are associated with FA6 (Fig. 7C). Facies association 2 characterizes the middle section of the Mata Amarilla Formation at the localities of South of Lake Viedma (SLV), Guanaco River (GR), Hornos Hill (CH), Fortaleza Hill (CF) and La Blanca Farm (LB) (Fig. 7A and B). This facies association is also

Fig. 7. (A) Uninterpreted and (B) interpreted photomontage for the South of Lake Viedma (SLV) locality, showing the relation between FA2 (sandy sheet bodies; white) and FA8 (fine-grained deposits; green) in the middle section of the Mata Amarilla Formation, and between FA4 (large-scale simple ribbon bodies; white) and FA8 (fine-grained deposits; grey) in the lower section of the Mata Amarilla Formation. (C) Sandy sheet bodies (FA2) at South of Lake Viedma (SLV) locality; note the development of large-scale inclined surfaces (black arrows). Person for scale is *ca* 1·8 m tall. (D) Detail of FA2 (sandy sheet bodies) showing trough and planar cross-bedding. (E) Annotated photograph for the middle section of the Mata Amarilla Formation for the La Blanca Farm (LB) locality, showing the relation between FA3 (large-scale complex ribbon bodies) (white dashed lines), FA8 (fine-grained deposits) (white arrows) and FA6 (tabular mudstones and fine-grained sandstones) (black arrows); person in white circle for scale (*ca* 1·8 m tall). (F) FA3 (large-scale complex ribbon bodies) at Fortaleza Hill (CF) locality, note the concave-up, erosional lower boundary and the horizontal top; person for scale. (G) FA4 (large-scale simple ribbon bodies) (black dashed lines) interbedded with FA8 (fine-grained deposits) (black arrows) at South of Lake Viedma (SLV) locality; shovel for scale is 1 m long. (H) FA5 deposits (small-scale simple ribbon bodies) (white dashed lines), note the small-scale trough cross-bedding and the relation with FA6 (tabular mudstones and fine-grained sandstones) (white arrow) and FA8 (fine-grained deposits) (black arrows); person for scale.


A
C
G
20
0 m
B
C
Middle Mata Amarilla Fm
G
Lower Mata Amarilla Fm
Piedra Clavada Fm
Lower datum
20
0 m
C
D
D
E
F
G
H

found in the upper section of the Mata Amarilla Formation, but in bodies of lower w/t ratio (<30) in the localities to the west, including South of Lake Viedma (SLV), Guanaco River (GR) and Hornos Hill (CH).

Interpretation

These multi-storey sandstone-dominated bodies with sheet geometry are interpreted as channel-belt deposits (*sensu* Gibling, 2006). Facies association 2 deposits are mainly related to fluvial in-channel processes, such as migration of sinuous-crested (3D) or straight-crested (2D) dunes or as lag deposits (cf. Clemente & Pérez-Arlucea, 1993; Miall, 2006). The presence of large-scale inclined surfaces within these channel deposits, which are mostly perpendicular to the main orientation of these channels, suggests lateral accretion on the inner bends of highly sinuous channels (Bridge, 1993). They are interpreted as fluvial channel-belt deposits of relatively high-sinuosity, possibly meandering, rivers.

Facies Association 3: Large-scale complex ribbon bodies

Description

This facies association (FA3) is composed of whitish, medium to coarse-grained sandstones in bodies of lenticular to tabular geometry (Fig. 7E) that are generally between 2 m and 6 m thick and *ca* 25 m wide (complex ribbons, *sensu* Friend *et al.*, 1979; w/t ratio between 4 and 12). The bases are concave-up and irregular, while the tops are sharp and horizontal (Fig. 7E and F). This facies association has a complex internal organization, defined by the vertical (and less frequently, lateral) amalgamation of individual channelized units (Fig. 7E and F). These complex ribbons are usually arranged in a fining-upward succession, and internally they show planar and trough cross-bedding. Current ripples are usually present towards the top of the sandbodies, whereas mud intraclasts occur towards their bases. Towards their margins these complex ribbons interfinger with fine-grained deposits to form wings (Friend *et al.*, 1979). Facies association 3 is laterally and vertically associated with FA6, FA7 and FA8. It overlies and passes laterally into FA6 (Fig. 7E) and is often overlain by FA8 (Fig. 7E). This facies association characterizes the middle section of the Mata Amarilla Formation in the eastern part of the study area, at the localities of Bajada de los Orientales Farm (BO), Pari Aike Farm (PA), La Blanca Farm (LB) and Fortaleza Hill (CF).

Interpretation

The large-scale complex ribbon bodies of FA3 were probably deposited by solitary channels with a minor degree of lateral migration, or by relatively straight channels with lateral bars and a meandering thalweg (cf. Veiga *et al.*, 2008). In each case, the mobility of the channels was always restricted to the main erosional bounding surface of the ribbon (Gibling, 2006; Veiga *et al.*, 2008). The channel deposits are vertically stacked with abundant preservation of laterally adjacent floodplain. This facies association is interpreted as the deposits of relatively low-sinuosity, possibly meandering, rivers that underwent aggradation, implying a moderate to high rate of creation of accommodation space.

Facies Association 4: Large-scale simple ribbon bodies

Description

This facies association (FA4) is characterized by single, isolated lenticular-shaped bodies that range from 1 to 2 m thick and from 8 to 15 m wide (low w/t ratio; Fig. 7A and B), and which are filled with whitish medium-grained sandstones (Fig. 7G). The bases are concave-up and irregular, and the tops are sharp and horizontal (Fig. 7G). They usually have no tractional sedimentary structures, but occasionally trough and planar cross-bedding with abundant mud intraclasts at the base of the bodies can be observed. These bodies are associated with FA8 and FA9, as well as with coal beds (Fig. 7G). This facies association is present in the lower section of the Mata Amarilla Formation, in the western part of the study area, at the localities of La Marina Outpost (LM), south of Lake Viedma (SLV; Fig. 7A and B), Guanaco River (GR) and Hornos Hill (CH). Facies association 4 is also found in the upper section of the Mata Amarilla Formation at the Fortaleza Hill (CF) and La Blanca Farm (LB) localities.

Interpretation

This facies association is interpreted to comprise single-story ribbon-shaped channel bodies (*sensu* Gibling, 2006). The occurrence of these deposits as isolated simple bodies within FA8 suggests a simple model of sinuous channels which flowed through muddy coastal plains (cf. Martinsen *et al.*, 1999; Veiga *et al.*, 2008; Varela *et al.*, 2011). This interpretation indicates that the facies association could be perceived as a system of small coastal distributary channels.

Facies Association 5: Small-scale simple ribbon bodies

Description

Bodies of this facies association (FA5) are also characterized by a lenticular external geometry, with an irregular concave-up lower surface, but are smaller than the previously described ribbon-shaped bodies of FA3 and FA4. They are typically between 40 cm and 120 cm thick and they have a lateral extent of 8 m (Fig. 7H). The most conspicuous feature of these small-scale simple ribbon bodies is that they have a simple infill, consisting of white to grey fine to medium-grained sandstones. They are usually massive, but occasionally show small-scale trough cross-bedding, plane parallel lamination and current ripples. Mud intraclasts are always present at the base of the bodies, with diameters averaging 2 cm. Also, they often have bioturbation and rhizoliths with different degrees of palaeosol development (Varela *et al.*, 2012b). Facies association 5 is always associated with FA6 (Fig. 7H) and FA7. Bodies of FA5 are present throughout the whole Mata Amarilla Formation, and have a close lateral and vertical co-occurrence with FA3 (large-scale complex ribbon bodies), FA4 (large-scale simple ribbon bodies) and, less frequently, with FA2 (sandy sheet bodies).

Interpretation

The small-scale channelized geometry of bodies of FA5 implies deposition in crevasse channels generated during episodes of high river discharge or floods, which cut through levées and flowed to low relief areas (cf. Mjøs *et al.*, 1993; Plint & Browne, 1994; Veiga *et al.*, 2008). Their subsequent subaerial exposure, which is indicated by the development of pedological features, supports this interpretation (Varela *et al.*, 2012b).

Facies Association 6: Tabular mudstones and fine-grained sandstones

Description

This facies association (FA6) is characterized by the thin intercalations (<10 cm) of grey to olive green mudstones and whitish fine to very fine-grained sandstones. Beds in this association are generally massive, but sometimes have both horizontal and inclined lamination; current ripples and cross-lamination also occur (Fig. 8A). Pedological features are present, such as rhizoliths, mottles, cutans and slickensides. The outcrop-scale geometry is typically tabular and successions frequently coarsen upwards (Fig. 8A); fining-upwards successions are less common. Facies association 6 has thicknesses ranging from 0·5 to 5 m with sharp to transitional, horizontal bases and tops (Fig. 8A). This facies association is laterally and vertically associated with FA3 (Fig. 7E) and FA4; it is also associated with FA2.

Interpretation

Coarsening and thickening upward heterolithic successions closely related to floodplain deposits can be interpreted as the result of progradation of levées (Bridge, 2003) or crevasse splays, related to overbank flows close to the channel margins (Clemente & Pérez-Arlucea, 1993; Mjøs *et al.*, 1993; Miall, 1996). The vertical and lateral association with FA3 and FA4 (fluvial channels) suggests that these deposits represent accumulation in proximal floodplain environments. This facies association is interpreted as levées and crevasse splay deposits. The presence of pedological features provides evidence of subaerial exposure and soil development (Retallack, 2001). Palaeosols associated with FA6 are interpreted as inceptisols (Varela *et al.*, 2012b).

Facies Association 7: Lobe-shaped bodies

Description

This facies association (FA7) is composed of whitish fine to medium-grained sandstones, which are predominantly massive. Low-angle cross-bedding and current ripples are also present locally. Facies association 7 is characterized by an external lenticular geometry with sharp horizontal basal surfaces and convex-up tops. These lensoidal-shaped bodies are between 0·1 m and 1·2 m thick and their lateral extent varies between 5 m and 15 m (Fig. 8B). Mud intraclasts and plant remains are commonly present at the base of these lobe-shaped bodies. The palaeocurrent directions measured in the low-angle cross-bedding and the axes of the lobes generally tend to be perpendicular to the flow direction of the main channels.

