Journal of South American Earth Sciences 43 (2013) 112–126

Contents lists available at SciVerse ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Facies analysis of a Toarcian–Bajocian shallow marine/coastal succession (Bardas Blancas Formation) in northern Neuquén Basin, Mendoza province, Argentina

Graciela S. Bressan*, Diego A. Kietzmann, Ricardo M. Palma

Grupo de Carbonatos y Cicloestratigrafía, Instituto de Estudios Andinos Don Pablo Groeber (IDEAN), Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires – Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina

A R T I C L E I N F O

Article history:
Received 1 August 2012
Accepted 26 January 2013

Keywords:
Early-Middle Jurassic
Siliciclastic shelf deposits
Fluvio-deltaic sedimentation
Ichnology
Sequence stratigraphy
Transgressive–regressive sequences

A B S T R A C T

Strata of the Bardas Blancas Formation (lower Toarcian–lower Bajocian) are exposed in northern Neuquén Basin. Five sections have been studied in this work. Shoreface/delta front to offshore deposits predominate in four of the sections studied exhibiting a high abundance of hummocky cross-stratified, horizontally bedded and massive sandstones, as well as massive and laminated mudstones. Shell beds and trace fossils of the mixed *Skolithos-Cruziana* ichnofacies appear in sandstone beds, being related with storm event deposition. Gravel deposits are frequent in only one of these sections, with planar cross-stratified, normal graded and massive orthoconglomerates characterizing fan deltas interstratified with shoreface facies. A fifth outcrop exhibiting planar cross-stratified orthoconglomerates, pebbly sandstones with low-angle stratification and laminated mudstones have been interpreted as fluvial channel deposits and overbank facies. The analysis of the vertical distribution of facies and the recognition of stratigraphic surfaces in two sections in Río Potimalal area let recognized four transgressive–regressive sequences. Forced regressive events are recognized in the regressive intervals. Comparison of vertical distribution of facies also shows differences in thickness in the lower interval among the sections studied. This would be related to variations in accommodation space by previous half-graben structures. The succession shows a retrogradational arrangement of facies related with a widespread transgressive period. Lateral variation of facies let recognize the deepening of the basin through the southwest.

1. Introduction

The Bardas Blancas Formation is a lower Toarcian–lower Bajocian succession composed mostly by hummocky cross-stratified and massive sandstones interpreted as a siliciclastic marine shelf dominated by storm events (Gulisano and Gutiérrez Pleimling, 1994; Bressan, 2011). These deposits are exposed in the Neuquén Basin, restricted to Mendoza province (Malargüe Department).

The Bardas Blancas Formation was first described by Gerth (1925) as "*Areniscas con* Pseudomonotis" ("sandstones with *Pseudomonotis*"). Later it received the informal name "*Areniscas Bardas Blancas*" ("Bardas Blancas Sandstones") by Gulisano (1981), as member of the Los Molles Formation, which consists in deeper marine facies developed in southern Neuquén Basin. At last, the formal name Bardas Blancas Formation was given by Riccardi and Westermann (1984) and Riccardi (1984).

The Bardas Blancas Formation had received little attention. Early works mentioning this unit mostly have been centered in the analysis of the stratigraphy of the Jurassic succession in the Neuquén Basin (Groeber, 1953; Dessanti, 1973, 1978). Only Gulisano and Gutiérrez Pleimling (1994) proposed a correlation among different outcrops and a description and interpretation of the stacking patterns of four sections. In the last decade, the first works focused in a detailed sedimentary analysis of these deposits were carried out (Junken, 2002; Sanci, 2005; Chacra, 2007; González Pelegri, 2011). The Bardas Blancas Formation has been mentioned by Mutti et al. (1996, 2003) as an example of flood-dominated deltas. An advance in the knowledge of this unit has been given by Bressan (2011) who recognized depositional environments and its regional distribution, and studied the paleontological content through taphonomic and ichnologic analysis.

Although sandstones are usually the most abundant facies seen in Bardas Blancas Formation, mudstones and gravels can be present,

* Corresponding author.
E-mail addresses: grabressan@yahoo.com, gbressan@gl.fcen.uba.ar (G.S. Bressan).

0895-9811/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jsames.2013.01.007

showing important regional variations. Fossil remains are dominated by mollusks bivalves, being more frequent the specimens from the Order Pterioida (e.g., *Meleagrinella*, *Entolium*, *Plagiostoma* and *Camptonectes*) and the Order Veneroida (e.g., *Neocrassina*, *Megapraeconia* and "*Lucina*") (Damborenea, pers. comm.). Less frequently, gastropods and cephalopods can be present, the last one including belemnites and ammonites. Fauna also includes brachiopods and echinoderm remains. Shells occur in shell beds. Taxonomic analysis has been prevented by the poor preservation and the highly cemented deposits which make difficult the collection of the fauna (Bressan and Palma, 2008). Paleontological content also includes trace fossils in sandstone and mudstone beds (Bressan and Palma, 2009; Bressan, 2011).