Interpretation

This association is attributed to isolated overflow deposits during flooding periods, in small crevasse splays. These deposits are characterized

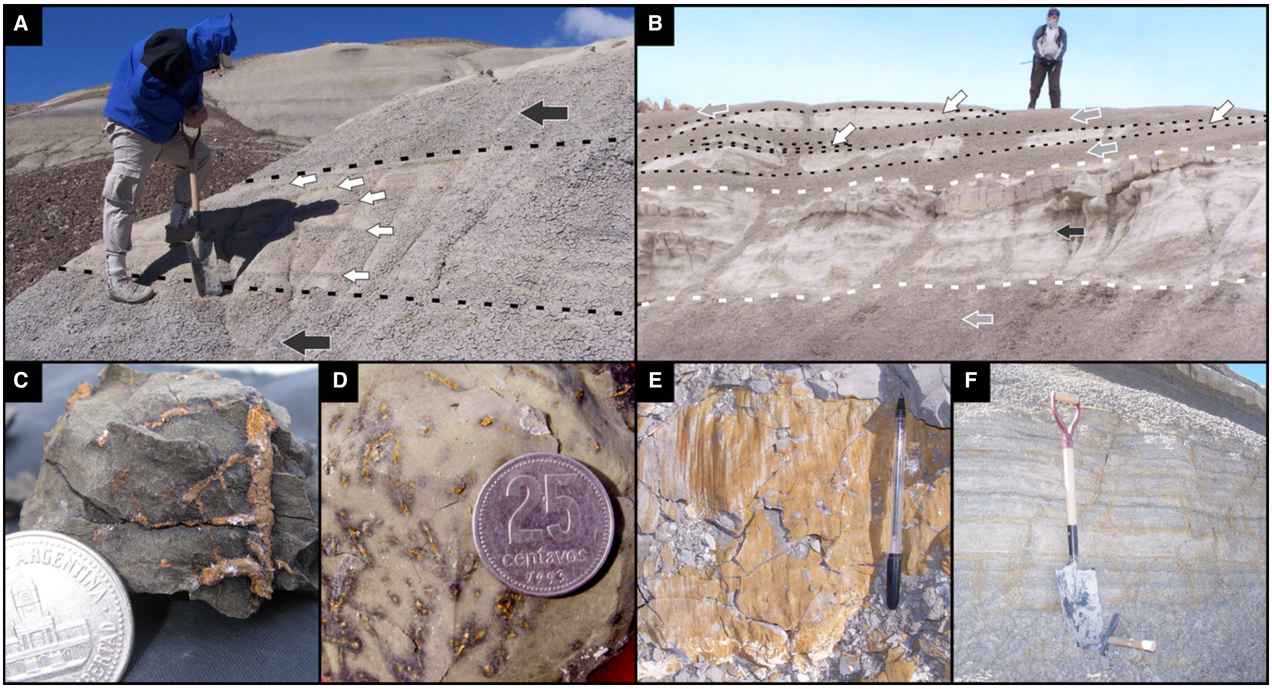


Fig. 8. (A) FA6 (tabular mudstones and fine-grained sandstones) (black dashed lines) with horizontal to inclined lamination (white arrows), interbedded with FA8 (fine-grained deposits) (black arrows); person for scale (*ca* 1·8 m tall). (B) FA7 (lobe-shaped bodies) (white arrows) at La Blanca Farm (LB) locality, note the sharp, horizontal bases and convex-up tops, and the association with FA8 (fine-grained deposits) (grey arrows) and FA2 (sandy sheet bodies) (black arrow). Pedological features of FA8 (fine-grained deposits); (C) rhizoliths; coin for scale is 2·5 cm; (D) orange mottles; coin for scale is 2·5 cm; (E) slickensides; pen for scale is 15 cm long. (F) FA9 (heterolithic deposits with continental fossils) at Bajada de los Orientales Farm (BO) locality; shovel for scale is 1 m long.

by their simple internal structure and lenticular geometry, which implies that they might be related to single flooding events (Mjøs *et al.*, 1993). In contrast, more complex deposits such as FA6 (crevasse splays), suggest multiple periodic flooding events (Mjøs *et al.*, 1993; Miall, 1996). These overflow events occurred towards the vegetated floodplains that are in topographically depressed areas, so the quick deposition of sand buried vegetation on the floodplain, leaving an exceptional record of angiosperm flora (Iglesias *et al.*, 2007; Varela, 2011; Varela *et al.*, 2012b).

Facies Association 8: Fine-grained deposits

Description

This facies association (FA8) is composed of grey to olive green mudstones, generally massive, with abundant pedogenic structures such as rhizoliths, mottles, nodules, cutans and slickensides (Fig. 8C to E); lamination is rarely preserved. The geometry is tabular; the bases and tops are sharp to transitional, and thicknesses range from centimetres to tens of metres (Fig. 7C, E and G). These fine-grained deposits have hydromorphic features, such as the presence of grey colours (in shades of grey and green), the preservation of roots with organic matter, mottles with purple halos and small nodules of iron and manganese (Varela *et al.*, 2012b). This association is present in all localities and sections of the Mata Amarilla Formation.

Interpretation

This facies association is interpreted as distal floodplains and coastal plains with palaeosol development. The abundance of hydromorphic features indicates that palaeosol development occurred under waterlogged drainage conditions (Varela *et al.*, 2012b).

Facies Association 9: Heterolithic deposits with continental fossils

Description

This facies association (FA9) is characterized by an alternation of centimetre-scale layers of greenish-grey to bluish-green mudstones and whitish fine-grained sandstones. The most common sedimentary structures are both parallel and cross-laminations, ripples, and flaser, lenticular and wavy bedding. The external geometry of bodies of FA9 is tabular, the bases and tops of the bodies are sharp to transitional and their thickness varies from centimetres to tens of metres (Fig. 8F). Successions of FA9 usually exhibit an increase in the proportion of sand in the heterolithic intervals towards their tops, with sandstone beds thickening-upwards. Facies association 9 is laterally and vertically interbedded with FA8, and has abundant plant remains, fish scales and remains, vertebrates and insects. This association is characteristic of the middle section of the Mata Amarilla Formation at the Bajada de los Orientales Farm (BO) locality. It is also found in the upper section in the localities of Pari Aike Farm (PA), Hornos Hill (CH) and Fortaleza Hill (CF; in this case, intercalated with coal beds).

Interpretation

The presence of flaser, lenticular and wavy structures demonstrates evidence of alternating traction and suspension-settling processes (Collinson & Thompson, 1989). Evidence of tidal processes, in the form of bidirectional palaeocurrents or marginal marine trace fossil assemblages, is absent. This facies association is interpreted as lacustrine deposits in completely waterlogged floodplains and/or as infilled oxbow lakes (Varela, 2011).

Facies Association 10: Sandstones with herringbone cross-bedding

Description

This facies association (FA10) consists of grey to greyish-green sandstones with yellowish staining, whose grain size ranges from fine to medium (Fig. 9A and B). It is characterized by herringbone cross-bedding, composed of low-angle cross-bedding sets occurring in opposing directions (Fig. 9B). Mud drapes are frequent and are internally grouped into 20 to 30 cm thick sets. The geometry of FA10 units is tabular at outcrop scale, and they are between 3 m and 6 m thick, with 50 m of lateral extent (Fig. 9A). This facies association is not intensely bioturbated, but contains rare *Skolithos* isp., *Planolites* isp. and *Ophiomorpha* isp. Facies association 10 has an abundant fossil content, including plesiosaur and fish remains, as well as shark and plesiosaur teeth, together with abundant plant remains (O'Gorman & Varela, 2010; Varela, 2011). This facies association is associated with FA13 (Fig. 9A) and underlies FA12 and FA11, characterizes the lower section of the Mata Amarilla Formation at the La Blanca Farm (LB) locality and is also present in the upper section of the Mata Amarilla Formation at the Hornos Hill (CH) locality.

Interpretation

These sandstones with herringbone cross-bedding exhibit typical tidal structures (Dalrymple *et al.*, 1992; Boyd *et al.*, 2006) and are interpreted as the deposits of subtidal sand bars in an estuarine environment. The abundant body fossil content (plesiosaur and fish remains, shark and plesiosaur teeth, together with abundant plant remains) and assemblage of trace fossils (*Skolithos* isp., *Planolites* isp. and *Ophiomorpha* isp.) which are feeding and dwelling traces in loose substrate (Pemberton *et al.*, 1982; Ekdale *et al.*, 1984; MacEachern *et al.*, 2005), support this interpretation. It is important to highlight the close association of FA10 with FA11, FA12 and FA13, which in combination are interpreted as an assemblage of inner to central estuarine environments. Facies associations 10 and 13 represent the central-estuarine environment and FA11 and FA12 are interpreted to represent the inner-estuarine environment, as outlined below.

Facies Association 11: Coarsening-upward succession with high-angle planar cross-bedding

Description

This facies association (FA11) is composed of yellowish-white coarse-grained to pebbly sandstones with a high lateral continuity (>200 m; Fig. 9C). The dominant sedimentary structures are medium-scale, high-angle planar cross-bedding; locally FA11 shows trough cross-bedding. The external geometry of bodies of FA11 is tabular to lenticular and their thickness is between 5 m and 10 m; these bodies show a coarsening-upward succession with abundant *Arenicolites* isp. and *Skolithos* isp. towards the top. This association has abundant mud intraclasts and occasional transported gymnosperm trunks of the *Podocarpaceae* family, which are characterized by *Teredolites* isp. Facies association 11 is vertically associated with FA12 and FA13. This facies association occurs in the lower section of the Mata Amarilla Formation at the La Blanca Farm (LB) locality.

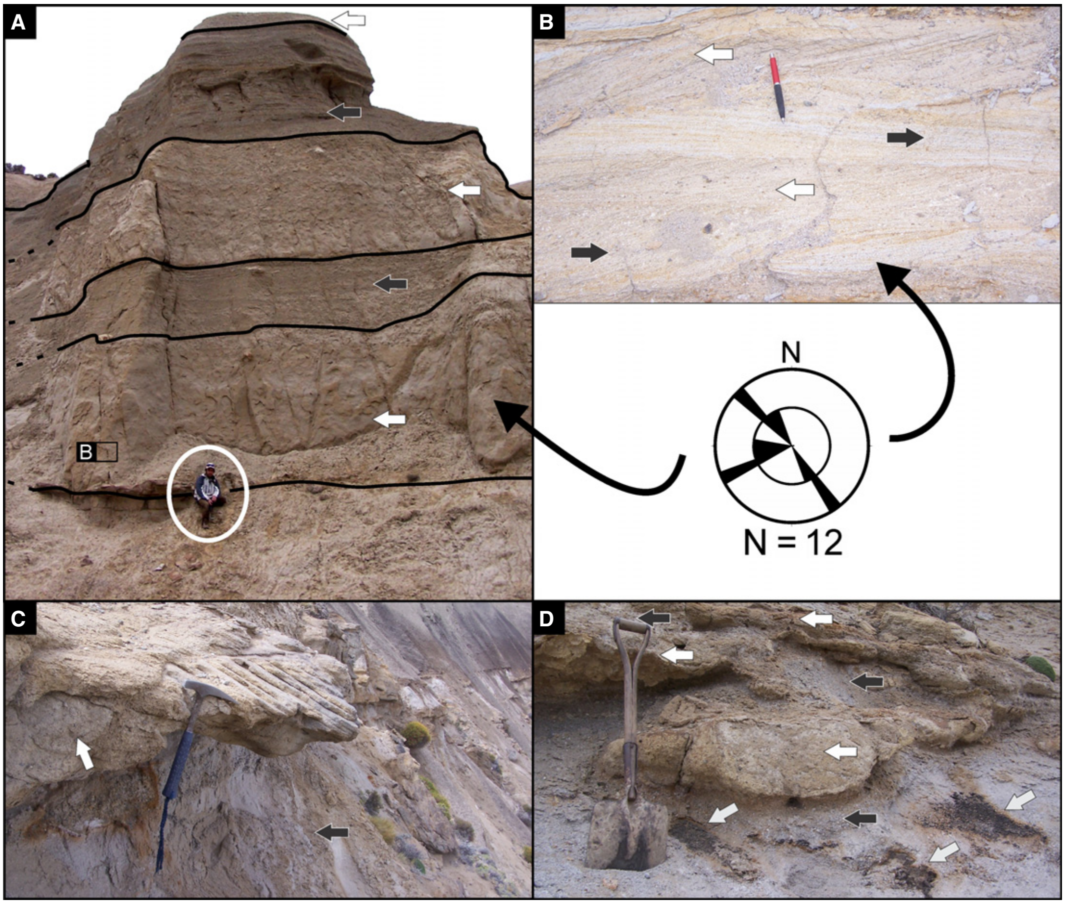


Fig. 9. (A) FA10 (sandstones with herringbone cross-bedding) (white arrows) interbedded with FA13 (heterolithic deposits with marine fossils) (black arrows) in the lower section of the Mata Amarilla Formation at the La Blanca Farm (LB) locality; person for scale (*ca* 1·8 m tall). (B) Detail of FA10 (sandstones with herringbone cross-bedding) showing the herringbone cross-bedding (pen for scale is 14 cm long) and rose diagram showing palaeocurrent data. (C) FA11 (coarsening-upward succession with high-angle planar cross-bedding) (white arrow) on top of FA12 (diamictites with small-scale gravel-filled channel-shaped bodies) (black arrow) at La Blanca Farm (LB) locality; hammer for scale is 40 cm long. (D) Detail of FA12; diamictites (black arrows) with large mud intraclasts (grey arrows) and encapsulated small-scale gravel-filled channel-shaped bodies (white arrows); shovel for scale is 0·8 m long.

Interpretation

This facies association is part of a coarsening-upward succession with high-angle planar cross-bedding, in which the close vertical relation with FA12 and FA13 suggests that these deposits represent a progradational arrangement caused by the migration of mouth bars in a small delta developed in the bay-head area of an estuary (i.e. bay-head delta; Dalrymple *et al.*, 1992). The up-dip connection to FA4 (interpreted as a system of small coastal distributary channels) in the western sector of the study area (at the LM, SLV, GR, CH and CF localities) suggests lateral confinement to a valley or embayment. The *in situ* bioturbation (*Skolithos* and *Arenicolites*) corresponds to high energy conditions, where filter-feeding and deposit-feeding organisms colonized the substrate, and generated dwelling structures (MacEachern *et al.*, 2007). *Teredolites* isp. are interpreted as dwelling and feeding traces of bivalves (Bromley *et al.*, 1984; Ekdale *et al.*, 1984; Beynon & Pemberton, 1992). The tree trunks in which these bivalve borings occur must have been immersed in marine water (Bromley *et al.*, 1984; Aguirre-Urreta, 1987; Beynon & Pemberton, 1992; Gingras *et al.*, 2004).

Facies Association 12: Diamictites with small-scale gravel-filled channel-shaped bodies

Description

This facies association (FA12) is characterized by massive green to greyish-green diamictites; the grain size varies from fine-grained sandstones to conglomerates in which small-scale gravel-filled channels are embedded (Fig. 9D). The diamictite is poorly sorted, matrix supported, and has abundant plant remains and carbonaceous debris scattered in the matrix. Large angular to subangular mud intraclasts (20 cm diameter on average) are present, scattered throughout the association (Fig. 9D). Bodies of FA12 have a tabular geometry of centimetres to tens of metres thickness. On the other hand, the embedded small-scale gravelly channels are characterized by a lenticular external geometry with irregular concave-up bases and sharp horizontal tops, with a thickness of 20 cm and lateral extent of 60 cm (Fig. 9D). Another feature of these channel-shaped bodies is that they are massive and have a simple infill with the presence of imbricated clasts as the sole tractional sedimentary structure. The infill is composed of clast-supported conglomerates with a greenish dirty matrix, with well-rounded clasts of grain size varying from 5 to 8 cm in diameter. Clast composition is dominated by quartz, with 5 to 10% volcanic lithic clasts. Facies association 12 overlies FA13 and underlies FA11; it is found in the lower section of the Mata Amarilla Formation at the La Blanca Farm (LB) locality.

Interpretation
This facies association is interpreted as prodelta debris-flow deposits (cf. Lowe, 1979; Orton & Reading, 1993; Mulder & Syvitski, 1995; Zavala *et al.*, 2006; Bhattacharya, 2006). These debris-flow deposits were generated during high discharge events of the fluvial system that flowed into the estuary. These flows bypassed the delta front, but produced coeval erosion and deposition towards the centre of the estuary. The presence of large angular to subangular mud intraclasts and the abundance of plant remains and carbonaceous debris scattered in the matrix support this interpretation.

Facies Association 13: Heterolithic deposits with marine fossils

Description
This facies association (FA13) is characterized by the intercalation of dark black to grey mudstones and whitish fine-grained sandstones (Fig. 9A). Sedimentary structures include parallel and cross-lamination, ripples, and flaser, lenticular and wavy bedding. The external geometry of bodies of FA13 is tabular and their thickness varies from centimetres to tens of metres (Fig. 9A); the bases and tops are from sharp to transitional. Successions of FA13 exhibit an increase in the proportion of sand in the heterolithic intervals towards their tops, with sandstone beds generally thickening-upward (Fig. 9A); rare thinning-upward successions are present. This association contains marine fossils such as shark teeth, turtle plates and plesiosaur remains (O'Gorman & Varela, 2010; Varela, 2011). There is a mixture between normal marine and brackish-water mollusc fauna (Griffin & Varela, 2012). Trace fossils are simple, small, scarce and very low in diversity. Facies association 13 is present in the lower section of the Mata Amarilla Formation at the La Blanca Farm (LB) locality, intercalated with FA10 (Fig. 9A) and is overlain by FA12 and FA11. It is also found in the upper section of the Mata Amarilla Formation at the Pari Aike Farm (PA) and Bajada de los Orientales Farm (BO) localities.

Interpretation
This facies association is interpreted as deposits of a littoral marine environment dominated by brackish water (Varela *et al.*, 2011; Griffin & Varela, 2012). The close vertical relation with FA10, FA11 and FA12 suggests a central bay depositional environment over which a prograding bayhead delta occurred (cf. Dalrymple *et al.*, 1992). The occurrence of flaser, lenticular and wavy bedding indicates an alternation of tractional and suspension-settling processes, which is consistent with the action of tides (Collinson & Thompson, 1989; Boyd *et al.*, 2006). The style of bioturbation is typical of an impoverished ichnofacies, which is commonly associated with salinity stressed, brackish water environments such as estuaries (e.g. MacEachern & Pemberton, 1992; Gingras *et al.*, 1999; Buatois *et al.*, 2002, 2005; MacEachern & Gingras, 2007).

STRATIGRAPHIC ARCHITECTURE

The vertical and lateral arrangement of the different facies associations makes it possible to differentiate between the three sections of the Mata Amarilla Formation, as well as to observe a west–east variation of the depositional systems (Figs 3 and 10). The vertical stratigraphic variations of the Mata Amarilla Formation are easily recognized in outcrop: the lower and upper sections have dark colouration due to the large proportion of fine-grained sediment, while the middle section has lighter colouration due to the higher proportion of sandstones (Fig. 3).

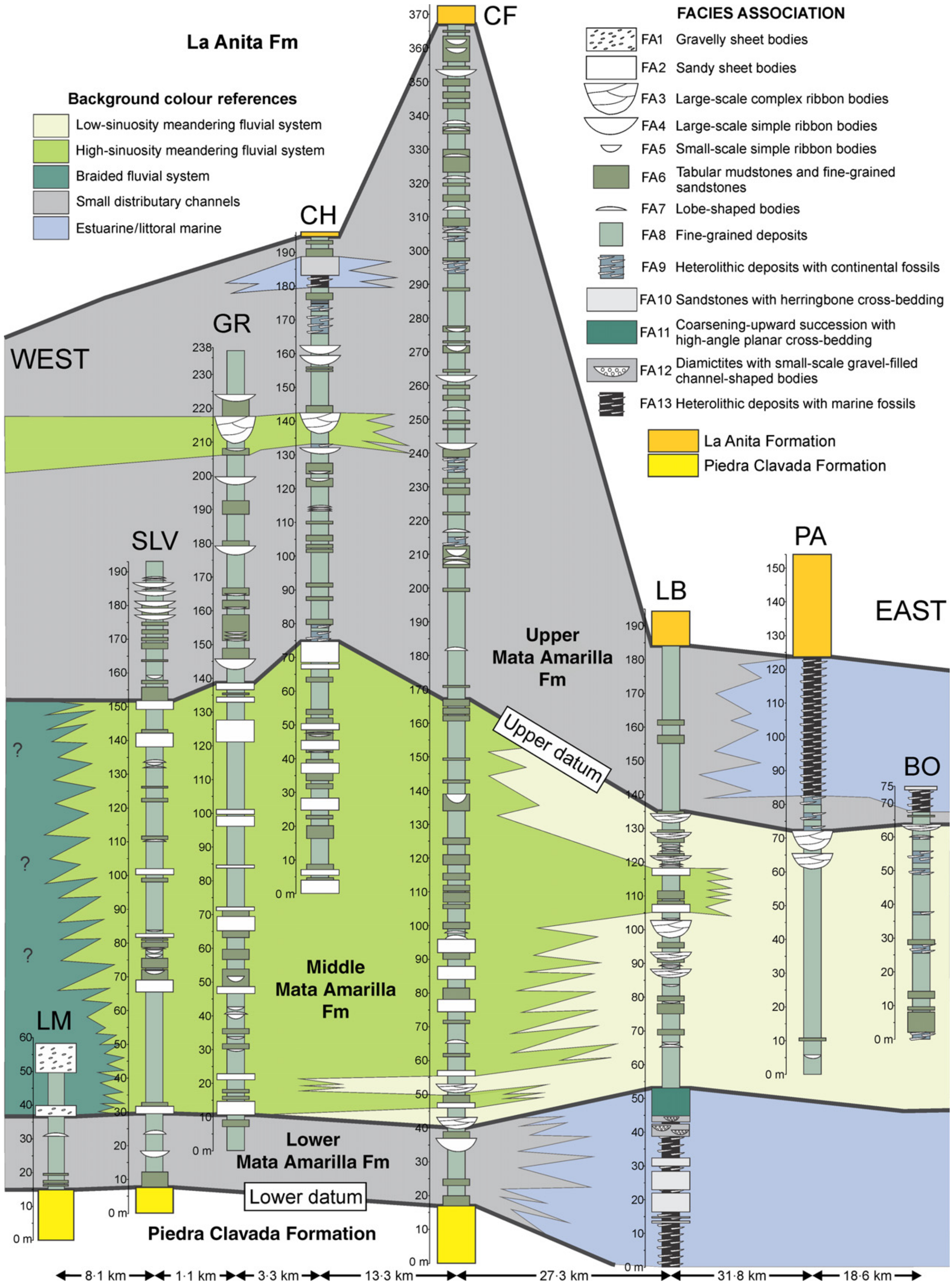


Fig. 10. Correlation panel showing vertical and lateral distribution of facies associations in the Mata Amarilla Formation in the study area. Localities are shown in Fig. 4.

This colour change is accompanied by distinct vertical variations in the stacking of facies associations (Fig. 10). The lower and upper sections are dominated by fine-grained deposits, both continental (FA8) and littoral (FA13) (Fig. 10). On the other hand, the middle section of the formation has a higher proportion of facies associations corresponding to channelized elements (FA1, FA2 and FA3) and attributed to crevasse processes (FA5, FA6 and FA7) (Fig. 10).

The base of the Mata Amarilla Formation, at its boundary with the underlying Piedra Clavada Formation, is sharp, concordant and easily recognized in the field (lower datum; Fig. 10). The contact between the Mata Amarilla Formation and the overlying La Anita Formation is discordant and erosional (Fig. 10).

Lower section of Mata Amarilla Formation

The lower section of the Mata Amarilla Formation comprises large-scale simple ribbon bodies (FA4) interbedded with fine-grained deposits (FA8) in the western sector of the study area, at the LM, SLV, GR, CH and CF localities (Fig. 10). This spatial arrangement of facies associations is considered to record small coastal distributary channels within floodplain deposits. The internal organization and the small thickness of the lower section make it impossible to discern any higher-frequency variation. In the eastern sector of the study area, at the LB locality (Fig. 4), the same stratigraphic interval is composed of heterolithic deposits with marine fossils (FA13) and sandstone with herringbone cross-bedding (FA10), which are overlain by diamictites with small-scale gravel-filled channel-shaped bodies (FA12) and a coarsening-upward succession with high-angle planar cross-bedding (FA11) (Fig. 10). This vertical stacking of facies associations is interpreted to record estuarine and littoral marine environments overlain by the progradation of a bayhead delta (Fig. 10). This vertical succession is interpreted to record a single shallowing-upward trend from inner to central estuarine environments.