In this paper we describe and interpret the sedimentary facies occurring in five outcrops of the Bardas Blancas Formation with the purpose of recognizing spatial and temporal variations in deposition. The association of shallow marine deposits and their relation to deltaic facies is discussed. Additionally, we propose a preliminary sequence stratigraphic interpretation.

2. Geological setting

The Neuquén Basin is developed at the west margin of South American platform and is bounded to the west by a magmatic arc and to the east by a tectonic foreland. The foreland consists of the Sierra Pintada belt to the northeast and the North Patagonian Massif to the south (Fig. 1a). The Neuquén Basin has been interpreted as a back-arc or retro-arc basin (Digregorio et al., 1984; Legarreta and Uliana, 1991, 1996; Ramos, 1999; amongst others) which started to develop in the Late Triassic overlying the basement consisting in early Paleozoic to Late Triassic metamorphic, plutonic, volcanic and sedimentary rocks. This basin is characterized by a quite continuous Mesozoic and Cenozoic sedimentary record, comprising continental and marine clastic, carbonate and evaporitic deposits which are up to 6000 m in thickness and cover an area of over 120,000 km^2 (Yrigoyen, 1991; Gulisano and Gutiérrez Pleimling, 1994). Marine influx took place at different time intervals by connection with the Pacific Ocean first and the Atlantic Ocean later (Legarreta and Uliana, 1991; Uliana and Biddle, 1988).

Basin development was controlled by different tectonic regimes (Legarreta and Uliana, 1991, 1996; Howell et al., 2005), which exerted a first-order control on the sedimentary evolution. An extensional regime was established during Late Triassic - Early Jurassic. The configuration of the basin was characterized by the development of isolated half-grabens with variable polarity, intersected by *en-echelon* transfer faults (Vergani et al., 1995; Cristallini et al., 2006). The depocenters were filled by continental sedimentary deposits, as well as volcaniclastic or volcanic deposits from the intense volcanism that took place favored by the process of relaxation, known as the Precuyo Cycle (Gulisano, 1981; Gulisano et al., 1984; Riccardi and Gulisano, 1990; Legarreta and Uliana, 1991). This deposition corresponds to the first rifting-stage of the Neuquén Basin. In southern Mendoza, six depocenters have been recognized (Giambiagi et al., 2008), which are known as Atuel, Río