Middle section of Mata Amarilla Formation

The middle section of the Mata Amarilla Formation in the LM locality shows gravelly sheet bodies (FA1), interbedded with fine-grained deposits (FA8) (Fig. 10). The occurrence of FA1 is interpreted as a braided fluvial system in the western part of the study area (Fig. 10). The localities SLV, GR, CH and CF are characterized by the presence of sandy sheet bodies (FA2), interbedded with fine-grained floodplain (FA8) and crevasse deposits (FA5, FA6 and FA7) (Fig. 10). This grouping of facies associations is attributed to a relatively high-sinuosity, possibly meandering, fluvial system and laterally adjacent, aggradational floodplain. There is a lateral transition of these deposits towards the eastern localities (LB, PA and BO) into large-scale complex ribbon bodies (FA3) interbedded with fine-grained deposits (FA8) and crevasse deposits (FA5, FA6 and FA7) (Fig. 10). The proportion of fine-grained deposits (FA8) also increases with respect to the channel elements (FA3) towards the east (Fig. 10). The spatial arrangement of facies associations in eastern localities reflects deposition from a relatively low-sinuosity, but probably meandering, fluvial system that underwent aggradation and avulsion.

Upper section of Mata Amarilla Formation

The upper section of the Mata Amarilla Formation at most localities (SLV, GR, CH, CF and LB) is characterized by the presence of large-scale simple ribbon bodies (FA4) interbedded with fine-grained floodplain (FA8) and crevasse deposits (FA5, FA6 and FA7) which are interpreted to record deposition from small coastal distributary channels and their floodplains (Fig. 10). A limited proportion of large-scale complex ribbon bodies (FA3), interpreted to record relatively high-sinuosity meandering fluvial systems, occur in the western localities (GR and CH) (Fig. 10). There is also an intercalation of sandstones with herringbone cross-bedding (FA10) and heterolithic deposits with marine fossils (FA13) in the southern localities (CF and CH) (Fig. 10). Finally, in the easternmost part of the study area, localities PA and BO are characterized by the predominance of heterolithic deposits with marine fossils (FA13) and, less frequently, by sandstones with herringbone cross-bedding (FA10), which are attributed to estuarine/littoral marine palaeoenvironments (Fig. 10).

Boundaries between the lower, middle and upper sections

The boundary between the lower and middle sections of the Mata Amarilla Formation (Fig. 10), which was developed at *ca* 96 Ma (Varela *et al.*, 2012a), is easily recognizable at outcrop and can be mapped regionally. In the western part of the study area, it is delimited by an erosional surface generated by pronounced lateral channel migration and overlain by widespread sheet-like channel deposits (FA1 and FA2), while in the eastern sector of the study area it appears as a paraconcordance marked by a very well-developed palaeosol (Varela *et al.*, 2012b). In addition to the colour change and the change in the vertical stacking of facies associations, this surface occurs in conjunction with the development of a petrified forest throughout the study area and is commonly associated with abundant trees (Zamuner *et al.*, 2004, 2006; Varela *et al.*, 2006, 2012b).

The boundary between the middle and upper sections of the Mata Amarilla Formation (upper datum; Fig. 10) is recognizable in the eastern portion of the study area through changes in colouration and in the vertical stacking of continental deposits above estuarine and littoral marine deposits coupled with the occurrence of fossil material. However, in the western and central parts of the study area, it is only recognizable through variation in colour and by subtle changes in vertical stacking of facies associations (for example, vertical transition from sandy sheet bodies, FA2, into overlying large-scale simple ribbon bodies, FA4, isolated within fine-grained deposits, FA8; Fig. 10).

PALAEOCURRENT ANALYSIS

Palaeocurrent data were collected from the eight main localities in the study area (Fig. 4) for each of the three sections of the Mata Amarilla Formation, and were grouped statistically according to facies associations, localities and stratigraphic intervals (Fig. 11A to C).

In the lower section of the Mata Amarilla Formation, the western part of the study area (locality SLV) is characterized by the occurrence of FA4, which is interpreted as small distributary channels. Palaeocurrent measurements indicate palaeoflow towards the south-east (Fig. 11A), into an inferred embayment situated to the east (Fig. 12). In the LB locality, palaeocurrents from FA11, interpreted as a bayhead delta mouth bar, indicate sediment transport towards the ENE (Fig. 11A). The data collected from imbricated clasts in prodelta channels (FA12) show that palaeocurrents flowed towards the ESE (Fig. 11A). Finally, sandstones with herringbone cross-bedding (FA10) display bidirectional palaeocurrents mostly oriented in a north-west/south-east direction, although there is a component to the WSW (Fig. 11A).

The middle section of the Mata Amarilla Formation in the western part of the study area (locality LM) is characterized by the presence of FA1, which is interpreted as a braided fluvial system; palaeocurrents measured in imbricated clasts and planar cross-bedding show a low dispersion towards the south-east (Fig. 11B). Palaeocurrents measured in trough cross-bedding, planar cross-bedding and imbricated clasts from FA2 (interpreted as a relatively high-sinuosity, probably meandering, fluvial system) have high dispersion. In localities SLV and CH palaeocurrents are mostly towards the NNE (Fig. 11B), whereas in localities GR and CF they are towards the SSE (Fig. 11B). This high dispersion in palaeocurrent data is typical of a high-sinuosity meandering fluvial system (cf. Bridge, 2003). The eastern localities LB, PA and BO are characterized by the presence of FA3, which is considered to represent a relatively low-sinuosity, probably meandering fluvial system undergoing aggradation. Palaeocurrent measurements obtained mainly in trough cross-bedding and, less frequently, in planar cross-bedding show low dispersion and are oriented towards the SSW (Fig. 11B).

The upper section of the Mata Amarilla Formation is only represented in two localities (CF and LB), and is characterized by the occurrence of FA4, interpreted as small distributary channels. Despite the scarcity of outcrops, it is possible to recognize that the channel flow was towards the east (Fig. 11C).

DISCUSSION

Variations in the ratio of accommodation space to sediment supply

The relation between the rate of creation of accommodation space in a basin and the amount of sediment that is supplied to it is a fundamental control on stratigraphic architecture (Blum & Törnqvist, 2000; Huerta *et al.*, 2011). From analysis of the spatial distribution and arrangement of facies associations (Figs 10 and 11), it is possible to document substantial changes in the relation between the rate of accommodation space creation and the amount of sediment delivered (e.g. Martinsen *et al.*, 1999; Veiga *et al.*, 2008; Varela, 2011; Jensen & Pedersen, 2010).

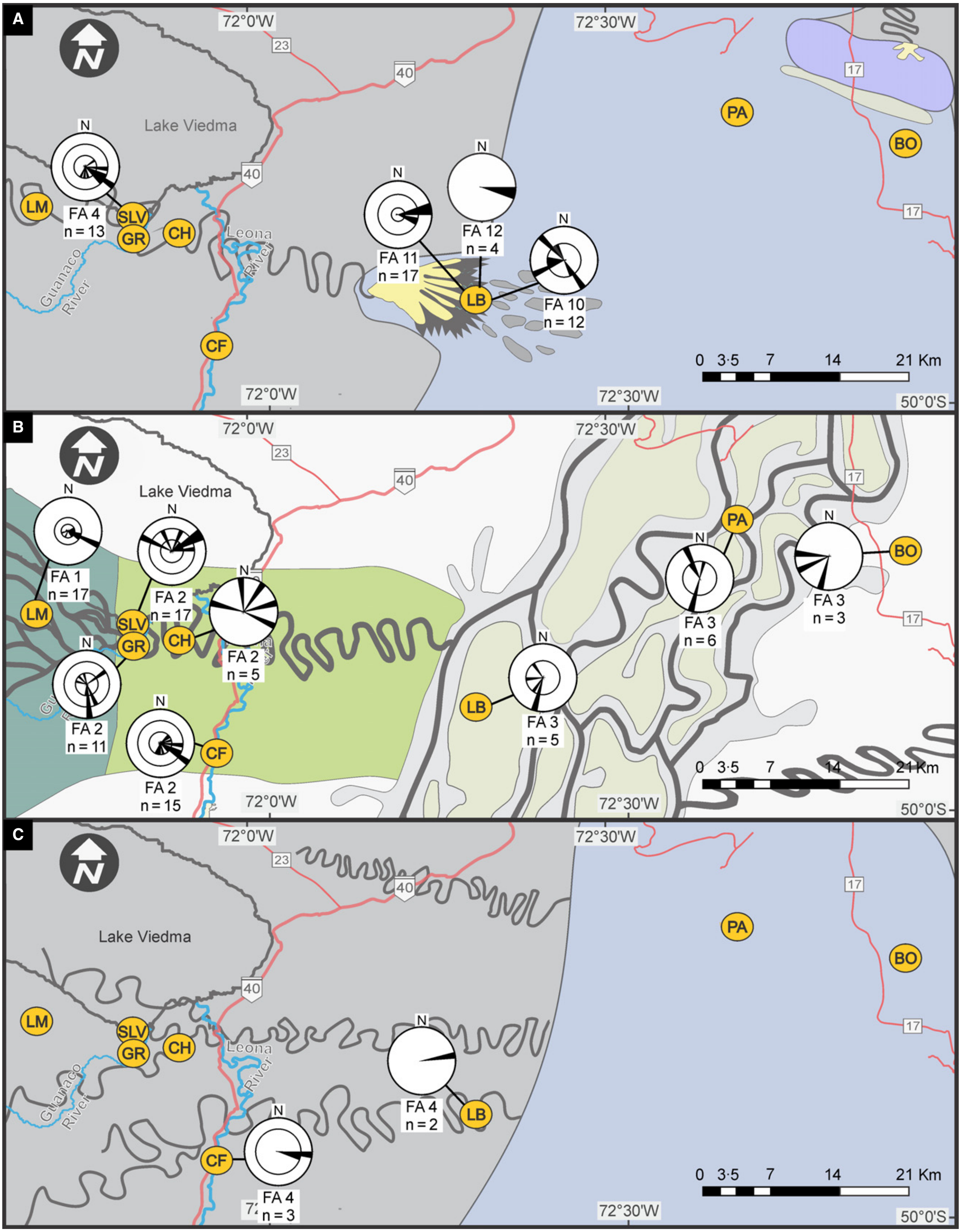


Fig. 11. Gross palaeogeographic maps of the study area showing palaeocurrent data grouped by localities and by facies association (FA) for the three stratigraphic intervals differentiated in the Mata Amarilla Formation (Fig. 10): (A) lower section; (B) middle section; and (C) upper section. For a key to the background colour scheme, see Fig. 10.