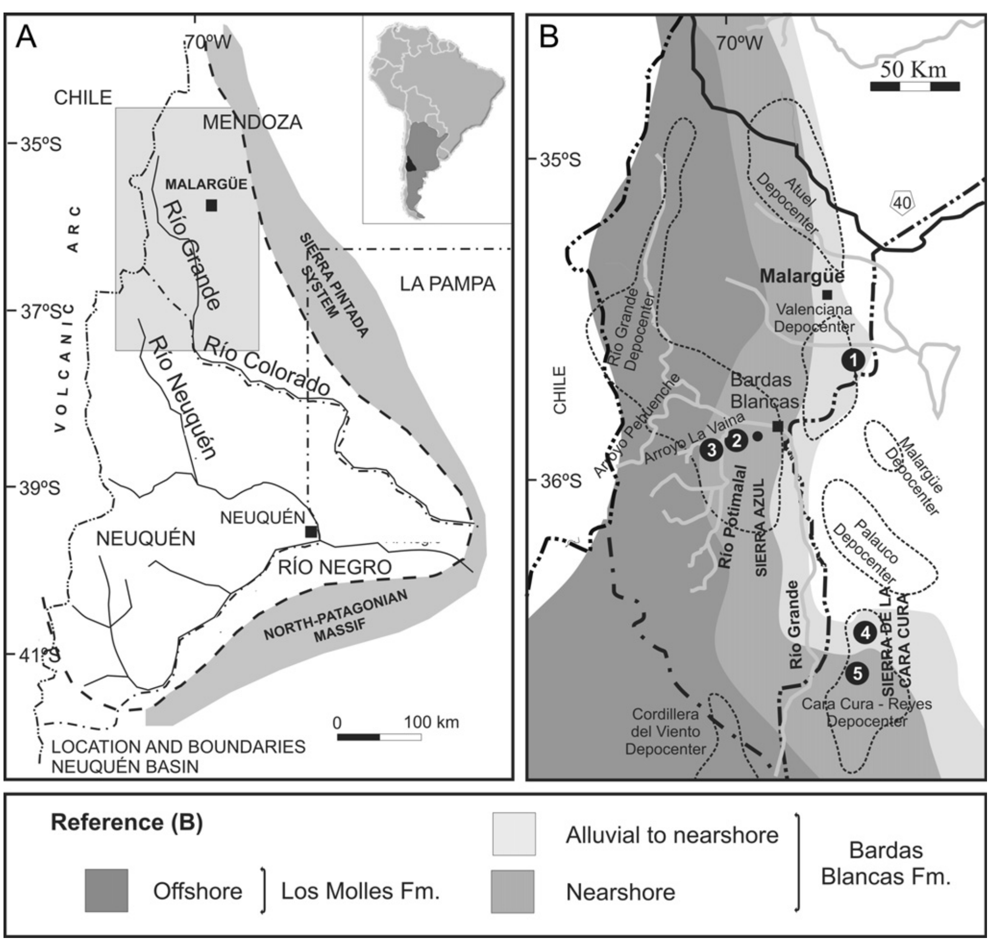

Fig. 1. A) South America map showing the location of Neuquén Basin in west-central Argentina. B) Map showing the geographic location of the outcrops. 1, Arroyo Loncoche; 2, Río Potimalal; 3, Arroyo La Vaina; 4, Río Seco del Altar; 5 Río Seco de la Cara Cura; this map also shows the depocenters in Mendoza province (modified from Giambiagi et al., 2008) and main sedimentary facies of the Bardas Blancas Formation (after Legarreta and Uliana, 1991).

Grande, Valenciana, Malargüe, Palauco and Cara Cura – Reyes depocenters (Fig. 1b).

The Early Jurassic to Late Cretaceous was characterized by a thermal subsidence regime with localized tectonic events. A second rifting stage occurred during the Pliensbachian–Toarcian and is composed mainly by marine deposits known as the Cuyano Cycle, which overlapped with the onset of the transition to the post-rift stage (Vergani et al., 1995). Under this conditions was deposited the sedimentary succession known as Bardas Blancas Formation. The relief generated by the extensional regime of the first rifting stage was a first-order control for subsequent sedimentary successions. That is how the marine flooding at the beginning of the Cuyano Cycle was controlled by the half-grabens topography resulting in a diachronic and stepwise transgression (Gulisano, 1981; Gulisano et al., 1984). Sedimentation during the rest of the Jurassic and the Cretaceous took place in a thermal subsidence regime, and include continental and marine siliciclastic, carbonate and evaporitic successions (Lotena, Mendoza and Rayoso Groups).

A compressive deformation regime was established during Late Cretaceous, and lasted throughout the Cenozoic alternating with extensional events (Ramos and Folguera, 2005; Ramos, 2010). The connection with the Pacific Ocean ends and starts a new connection with the Atlantic Ocean. This interval includes continental and marine sedimentation (Neuquén and Malargue Groups).

3. Area of study and stratigraphy

The studied sections belong to five different outcrops which are located in the department of Malargüe (Mendoza Province) (Fig. 1b). According to their distribution along a north–south transect, these outcrops will be mentioned here as Arroyo Loncoche, Río Potimalal, Arroyo La Vaina, Río Seco del Altar and Río Seco de la Cara Cura sections. Because of their proximity and similarities in stacking patterns and paleontological content, Río Potimalal and Arroyo La Vaina sections in some occasions will be referred together as the outcrops in the Río Potimalal area. It is important to emphasize that this distribution reflects important regional facies changes.

The stratigraphy of the Bardas Blancas Formation is shown in Table 1. These deposits lay over the continental facies of the Remoredo Formation (Rhaetian-lower Hettangian), separated by a regional unconformity called Intraliassic unconformity (Gulisano et al., 1984). Overlying deposits varies among localities. In Arroyo Loncoche section, the deposits of the Bardas Blancas Formation are overlain by fluvial deposits without formal stratigraphic name, followed by the gypsum of the Auquilco Formation (Oxfordian-Kimmeridgian). In Río Potimalal area, the overlaying deposits correspond to the shelf black mudstones of the Tres Esquinas Formation (Pliesbachian–Bajocian). In Río Seco de la Cara Cura, carbonate facies of La Manga Formation (Callovian–Oxfordian) appear overlying the studied deposits, whereas in the northern extreme of the Cara Cura mountain range, the overlaying deposits are represented by siliciclastic facies equivalent to the carbonates mentioned before.

Table 1
Stratigraphic chart of the Neuquén basin in south Mendoza province for Triassic-Jurassic interval (Modified from Gulisano and Gutiérrez Pleimling, 1994).