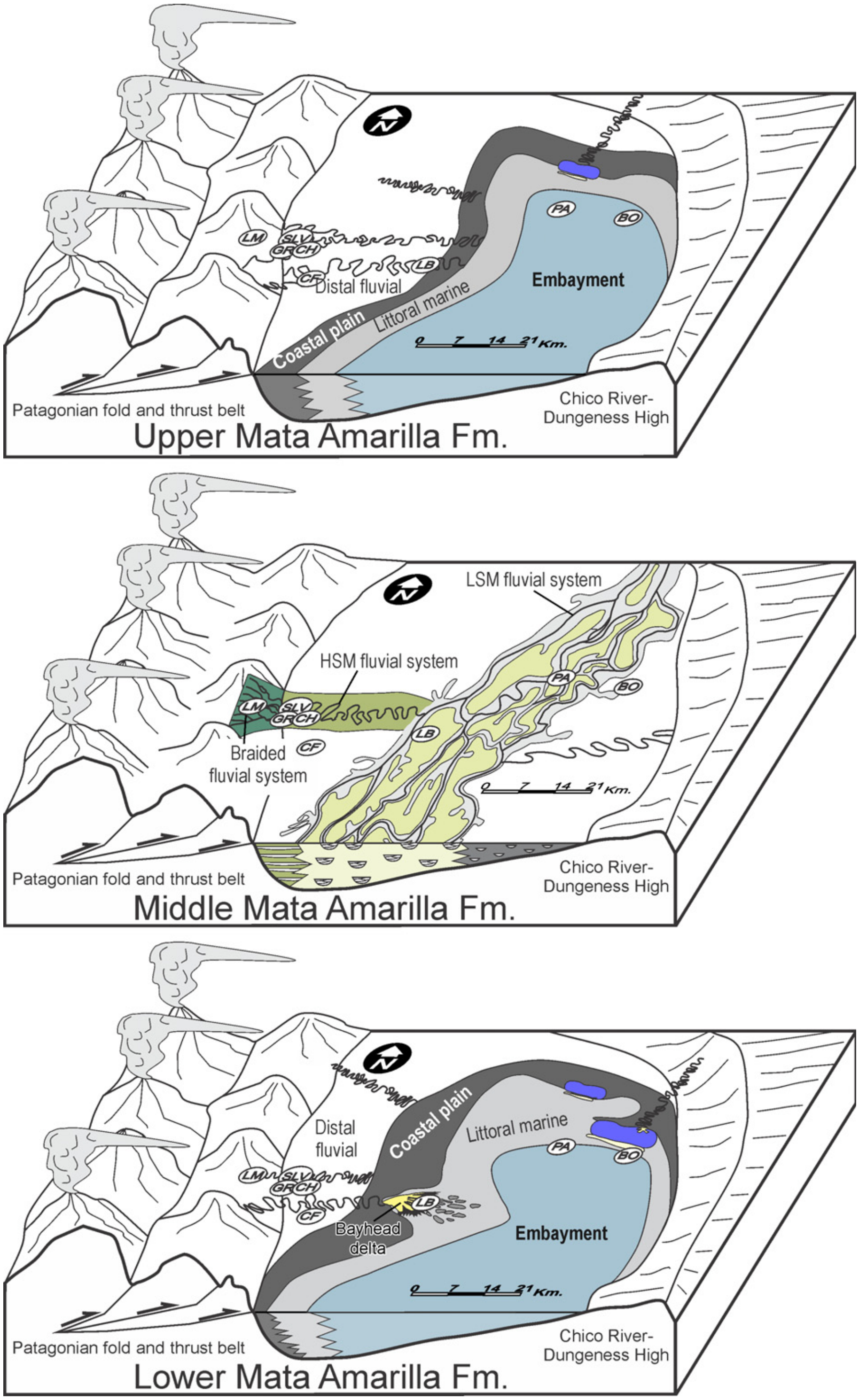


Fig. 12. Block diagrams showing the gross palaeoenvironmental and palaeogeographic context of the lower, middle and upper intervals of the Mata Amarilla Formation (Figs 10 and 11): HSM, high-sinuosity meandering; LSM, low-sinuosity meandering. No vertical scale is implied and stratal thicknesses are shown schematically. For a key to the colour scheme, see Fig. 10.

In the lower section of the Mata Amarilla Formation, a high A/S ratio is suggested by the stacking of large-scale simple ribbon bodies (FA4), isolated within fine-grained floodplain deposits (FA8) (Wright & Marriott, 1993; Shanley & McCabe, 1994; Veiga *et al.*, 2008; Jensen & Pedersen, 2010) (Figs 12 and 13). In the upper section of the Mata Amarilla Formation, there is also a high A/S ratio accompanied by a migration of littoral deposits towards the east of the study area. Thus, in locality LB small distributary channel deposits (FA4 and FA8) are present in the upper section, while in the lower section in the same locality there are littoral deposits (FA10, FA11, FA12 and FA13) (Figs 10, 12 and 13), which might suggest a shift of the basin depocentre to the east with respect to the lower section.

The middle section of the Mata Amarilla Formation shows a significant decrease in A/S ratio, which is evidenced by the increase in sediment grain size and by the presence of a higher proportion of channelized fluvial bodies (FA1, FA2 and FA3) with respect to fine-grained floodplain deposits (FA8). Nevertheless, the most diagnostic feature is the presence of laterally migrating channelized bodies of relatively high sinuosity (Figs 7A, 7B and 10); this is the response of the fluvial systems to conditions of limited accommodation, i.e. low A/S ratio (Legarreta & Uliana, 1991, 1998; Wright & Marriott, 1993; Shanley & McCabe, 1994; Veiga *et al.*, 2008; Fielding *et al.*, 2009; Jensen & Pedersen, 2010; Varela, 2011). However, in the western sector of the study area, both gravelly and sandy sheet bodies (FA1 and FA2) are usually interbedded with fine-grained deposits (FA8) (Fig. 10). These fine-grained deposits (FA8) have a large lateral extent and are relatively thick, which appears to be inconsistent with their occurrence in a gravelly braided fluvial system (Orton & Reading, 1993; Bridge, 2003). The intervals of fine-grained floodplain deposits (FA8) may correspond to deposition from relatively low-sinuosity and/or high-sinuosity fluvial systems that are interbedded with a gravelly braided fluvial system (Figs 10 and 13). These vertical changes in the interpreted type of fluvial systems in the middle section of the Mata Amarilla Formation in the western sector of the study area, are attributed to alternating periods of low and high A/S ratio. Thus, the channelized FA1 units (gravelly sheet bodies) indicate a low A/S ratio, while the late-

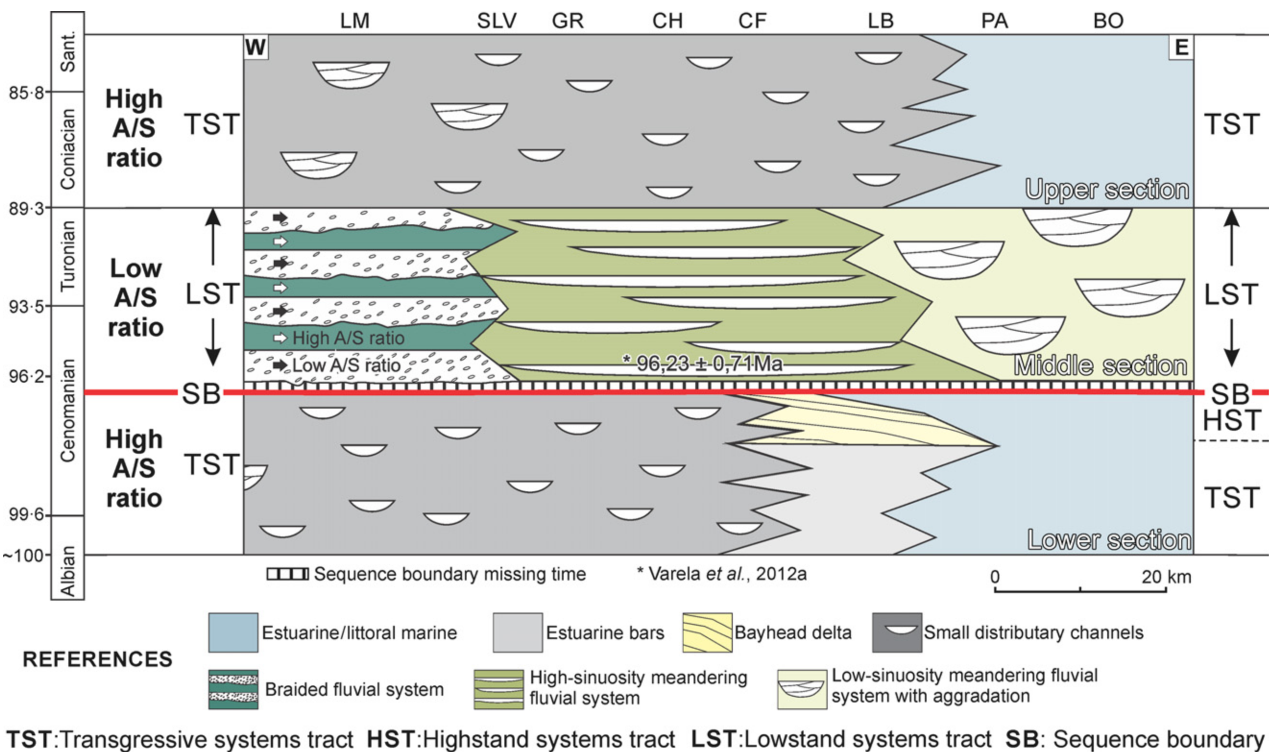


Fig. 13. Sequence stratigraphic and schematic chronostratigraphic interpretation of the Mata Amarilla Formation, based on the spatial arrangement of facies associations and related fluvial architecture. For a key to the colour scheme, see Fig. 10.

rally extensive and relatively thick, fine-grained floodplain deposits (FA8) represent a high A/S ratio.

These interpreted variations in A/S ratio in the middle section of the Mata Amarilla Formation are an order of magnitude smaller in duration than those that generated the three sections of the Mata Amarilla Formation (Fig. 3). It is important to clarify that in the eastern part of the study area the facies associations are dominated by relatively high A/S ratios. Even during the deposition of the middle section of the Mata Amarilla Formation, a relatively high rate of creation of accommodation space is interpreted for the relatively low-sinuosity, probably meandering, fluvial system undergoing aggradation in the eastern part of the study area (Figs 12 and 13).

Relative sea-level oscillations

The changes in the A/S ratio in the Mata Amarilla Formation, in the western sector of the study area, suggest strong variations in the base level of the fluvial systems. These variations in the eastern sector of the study area are clearly associated with changes in relative sea-level, where the lower and upper sections are composed of littoral to marginal marine deposits, while the middle section is purely continental (Figs 10 and 13).

A sequence stratigraphic interpretation can be constructed considering A/S ratio for the three intervals of the Mata Amarilla Formation (Fig. 13). The relatively high A/S ratio inferred for the lower section can be correlated with the development of littoral to marginal marine systems in the eastern area (FA10 to FA13) suggesting the development of a transgressive systems tract (TST). The boundary between the lower and middle sections of the Mata Amarilla Formation is interpreted to be marked by an abrupt decrease in A/S ratio evidenced by an increase in the degree of amalgamation of fluvial sandbodies (FA1, FA2 and FA3), together with the onset of fluvial sedimentation across the whole area (Figs 12 and 13). This boundary is also characterized by the presence of a strongly developed palaeosol (Zamuner *et al.*, 2004, 2006; Varela *et al.*, 2006, 2012b). This evidence points to the development of a sequence boundary (*sensu* Catuneanu *et al.*, 2009) (Fig. 13). The rest of the middle section is dominated by the accumulation of sandy sheet bodies (FA2) in the western sector and large-scale complex ribbon bodies (FA3) in the eastern sector, which are interpreted as a lowstand systems tract (LST; Fig. 13). Finally, the upper section of the Mata Amarilla Formation is similar to the lower section in terms of A/S ratio, and it is also interpreted as a transgressive package (TST; Fig. 13).

Changes in stratigraphic architecture may be developed in response to different controlling factors, including source area tectonism, basin subsidence, eustasy and climate (Shanley & McCabe, 1994). Concerning the climate, the Mata Amarilla Formation was deposited during the Upper Cretaceous greenhouse period, which began in the late Albian to the early Cenomanian (White *et al.*, 2001; Royer, 2010). The climate was warm and humid with a pronounced seasonality (i.e. warm temperate), as indicated by analysis of palaeosols developed in floodplain and coastal plain deposits (Varela, 2011; Varela *et al.*, 2012b). As regards eustasy and tectonics, it should be noted that the strong west–east change in facies composition coupled with palaeocurrent directions (Figs 11 and 12) are consistent with the direction of migration of the Patagonian fold and thrust belt (Fosdick *et al.*, 2011; Varela, 2011; Varela *et al.*, 2012a, 2013). However, the facies association distribution within the middle Mata Amarilla lowstand wedge shows that coarse sediment was delivered from the west (Figs 10 and 11), consistent with studies of sediment provenance (Varela *et al.*, 2013), which may indicate that the relative sea-level changes were driven by tectonic controls related to growth of the Patagonian fold and thrust belt.