Chronostratigraphic unit				Lithostratigraphic nomenclature		
Mesozoic	Jurassic	Upper	Tithonian	Mendoza Group	Vaca Muerta Fm.	
			Kimmeridgian		Tordillo Fm.	
			Oxfordian	Lotena Group	Auquilco Fm.	
		Middle	Callovian		La Manga Fm.	
			Bathonian		Lotena Fm.	
			Bajocian	Cuyo Group	Tábanos Fm.	
			Aalenian		Calabozo Fm.	
		Lower	Toarcian		Lajas Fm.	
			Pliensbaquian		Tres Esquinas Fm.	BARDAS BLANCAS FORMATION
			Sinemurian		Puesto Araya Fm.	
			Hettangian		El Freno Fm.	
Paleoz.	Triassic			Precuyo Group	Remoredo Fm.	
	Permian-Triassic			Choiyoi Group (Basement)		

4. Age

Preliminary biostratigraphic analysis in this unit suggested an Aalenian-lower Bajocian age (Groeber, 1918, 1946, 1953; Stipanicic, 1969), while for other authors it was Toarcian-lower Bajocian (Jaworski, 1926; Weaver, 1931). Further works indicated an age between upper Toarcian and lower Bajocian (Gulisano, 1981; Gulisano and Gutiérrez Pleimling, 1994; Damborenea, 1996) on the base of ammonites and bivalves fauna. Only in the last decade the presence of ammonites of the *Dactylioceras hoelderi* Association Zone (von Hillebrandt and Schmidt-Effing, 1981; Riccardi, 1984, 2008) let establish the base of the Bardas Blancas Formation in the lower Toarcian (Sanci, 2005).

In the present study, the fossil record of the Bardas Blancas Formation allows us to determine its age as lower Toarcian to lower Bajocian. The age of the base has been determined as lower Toarcian using the state of knowledge of adjacent strata studied by Sanci (2005) mentioned before. These data come from another section in the Río Potimalal area which is laterally continuous with the section studied in this work and can be easily correlated with the sections in Río Potimalal and Arroyo La Vaina.

The assignation to the top is based in the presence of ammonites of the *Malarguensis* Standard Zone and *Singularis* Standard Zone, indicating upper Aalenian–lower Bajocian the former and lower Bajocian the second one (Westermann and Riccardi, 1979; Riccardi, 2008). This information comes from the Arroyo Loncoche section and the Río Potimalal area and is consistent with previous data. Only in Sierra de Reyes, Spalletti et al. (2012) assigned the upper half of the Bardas Blancas Formation to the Lower Bathonian based in the presence of fragmentary specimens of *Morphoceras* sp.

The age and correlation of the outcrops in the Sierra de la Cara Cura are still undetermined by the scarcity of data as well as the base of the Loncoche creek section.

5. Facies associations

Most of the studied sections are characterized by marine facies. The stacking patterns are usually poorly defined with exception of the Río Potimalal (69 m) and Arroyo La Vaina (67 m) sections. In these localities the deposits display a well-defined facies shift conforming at least four intervals (Fig. 2a) (see Section 5.6 and 6). The most important facies in these sections are amalgamated hummocky cross-stratified sandstones and massive and laminated mudstones (Fig. 2b, c). Gravel deposits develop only at the base of these outcrops. The beds show remarkable continuity and can be traced for tens of kilometers with no interruptions in this area (Fig. 2d). Shell beds are abundant in sandstone deposits. Trace fossils appear in sandstone and mudstone beds, being much more abundant and diverse in the former.

The Arroyo Loncoche section (157 m) (Fig. 3a) is composed mostly by massive, graded and stratified gravels (Fig. 3b) and

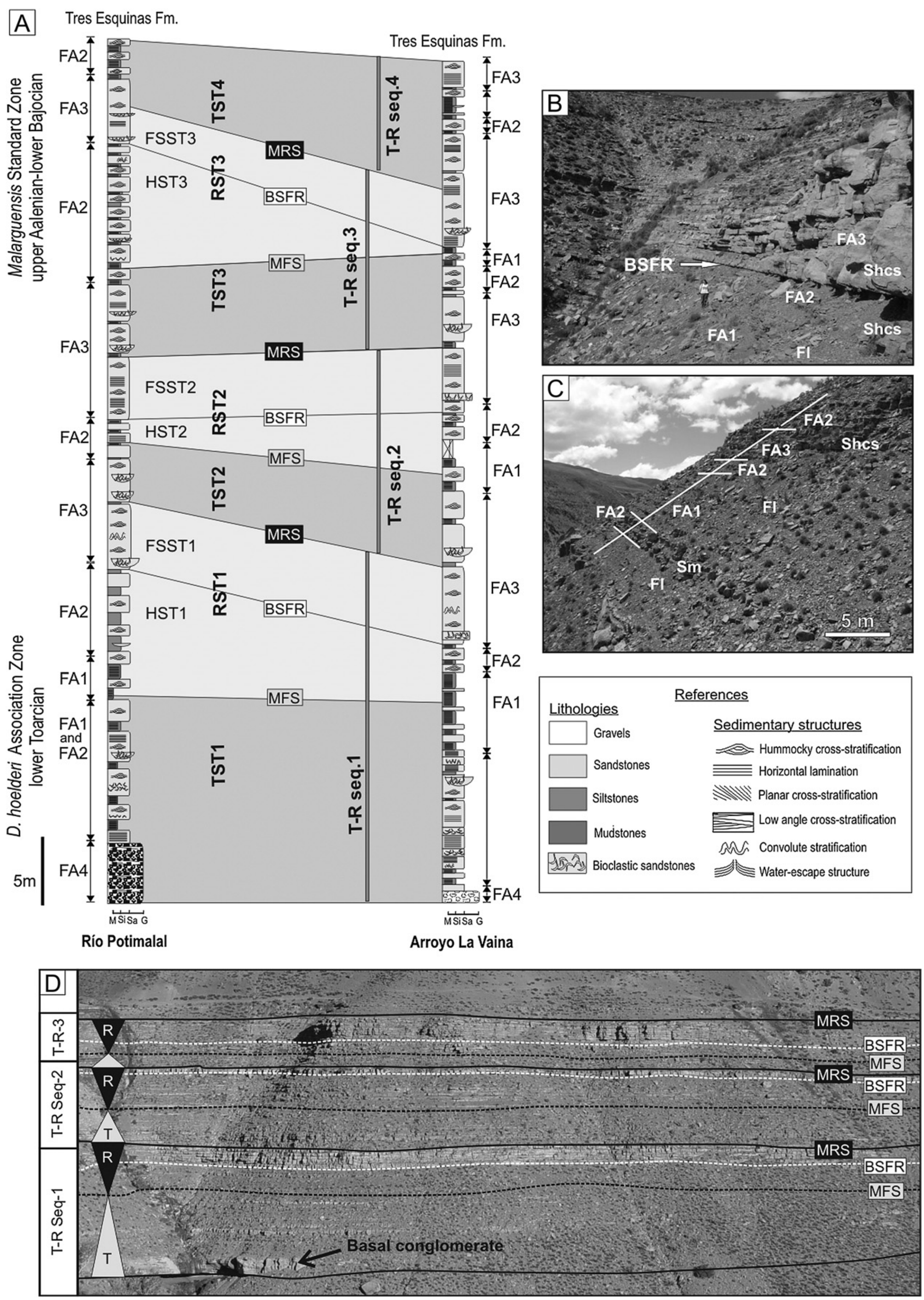

Fig. 2. A) Schematic stratigraphic section showing the distribution of facies associations (FA) in the outcrops of the Bardas Blancas Formation in Río Potimalal area and the sequence stratigraphic analysis. TST, transgressive system tract; RST, regressive system tract; T–R Seq., transgressive–regressive sequence; MFS, maximum flooding surface; MRS, maximum regressive surface; BSFR, basal surface of forced regression; HST, highstand system tract; FSST, falling-stage system tract. B) General aspect of facies associations 1 to 3 in Arroyo La Vaina. C) Detail of facies distribution in the base of Río Potimalal section. D) General aspect of Río Potimalal section. Shcs: hummocky cross-stratified sandstones; Sm: massive sandstones; Fl: laminated mudstones.