Tectonic control

The subsidence patterns and stratigraphic architecture of foreland basins have been modelled by Beaumont (1981), Quinlan & Beaumont (1984), Watts (1989), Flemings & Jordan (1990), Jordan & Flemings (1991), Sinclair *et al.* (1991) and Jordan (1995), whose studies provided the basis for geodynamic interpretations of foreland basin successions (DeCelles & Giles, 1996). Variations in A/S ratio are produced by variations in the magnitude of the thrust-sheet load and corresponding crustal flexure, in response to loading by fold and thrust belt growth and to unloading by erosion of the fold and thrust belt (e.g. Heller *et al.*, 1988).

During periods of growth and associated weight gain of the fold and thrust belt, the underlying crust deflects downward, increasing the rate of creation of accommodation space

(Heller *et al.*, 1988). During such periods, uplift and evolution of the Patagonian fold and thrust belt prevented the full integration of the drainage network, such that sediment supply was hindered by inefficient delivery from the fluvial systems that formed the drainage network (e.g. Leeder, 1993; Yoshida, 2000). Therefore, the A/S ratio was high due to an increased rate of accommodation creation in conjunction with a decrease in sediment supply (Fig. 14A and C) (Heller *et al.*, 1988) and may be associated with transgression (Kamola & Huntoon, 1995; Houston *et al.*, 2000). The lower and upper sections of the Mata Amarilla Formation are interpreted to represent such periods during the evolution of the Patagonian fold and thrust belt (Fig. 14A and C) and are correlated accordingly to the transition from the shelf marine deposits of the Zapata Formation to the deep-marine succession of the Punta Barrosa Formation in the south-west (Última Esperanza District) of the Austral Basin (Figs 1 and 2) (Wilson, 1991; Fildani *et al.*, 2003; Romans *et al.*, 2010, 2011).

On the other hand, during periods of tectonic quiescence, the rate of migration and growth of the fold and thrust belt was smaller and the thrust-load was decreased by erosion. This generated isostatic rebound of the underlying crust and, as a consequence, the rate of creation of accommodation space in the basin declined (Heller *et al.*, 1988; Watts, 1989). In addition, during these quiescent periods the erosion of previously uplifted areas favoured the integration of the drainage network (e.g. Leeder, 1993) (Fig. 12). In other words, geomorphological evolution of the landscape generated a substantial increase in sediment input to the basin. Consequently, tectonically quiescent periods were characterized by a low A/S ratio, caused by a decrease in the rate of creation of accommodation space and an increase in sediment supply (Fig. 14B).

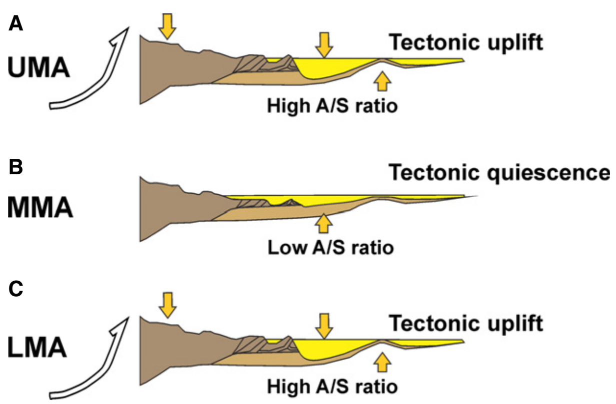


Fig. 14. Tectonic flexural model to explain A/S ratio variations between the three stratigraphic intervals of the Mata Amarilla Formation (Figs 10, 11 and 12): (A) lower section; (B) middle section; and (C) upper section.

Because many factors are involved (including episodic movement on the thrust fault, emplacement rate and geometry of the fault, flexural rigidity, climatic fluctuations, and lithological and topographic variations) the alternation between these two tectonic periods will occur many times during a single orogenic event, and the final stratigraphic architecture may be more complicated than portrayed in Fig. 14 (Heller *et al.*, 1988). Thus, the interpreted high-frequency variations in the A/S ratio in the middle section of the Mata Amarilla Formation (Fig. 13) could be the stratigraphic architectural result of such complicating factors, including the response to development of localized thrust loads within the Patagonian fold and thrust belt.

Considering that only the lower and middle sections of the Mata Amarilla Formation are temporally delimited, and the contact with the overlying La Anita Formation is discordant and erosional, the specific duration of each stratigraphic interval cannot be constrained accurately (Fig. 2). However, it is inferred that large-scale changes in A/S ratio between the lower, middle and upper sections of the formation occur over periods in the order of *ca* 5 Myr, while high-frequency variations in A/S ratio during the middle Mata Amarilla Formation would have been less than 1 Myr in duration (Fig. 13). The proposed ages and durations of large-scale variations in A/S ratio coincide with stages I and II of the evolution of the Patagonian fold and thrust belt (Fosdick *et al.*, 2011).

Similar west to east changes in depositional style noted in the study area in the Mata Amarilla Formation are also evident in the foredeep during deposition of the Cerro Toro Formation (Santonian–Campanian; Fig. 2), which contains conglomerate delivered from the Patagonian fold and thrust belt (Hubbard *et al.*, 2008; Romans *et al.*, 2010; Romans *et al.*, 2011). The specific stratigraphic architecture in a foreland basin is strongly controlled by the flexural rigidity of the lithosphere (Heller *et al.*, 1988; Watts, 1989). The Austral Foreland Basin developed on a fully continental crust in the study area (Fig. 1) and on quasi-oceanic and attenuated continental crust of the predecessor Rocas Verdes Basin in the south-western Última Esperanza District

(Romans *et al.*, 2010) (Figs 1 and 2); thus different stratigraphic architectures in the two parts of the Austral Basin were generated. As a result, the Mata Amarilla Formation constitutes a key element in understanding the transition from the rift/thermal subsidence stages to the foreland stage of the Austral Basin.

CONCLUSIONS

1 The Mata Amarilla Formation was studied in eight different localities, where detailed sedimentological observations and architectural element analysis were used to identify 13 facies associations (FA) from fluvial to estuarine depositional environments.

2 Spatial variations in the lateral and vertical distribution of facies association and associated fluvial architecture are interpreted to indicate variations in the ratio between accommodation space and sediment supply (A/S ratio). These variations were controlled by base level changes that can be tied to relative sea-level oscillations.

3 The Mata Amarilla Formation is subdivided into three stratigraphic intervals (lower, middle and upper sections) which are characterized by different types, abundances and distributions of facies associations. The lower and upper sections of the Mata Amarilla Formation both comprise large-scale simple ribbon bodies (FA4) that are isolated within fine-grained floodplain deposits (FA8), which pass towards the east into an estuarine assemblage of facies associations (FA10, FA11, FA12 and FA13). These stratigraphic architectures indicate deposition under a high A/S ratio within transgressive systems tracts. The middle section of the Mata Amarilla Formation contains a relatively high proportion of channelized fluvial bodies (FA1, FA2 and FA3) within fine-grained floodplain deposits (FA8). Fluvial sandstones are braided in the west and pass into high-sinuosity river deposits further east. This stratigraphic architecture indicates deposition under a low A/S ratio within a lowstand systems tract. The base of the middle section is a widespread fluvial erosion surface that passes eastwards into a well-developed palaeosol, and which is interpreted as a sequence boundary.

4 Palaeosol character indicates that palaeoclimatic conditions were relatively uniform during deposition.

5 The strong west to east trends in fluvial style and stratigraphic architecture coincide with the direction of propagation of the Patagonian retroarc fold and thrust belt.

6 A tectonic control on stratigraphic architecture is favoured. Transgressive intervals of high A/S ratio (i.e. lower and upper sections of the Mata Amarilla Formation) are interpreted to have developed during periods of increased loading by the fold and thrust belt caused by tectonic uplift. In contrast, intervals of low A/S ratio (i.e. middle section of the Mata Amarilla Formation) were developed during periods of tectonic quiescence.

7 Two temporal scales of variation in A/S ratio were identified: (i) low-frequency variation (*ca* 5 Myr) that is related to different rates of migration and growth of the Patagonian fold and thrust belt; and (ii) high-frequency variation (<1 Myr) that could have occurred in response to specific periods of thrusting and folding in the Patagonian fold and thrust belt. High-frequency variations in A/S ratio are only present in the middle section of the Mata Amarilla Formation, and are expressed as vertical alternations between sheet-like fluvial sandbodies (low A/S ratio) and laterally extensive floodplain deposits (high A/S ratio).

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REFERENCES

Aguirre-Urreta, M.B. (1987) La icnofacies Teredolites en el Cretácico de la Cuenca Austral Argentina. *X Congreso Geológico Argentino, Actas*, **III**, 143–148.

Arbe, H.A. (1989) Estratigrafía, discontinuidades y evolución sedimentaria del Cretácico en la Cuenca Austral, Prov. de Santa Cruz. In: *Cuencas Sedimentarias Argentinas* (Eds G. Chebli and L.A. Spalletti), *Instituto Superior de*

Correlación Geológica, Universidad Nacional de Tucumán, Serie de Correlación Geológica, **6**, 419–442.

Arbe, H.A. (2002) Análisis estratigráfico del Cretácico de la Cuenca Austral. In: *Geología y Recursos Naturales de Santa Cruz* (Ed. M.J. Haller), pp. 103–128 XV Congreso Geológico, Argentino.

Beaumont, C. (1981) Foreland Basins. *Geophys. J. Roy. Astron. Soc.*, **65**, 291–329.

Beynon, B.M. and **Pemberton, S.G.** (1992) Ichnological signature of a brackish water deposit; an example from the Lower Cretaceous Grand Rapids Formation, Cold Lake oil sands area, Alberta. In: *Applications of Ichnology to Petroleum Exploration: A Core Workshop* (Ed. S.G. Pemberton), *SEPM. Core Workshop*, **17**, 199–221.

Bhattacharya, J.P. (2006) Deltas. In: *Facies Models Revisited* (Eds H.W. Posamentier and R.G. Walker), *SEPM Spec. Publ.*, **84**, 237–292.

Biddle, K., **Uliana, M., Jr.**, **Mitchum, R.**, **Fitzgerald, M.** and **Wright, R.** (1986) The stratigraphic and structural evolution of central and eastern Magallanes Basin, Southern America. In: *Foreland Basins* (Eds P. Allen and P. Homewood), *Int. Assoc. Sedimentol. Spec. Publ.*, **8**, 41–61.

Blum, M.D. and **Törnqvist, T.E.** (2000) Fluvial responses to climate and sea-level change: a review and look forward. *Sedimentology*, **47**, 2–48.

Bossi, G.E. (2007) *Análisis de Paleocorrientes*. Ediciones Magna, San Miguel de Tucumán, 200 pp.

Boyd, R., **Dalrymple, R.W.** and **Zaitlin, B.A.** (2006) Estuarine and Incised-Valley Facies Model. In: *Facies Models Revisited* (Eds H.W. Posamentier and R.G. Walker), *SEPM Spec. Publ.*, **84**, 171–235.

Bridge, J.S. (1993) Description and interpretation of fluvial deposits: a critical perspective. *Sedimentology*, **40**, 801–810.

Bridge, J.S. (2003) *Rivers and Floodpplains: Forms, Processes, and Sedimentary Record*. Blackwell Science Publishing, Oxford, 491 pp.

Bridge, J.S. and **Leeder, M.R.** (1979) A simulation model of alluvial stratigraphy. *Sedimentology*, **26**, 599–623.

Bromley, R.G., **Pemberton, S.G.** and **Rahmani, R.A.** (1984) A Cretaceous woodground: the Teredolites ichnofacies. *J. Paleontol.*, **58**, 488–498.

Buatois, L.A., **Mangano, M.G.**, **Alissa, A.** and **Carr, T.R.** (2002) Sequence stratigraphic and sedimentologic significance of biogenic structures from a late Paleozoic marginal- to open-marine reservoir, Morrow Sandstone, subsurface of southwest Kansas, USA. *Sed. Geol.*, **152**, 99–132.