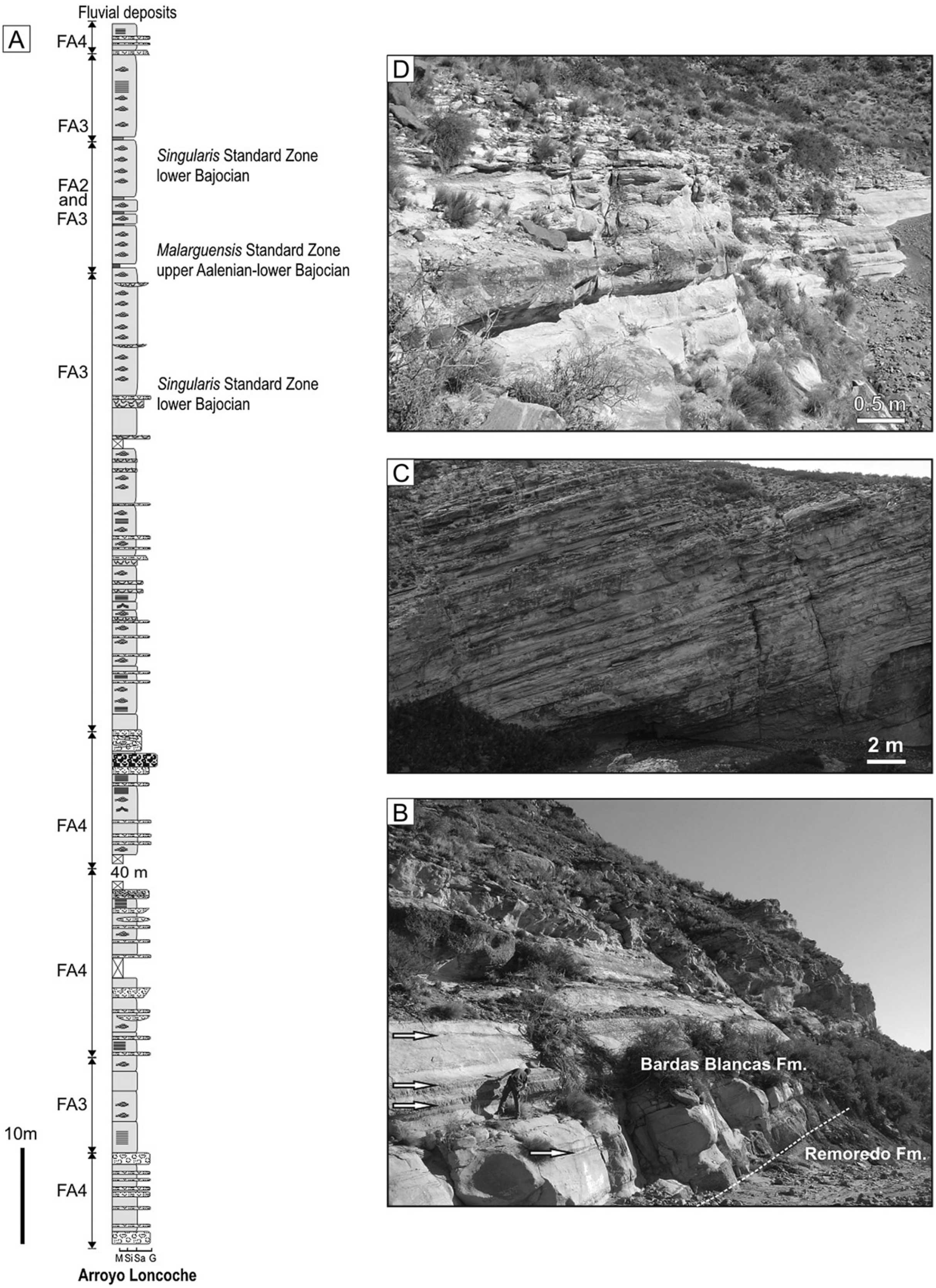

Fig. 3. A) Schematic stratigraphic section showing the distribution of facies associations (FA) in the Bardas Blancas Formation in Arroyo Loncoche section. B) General aspect of basal deposits: interstratification of massive sandstones and conglomerates (white arrows). C) Facies association 3 in the upper half. D) General aspect of hummocky cross-stratified and massive sandstones at the top of Arroyo Loncoche section.

hummocky cross-stratified and massive sandstones (Fig. 3c, d). Shell beds are extremely scarce. Trace fossils are present all over the outcrop, always in sandstone beds.

In Río Seco de la Cara Cura the succession (75 m) is composed by massive, horizontally stratified and hummocky cross-stratified sandstones and massive mudstones (Fig. 4a, b). Shell beds and trace fossils are scarce.

Río Seco del Altar (15 m) section differs in its facies (Fig. 4a), being dominated by lenticular although laterally extensive beds of planar cross-stratified orthoconglomerates, pebbly sandstones with low angle stratification and laminated mudstones (Fig. 4c). Bioturbation has been registered only occasionally.

For the purposes of definition and analysis, facies were distinguished mainly on the basis of physical and biogenic sedimentary structures and paleontological content. Five representative facies associations (FA) were described (Table 2).

5.1. Facies association 1: lower transition zone-outer shelf

5.1.1. Description

This facies association is present in Río Potimalal, Arroyo La Vaina and Río Seco de la Cara Cura. Consists of massive and laminated mudstones (Fm, Fl) interstratified with massive and horizontally bedded fine grained sandstones (Sm, Sh) (Fig. 5a). Mudstone beds are tabular, with gradational lower contacts and sharp upper contacts, varying in thickness between 20 and 115 cm. Sandstones are erosive-based lenticular and tabular beds, which varies from 15 to 38 cm in thickness.