Buatois, L.A., **Gingras, M.K.**, **MacEachern, J.**, **Mángano, M.G.**, **Zonneveld, J.P.**, **Pemberton, S.G.**, **Netto, R.G.** and **Martin, A.J.** (2005) Colonization of brackish-water systems through time: evidence from the trace-fossil record. *Palaios*, **20**, 321–347.

Calderón, M., **Fildani, A.**, **Hervé, F.**, **Fanning, C.M.**, **Weislogel, A.** and **Cordani, U.** (2007) Late Jurassic bimodal magmatism in the northern sea-floor remnant of the Rocas Verdes basin, southern Patagonian Andes. *J. Geol. Soc. London*, **162**, 1011–1022.

Catuneanu, O., **Abreu, V.**, **Bhattacharya, J.P.**, **Blum, M.D.**, **Dalrymple, R.W.**, **Eriksson, P.G.**, **Fielding, C.R.**, **Fisher, W.L.**, **Galloway, W.E.**, **Gibling, M.R.**, **Giles, K.A.**, **Holbrook, J.M.**, **Jordan, R.**, **Kendall, C.G.St.C.**, **Macurda, B.**, **Martinsen, O.J.**, **Miall, A.D.**, **Neal, J.E.**, **Numedal, D.**, **Pomar, L.**, **Posamentier, H.W.**, **Pratt, B.R.**, **Sarg, J.F.**, **Shanley, K.W.**, **Steel, R.J.**, **Strasser, A.**, **Tucker, M.E.** and **Winker, C.** (2009) Towards the standardization of sequence stratigraphy. *Earth-Sci. Rev.*, **92**, 1–33.

Clemente, P. and **Pérez-Arlucea, M.** (1993) Depositional architecture of the Cuerda del Pozo Formation, Lower Cretaceous of the extensional Cameros Basin, North-Central Spain. *J. Sed. Petrol.*, **63**, 437–452.

Collinson, J.D. and **Thompson, D.B.** (1989) *Sedimentary Structures*, 2nd edn. Unwin Hyman, London, 207 pp.

Dalrymple, R.W., **Zaitlin, B.A.** and **Boyd, R.** (1992) Estuarine facies models: conceptual basis and stratigraphic implications. *J. Sed. Petrol.*, **62**, 1130–1146.

Dalziel, I.W.D. (1981) Back-arc extension in the southern Andes: a review and critical reappraisal. *Phil. Trans. Roy. Soc. London Ser. A*, **300**, 319–335.

Dalziel, I.W.D., **de Wit, M.J.** and **Palmer, K.F.** (1974) Fossil marginal basin in the southern Andes. *Nature*, **250**, 291–294.

DeCelles, P.G. and **Giles, K.A.** (1996) Foreland basin system. *Basin Res.*, **8**, 105–123.

DeCelles, P.G., **Langford, R.P.** and **Schwartz, R.K.** (1983) Two new methods of paleocurrent determination from trough cross-stratification. *J. Sed. Petrol.*, **53**, 629–642.

Ekdale, A.A., **Bromley, R.G.** and **Pemberton, S.G.** (1984) Ichnology: the use of trace fossils in sedimentology and stratigraphy. *SEPM. Short Course Notes*, **15**, 317.

Fielding, C.R., **Corbett, M.J.** and **Birgenheier, L.P.** (2009) Sheet-like fluvial architecture on regional scales: examples from the Cretaceous western interior seaway of North Americca. *9th Int. Conf. Fluvial Sedimentol. Actas Geol. Lilloana*, **21**, 32–33.

Fildani, A. and **Hessler, A.M.** (2005) Stratigraphic record across a retroarc basin inversion: Rocas Verdes-Magallanes Basin, Patagonian Andes, Chile. *Geol. Soc. Am. Bull.*, **117**, 1596–1614.

Fildani, A., **Cope, T.D.**, **Graham, S.A.** and **Wooden, J.L.** (2003) Initiation of the Magallanes Foreland basin: timing of the southermost Patagonian Andes orogeny revised by detrital zircon provenance analysis. *Geology*, **31**, 1081–1084.

Flemings, P.B. and **Jordan, T.E.** (1990) Stratigraphic modeling of foreland basins: interpreting thrust deformation and lithosphere rheology. *Geology*, **18**, 430–434.

Fosdick, J.C., **Romans, B.W.**, **Fildani, A.**, **Bernhardt, A.**, **Calderón, M.** and **Graham, S.A.** (2011) Kinematic evolution of the Patagonian retroarc fold-and-thrust belt and Magallanes foreland basin, Chile and Argentina, 51°30′S. *Geol. Soc. Am. Bull.*, **123**, 679–1698.

Friend, P.F. (1983) Towards the field classification of alluvial architecture or sequence. In: *Alluvial Sedimentation* (Eds J.D. Collinson and J. Lewin), *Int. Assoc. Sedimentol. Spec. Publ.*, **6**, 345–354.

Friend, P.F., **Slater, M.J.** and **Williams, R.C.** (1979) Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain. *J. Geol. Soc. London*, **136**, 39–46.

Gibling, M.R. (2006) Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. *J. Sed. Res.*, **76**, 731–770.

Gingras, M.K., **Pemberton, S.G.**, **Saunders, T.** and **Clifton, H.E.** (1999) The ichnology of modern and Pleistocene brackish-water deposits at Willapa Bay, Washington; variability in estuarine settings. *Palaios*, **14**, 352–374.

Gingras, M.K., **MacEachern, J.A.** and **Pickerill, R.K.** (2004) Modern perspectives on the Teredolites Ichnofacies: observations from Willapa Bay, Washington. *Palaios*, **19**, 79–88.

Griffin, M. and **Varela, A.N.** (2012) Systematic palaeontology and taphonomic significance of the mollusc fauna from the Mata Amarilla Formation (lower Upper Cretaceous), southern Patagonia, Argentina. *Cretaceous Res.*, **37**, 164–176.

Heller, P.L., **Angevine, C.L.** and **Winslow, N.S.** (1988) Two-phase stratigraphic model of foreland-basin sequences. *Geology*, **16**, 501–504.

Houston, W.S., **Huntoon, J.E.** and **Kamola, D.L.** (2000) Modeling of Cretaceous Foreland-basin parasequences, Utah, with implications for timing of Sevier thrusting. *Geology*, **28**, 267–270.

Howell, J.A. and **Flint, S.S.** (2003) Siliciclastic case study: The Book Cliffs. In: *The Sedimentary Record of Sea-Level Change* (Ed. A.L. Coe), pp. 135–208. Cambridge University Press, Cambridge, UK.

Hubbard, S.M., **Romans, B.W.** and **Graham, S.A.** (2008) Deepwater foreland basin deposits of the Cerro Toro Formation, Magallanes basin, Chile: architectural elements of a sinuous basin axial channel belt. *Sedimentology*, **55**, 1333–1359.

Huerta, P., **Armenteros, I.** and **Silva, P.G.** (2011) Large-scale architecture in non-marine basins: the response to the interplay between accommodation space and sediment supply. *Sedimentology*, **58**, 1716–1736.

Iglesias, A., **Zamuner, A.B.**, **Poiré, D.G.** and **Larriestra, F.** (2007) Diversity, taphonomy and palaeoecology of an angiosperms flora from Cretaceous (Cenomanian-Coniacian) in Southern Patagonia, Argentina. *Palaeontology*, **50**, 445–466.

Jensen, M.A. and **Pedersen, G.K.** (2010) Architecture of vertically stacked fluvial deposits, Atane Formation, Cretaceous, Nuussuaq, central West Greenland. *Sedimentology*, **57**, 1280–1314.

Jordan, T.E. (1995) Thrust loads and foreland basin evolution, Cretaceous, western United States. *Am. Assoc. Petrol. Geol. Bull.*, **65**, 2506–2520.

Jordan, T.E. and **Flemings, P.B.** (1991) Large scale stratigraphic architecture, eustatic variation and unsteady tectonism: a theoretical evaluation. *J. Geophys. Res.*, **96**, 6681–6699.

Kamola, D.L. and **Huntoon, J.E.** (1995) Repetitive strata patterns in a foreland basin sandstone and their possible tectonic significance. *Geology*, **23**, 177–180.

Kraemer, P., **Ploszkiewicz, J.V.** and **Ramos, V.A.** (2002) Estructura de la Cordillera Patagónica Austral entre los 40° y 52°S. In: *Geología y Recursos Naturales de Santa Cruz* (Ed. M.J. Haller), *15 Relatorio del Congreso Geológico Argentino*, **I-22**, 353–364.

Leeder, M.R. (1993) Tectonic controls upon drainage basin development, river channel migration and alluvial architecture: implications for hydrocarbon reservoir development and characterization. *Geol. Soc. London Spec. Publ.*, **73**, 7–22.

Legarreta, L. and **Uliana, M.A.** (1991) Jurassic-Cretaceous marine oscillations and geometry of a back-arc basin fill, central Argentine Andes. In: *Sedimentation, Tectonics and Eustacy. Sea Level Changes at Active Margins* (Ed. D.I.M. MacDonald), *Int. Assoc. Sedimentol. Spec. Publ.*, **12**, 429–450.

Legarreta, L. and **Uliana, M.A.** (1998) Anatomy of hinterland depositional sequences: Upper Cretaceous fluvial strata, Neuquen Basin, West-Central Argentina. In: *Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks* (Eds K.W. Shanley and P.J. McCabe), *SEPM Spec. Publ.*, **59**, 83–92.

Lowe, D.R. (1979) Sediment gravity flows: their classification and some problems of applications to natural flows and deposits. In: *Geology of Continental Slopes* (Eds L.J. Doyle and O.H. Pilkey, Jr.), *SEPM Spec. Publ.*, **27**, 75–82.

MacEachern, J.A. and **Gingras, M.K.** (2007) Recognition of brackish-water trace fossil assemblages in the Cretaceous western interior seaway of Alberta. In: *Sediment-Organism Interactions: A Multifaceted Ichnology* (Eds R. Bromley, L.A. Buatois, M.G. Mángano, J. Genise and R. Melchor), *SEPM Spec. Publ.*, **88**, 149–194.

MacEachern, J.A. and **Pemberton, S.G.** (1992) Ichnological aspects of Cretaceous shoreface successions and shoreface variability in the Western Interior Seaway of North America. In: *Applications of Ichnology to Petroleum Exploration: A Core Workshop* (Ed. S.G. Pemberton), *SEPM Core Workshop*, **17**, 1–32.

MacEachern, J.A., **Bann, K.L.**, **Bhattacharya, J.P.** and **Howell, C.D., Jr.** (2005) Ichnology of deltas: organism responses to the dynamic interplay of rivers, waves, storms, and tides. In: *River Deltas-Concepts, Models, and Examples* (Eds J.P. Bhattacharya and L. Giosan), *SEPM Spec. Publ.*, **83**, 49–85.

MacEachern, J.A., **Bann, K.L.**, **Pemberton, S.G.** and **Gingras, M.K.** (2007) The Ichnofacies Paradigm: high-resolution palaeoenvironmental interpretation of the rock record. In: *Applied Ichnology* (Eds J.A. MacEachern, K.L. Bann, M.K. Gingras and S.G. Pemberton), *SEPM Short Course Notes*, **52**, 380.

Martinsen, O.J., **Ryseth, A.**, **Helland-Hansen, W.**, **Flesche, H.**, **Torkildsen, G.** and **Idil, S.** (1999) Stratigraphic base level andfluvial architecture: Ericson Sandstone (Campanian), Rock Spring Uplift, SW Wyoming, USA. *Sedimentology*, **46**, 235–259.