Trace fossils are scarce, represented by *Chondrites* in massive and laminated siltstones (*Zoophycos* ichnofacies), whereas in sandstone beds is possible the recognition of isolated *Skolithos* (*Skolithos* ichnofacies). Fossil remains are scarce except for the presence of internal moulds of *Pholadomya laevigata* Hupé and *Pholadomya* sp. (both deep burrowers) found in siltstone beds in situ, as well as *Camptonectes* (*C.*) sp. (epifaunal) and *Grammatodon* sp. (shallow infaunal) in a few sandstone beds. Occasionally, fragments of *Trigonia* (*Trigonia*) sp. appear reworked. All this specimens come from Río Potimalal area.

5.1.2. Interpretation

Mudstones are interpreted as fallout of suspended fine material accumulated during fair-weather periods, below fair-weather wave base (Seilacher and Aigner, 1991). Poorly preserved laminated mudstone facies may record slight changes in the texture of suspended sediment, while sandstones reflect the waning flow deposits of storm-generated currents (Brenchley et al., 1993; Cantalamessa and Di Celma, 2004). Internal moulds of infaunal bivalves in life position suggest low erosion rates which let them keep in life position.

The isolated presence of *Chondrites* in mudstone beds indicates poor oxygenation, probably anoxic or dysoxic poral water and dysoxic bottom water (Savrda et al., 1991). The presence of r-strategists as *Skolithos* in sandstone beds suggests that storm processes would represent improvements in oxygenation (Bressan and Palma, 2009), whereas the absence of k-strategists and infaunal or epifaunal shelly organisms indicate that the improvement has been short, returning to poor oxygenated normal conditions. Only the intervals with bivalves in Río Potimalal area show permanent better circulation conditions.

Taking into account the mentioned characteristics, these deposits can be interpreted as lower transition zone-outer shelf settings (Reading and Collinson, 1996). However, taking into consideration the model of Mutti et al. (1996, 2003), these facies could represent prodeltaic deposits related with hyperpycnal flows.

5.2. Facies association 2: lower shoreface-transition zone

5.2.1. Description

This association is frequent in sections studied in Río Potimalal area. It appears also in Arroyo Loncoche and Río Seco de la Cara Cura, although less frequently.

It comprises hummocky cross-stratified fine-grained sandstones (Shcs), horizontally bedded fine-grained sandstones (Sh) and laminated siltstones (Fl), with a total thickness which varies between 60 and 150 cm (Fig. 5b).

Hummocky cross-stratified beds are sharp based sheet-like bodies, commonly 50–90 cm thick. These beds display the diagnostic characteristics defined by Harms et al. (1975). Two different varieties of hummocky cross-stratified sandstones have been recognized, the scour and drape form (Cheel and Leckie, 1993), and the migrating form (Brenchley, 1989; Cheel and Leckie, 1993) defined originally as “low-angle trough cross-stratification” by Arnott and Southard (1990), being the former much more abundant. Wavelength varies between 1 and 2.2 m in range. Water-escape structures can be present (Fig. 5c) whereas ripples at the top of the hummocky zone are uncommon.

Hummocky beds are overlaid by Sh which varies between 5 and 20 cm in thickness. Laminated deposits have sharp base and sharp or gradational upper contact with overlaying laminated siltstones which varies between 5 and 15 cm in thickness. Frequently, Shcs or Sh can be replaced by thick (20–40 cm) massive very fine to fine sandstone deposits, occasionally with shale and sandy rip-up clasts at their base.

A diverse range of trace fossils were recognized in sandstone beds (Shcs, Sh and Sm) (Bressan and Palma, 2009). They include elements of the *Skolithos* ichnofacies as *Skolithos* and elements of the *Cruziana* ichnofacies as *Gyrochorte*, *Taenidium*, *Thalassinoides*, *Planolites*, *Palaeophycus*, *Chondrites* and horizontal structures poorly preserved assigned to the fodinichnia and pascichnia ethologic categories. Traces represented by *Chondrites* have been found in siltstone facies (*Zoophycos* ichnofacies).

Shell concentrations appear in sandstone beds in both sections in Río Potimalal area. At first sight, these deposits can be persistent across an outcrop for tens of meters or pinch out laterally reaching a few meters in lateral extension. Shell concentrations vary between 9 and 80 cm in thickness, being thicker the tabular ones. In both cases (tabular and lenticular deposits), shell beds exhibit a complex internal structure composed by the vertical accretion of internally simple shell beds (Fig. 5d). These internally simple concentrations are laterally discontinuous reaching a few meters in wide and 2–7 cm in thickness and can exhibit erosive base. The geometry of the tabular deposits is produced by the lateral accretion of single concentrations. These concentrations are composed by disarticulated and highly fragmented bivalve shells. Valves usually appear recristallized, although dissolution and preservation as moulds can occur. Internal moulds of gastropods and calcitic rostrum of belemnites appear occasionally. Bivalve shell fragments are poorly sorted (0.2–7 cm), biofabric is loosely to densely packed and usually exhibit a concordant orientation with no concave/convex preference in cross-section, and less usually chaotic.