Miall, A.D. (1996) *The Geology of Fluvial Deposit: Sedimentary Facies, Basin Analysis and Petroleum Geology*. Springer-Verlag, Berlin, 582 pp.

Miall, A.D. (2006) Reconstructing the architecture and sequence stratigraphy of the preserved fluvial record as a tool for reservoir development: a reality check. *AAPG Bull.*, **90**, 989–1002.

Mjøs, R., **Walderhaug, O.** and **Prestholm, E.** (1993) Crevasse splays sandstone geometries in the Middle Jurassic Ravenscar Group Yorkshire, UK. In: *Alluvial Sedimentation* (Eds M. Marzo and C. Puigdefáfregas), *Int. Assoc. Sedimentol. Spec. Publ.*, **17**, 167–184.

Mulder, T. and **Syvitski, J.P.M.** (1995) Turbidity currents generated at river mouths during exceptional discharge to the world's oceans. *J. Geol.*, **103**, 285–298.

O'Gorman, J.P. and **Varela, A.N.** (2010) The oldest lower Upper Cretaceous plesiosaurs (Reptilia, Sauropterygia) from the southern Patagonia, Argentina. *Ameghiniana*, **47**, 447–459.

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

Pankhurst, R.J., **Riley, T.R.**, **Fanning, C.M.** and **Kelley, S.P.** (2000) Episodic silicic Volcanism in Patagonia and Antarctic Peninsula: chronology of magmatism associated with the break-up of Gondwana. *J. Petrol.*, **41**, 605–625.

Pemberton, S.G., **Flach, P.D.** and **Mossop, G.D.** (1982) Trace fossils from the Athabasca oil sands, Alberta, Canada. *Science*, **217**, 825–827.

Peroni, G., **Cagnolatti, M.** and **Pedrazzini, M.** (2002) Cuenca Austral: marco geológico y reserva histórica de la actividad petrolera. In: *Simposio Rocas Reservorio de las Cuencas*

Productivas de la Argentina (Eds M. Schiuma, G. Hinterwimmer and G. Vergani), *5 Congreso de Exploración y Desarrollo de Hidrocarburos*, 11–19.

Plint, A.G. and **Browne, G.H.** (1994) Tectonic event stratigraphy in a fluvio/lacustrine, strike-slip setting: the Boss Point Formation (Wesphalia A), Cumberland Basin, Maritime Canada. *J. Sed. Res.*, **64**, 341–364.

Poiré, D.G., **Zamuner, A.B.**, **Goin, F.**, **Iglesias, A.**, **Canessa, N.**, **Larriestra, C.N.**, **Varela, A.N.**, **Calvo Marcillese, L.** and **Larriestra, F.** (2004) Ambientes sedimentarios relacionados a las tafofloras de las formaciones Piedra Clavada y Mata Amarilla (Cretácico), Tres Lagos, Cuenca Austral, Argentina. *Proc. X Reunión Argentina de Sedimentología*, **San Luis**, 140–141.

Quinlan, G.M. and **Beaumont, C.** (1984) Appalachian thrusting, lithospheric flexure and Paleozoic stratigraphy of eastern interior of North America. *Can. J. Earth Sci.*, **21**, 973–996.

Ramos, V.A. (1989) Andean Foothills structures in northern Magallanes Basin, Argentina. *AAPG Bull.*, **73**, 887–903.

Ramos, V.A., **Niemeyer, H.**, **Skarmeta, J.** and **Muñoz, J.** (1982) Magmatic evolution of the austral patagonian Andes. *Earth-Sci. Rev.*, **18**, 411–443.

Retallack, G.J. (2001) *Soils of the Past: An Introduction to Paleopedology*, 2nd edn. Blackwell Science, Oxford, 404 pp.

Richiano, S.M., **Varela, A.N.**, **Cereceda, A.** and **Poiré, D.G.** (2012) Evolución paleoambiental de la Formación Río Mayer, Cretácico inferior, Cuenca Austral, Patagonia Argentina. *Latin Am. J. Sedimentol. Basin Anal.*, **19**, 3–26.

Richiano, S.M., **Poiré, D.G.** and **Varela, A.N.** (2013) Icnología De La Formación Río Mayer, Cretácico Inferior, SO Gondwana, Patagonia, Argentina. *Ameghiniana*, **50**, 273–286.

Robbiano, J.A., **Arbe, H.** and **Bangui, A.** (1996) Cuenca Austral Marina. In: *Geología y Recursos Naturales de la Plataforma continental Argentina* (Eds V.A. Ramos and M. Turic), *13 Relatorio del Congreso Geológico Argentino and 3 Congreso de Exploración de Hidrocarburos*, 343–358.

Rodríguez, J.F. and **Miller, M.** (2005) Cuenca Austral. In: *Frontera Exploratoria de la Argentina* (Ed. G. Chebli), *6 Congreso de Exploración y Desarrollo de Hidrocarburos*, 308–323.

Romans, B.W., **Fildani, A.**, **Graham, S.A.**, **Hubbard, S.M.** and **Covault, J.A.** (2010) Importance of the predecessor basin history on the sedimentary fill of a retroarc foreland basin: provenance analysis of the Cretaceous Magallanes basin, Chile (50-52S). *Basin Res.*, **22**, 648–658.

Romans, B.W., **Fildani, A.**, **Hubbard, S.M.**, **Covault, J.A.**, **Fosdick, J.C.** and **Graham, S.A.** (2011) Evolution of deep-water stratigraphic architecture, Magallanes Basin, Chile. *Mar. Petrol. Geol.*, **28**, 612–628.

Royer, D.L. (2010) Fossil soils constrain ancient climate sensitivity. *Proc. Natl. Acad. Sci. U. S. A.*, **107**, 517–518.

Scasso, R.A. and **Limarino, C.O.** (1997) *Petrología y Diagénesis de Rocas Clásticas*. Asociación Argentina de Sedimentología, Publicación Especial 1, Buenos Aires, 259 pp.

Shanley, K.W. and **McCabe, P.J.** (1994) Perspectives on the sequence stratigraphy of continental strata. *AAPG Bull.*, **78**, 544–568.

Sinclair, H.D., **Coakley, B.J.**, **Allen, P.A.** and **Watts, A.** (1991) Simulation of foreland basin stratigraphy using a diffusional model of mountain belt uplift and erosion: an example from central Alps, Switzerland. *Tectonics*, **10**, 599–620.

Spalletti, L.A. and **Franzese, J.R.** (2007) Mesozoic Paleogeography and Paleoenvironmental evolution of Patagonia (Southern South America). In: *Patagonian Mesozoic Reptiles* (Eds Z. Gasparini, Z. , L. Salgado and R.A. Coria), pp. 29–49. Indiana University Press, Bloomington & Indianapolis.

Van Wagoner, J.C. (1995) Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, USA. In: *Sequence Stratigraphy of Foreland Basin Deposits—Outcrop and Subsurface Examples from the Cretaceous of North America* (Eds J.C. Van Wagoner and G.T. Bertram), *Am. Assoc. Petrol. Geol. Mem.*, **64**, 137–223.

Van Wagoner, J.C. (1998) Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A. Reply. *Am. Assoc. Petrol. Geol. Bull.*, **82**, 1607–1618.

Varela, A.N. (2011) *Sedimentología y Modelos Deposicionales de la Formación Mata Amarilla, Cretácico de la Cuenca Austral, Argentina*. PhD Thesis, Universidad Nacional de La Plata, Facultad de Ciencias Naturales y Museo.

Varela, A.N., **Poiré, D.G.**, **Richiano, S.** and **Zamuner, A.** (2006) Los paleosuelos asociados al Bosque Petrificado María Elena, Formación Mata Amarilla, Cuenca Austral, Patagonia, Argentina. *IV Congreso Latinoamericano de Sedimentología y XI Reunión Argentina de Sedimentología*, **Bariloche, Actas**, 235.

Varela, A.N., **Richiano, S.** and **Poiré, D.G.** (2011) Tsunami vs storm origin for shell bed deposits in a lagoon environment: an example from the Upper Cretaceous of Southern Patagonia, Argentina. *Latin Am. J. Sedimentol. Basin Anal.*, **18**, 63–85.

Varela, A.N., **Poiré, D.G.**, **Martin, T.**, **Gerdes, A.**, **Goin, F.J.**, **Gelfo, J.N.** and **Hoffmann, S.** (2012a) U-Pb zircon constraints on the age of the Cretaceous Mata Amarilla Formation, Southern Patagonia, Argentina: its relationship with the evolution of the Austral Basin. *Andean Geol.*, **39**, 359–379.

Varela, A.N., **Veiga, D.G.** and **Poiré, D.G.** (2012b) Sequence stratigraphic analysis of Cenomanian greenhouse palaeosols: a case study from southern Patagonia, Argentina. *Sed. Geol.*, **271–272**, 67–82.

Varela, A.N., **Gómez-Peral, L.E.**, **Richiano, S.** and **Poiré, D.G.** (2013) Distinguishing similar volcanic source areas from an integrated provenance analysis: implications for foreland Andean basins. *J. Sed. Res.*, **83**, 258–276.

Veiga, D.G., **Spalletti, A.L.** and **Flint, S.S.** (2008) Anatomy of fluvial lowstand wedge: the Avilé member of the Agrio Formation (Hauterivian) in central Neuquén Basin (northwest Neuquén Province), Argentina. In: *Sedimentary Processes, Environments and Basins, A tribute to Peter Friend* (Eds G. Nichols, E. Williams and C. Paola), *Int. Assoc. Sedimentol. Spec. Publ.*, **38**, 341–365.

Watts, A.B. (1989) Lithospheric flexure due to prograding sediment loads: implications for the origin of offlap/onlap patterns in sedimentary basins. *Basin Res.*, **2**, 133–144.

White, T., **González, L.**, **Ludvigson, G.** and **Poulsen, C.** (2001) Middle Cretaceous greenhouse hydrologic cycly of North America. *Geology*, **29**, 363–365.

Wilson, T.J. (1991) Transition from back-arc to foreland basin development in southernmost Andes: stratigraphic record from the Última Esperanza District, Chile. *Geol. Soc. Am. Bull.*, **103**, 98–111.

Wright, V.P. and **Marriott, S.B.** (1993) The sequence stratigraphy of fluvial depositional systems: the role of floodplain storage. *Sed. Geol.*, **86**, 203–210.

Yoshida, S. (2000) Sequence and facies architecture of the upper Blackhawk Formation and the Lower Castlegate Sandstone (Upper Cretaceous), Book Cliffs, Utah, USA. *Sed. Geol.*, **86**, 203–210.

Yoshida, S., **Miall, A.D.** and **Willis, A.** (1998) Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A. *Am. Assoc. Petrol. Geol. Bull.*, **82**, 1596–1606.

Zamuner, A.B., **Poiré, D.G.**, **Iglesias, A.**, **Larriestra, F.** and **Varela, A.N.** (2004) Upper Cretaceous In Situ Petrified Forest In Mata Amarilla Formation, Tres Lagos, Southern Patagonia, Argentina. *Proc. 7th Int. Org. Paleobot. Conf.*, **Bariloche**, 150.

Zamuner, A., **Falaschi, P.**, **Bamford, M.**, **Iglesias, A.**, **Poiré, D.G.**, **Varela, A.N.** and **Larriestra, F.** (2006) Anatomía y Paleocología de dos Bosques *in situ* de la Zona de Tres Lagos, Formación Mata Amarilla, Cretácico superior, Patagonia, Argentina. *Proc. XIII Simposio Argentino de Paleobotánica y Palinología*, **Bahía Blanca**, 55.

Zavala, C., **Ponce, J.J.**, **Arcuri, M.**, **Drittanti, D.**, **Freije, H.** and **Asensio, M.** (2006) Ancient lacustrine hyperpycnites: a depositional model from a case study in the Rayoso Formation (Cretaceous) of West-Central Argentina. *J. Sed. Res.*, **76**, 41–59.

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