A third kind of shell deposit appears occasionally, developed as laterally discontinuous internally simple lags with centimetric thickness (no more than 9 cm). Concentration attributes are similar to those described previously, but in this case packing is invariably dense and shell remains appear oriented parallel to bedding.

5.2.2. Interpretation

The hummocky cross-stratification can be interpreted as deposited by waning oscillatory flows, and waning of combined oscillatory flow and unidirectional currents created by periodic

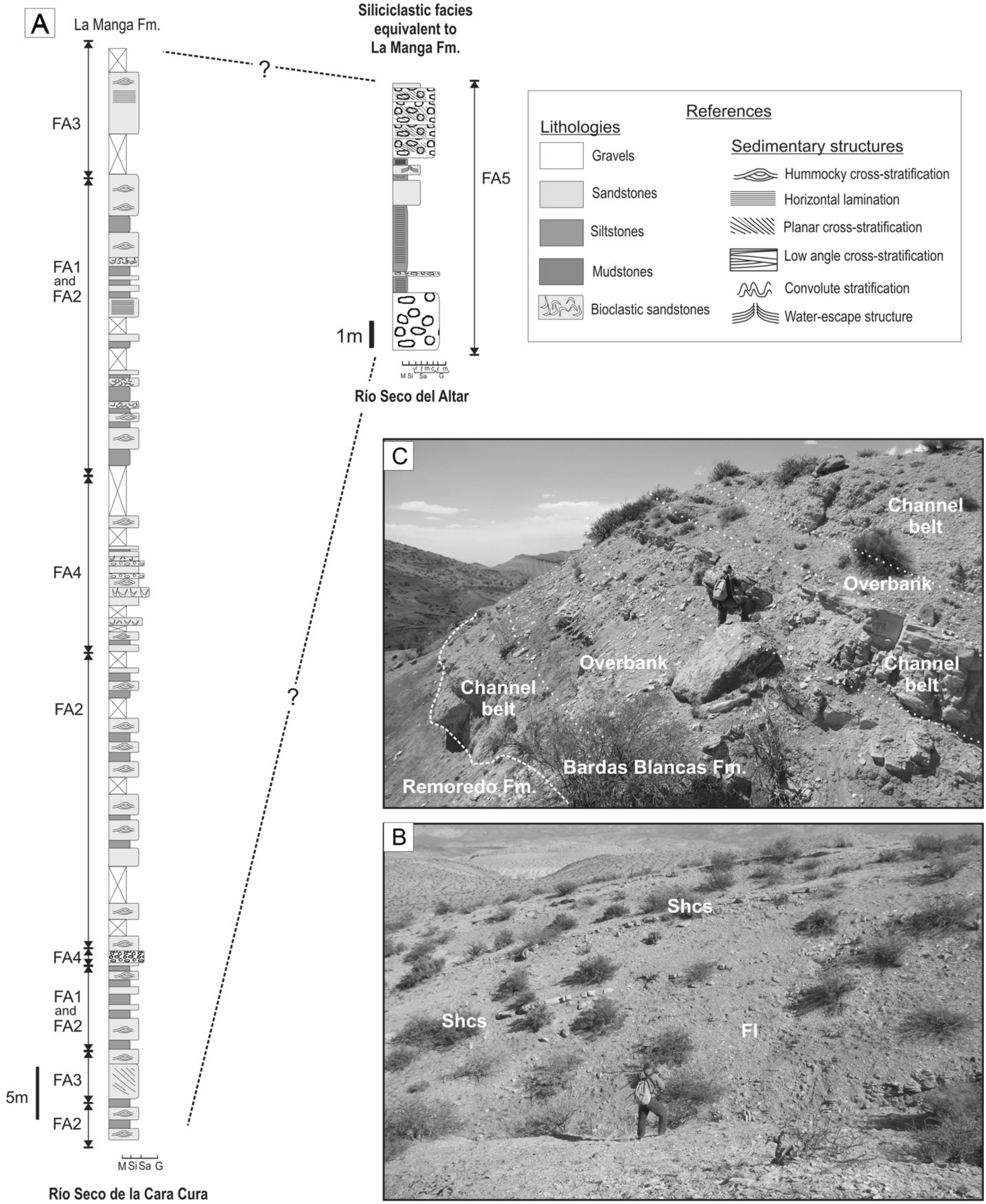

Fig. 4. A) Schematic stratigraphic section showing the distribution of facies associations (FA) in the Bardas Blancas Formation in two outcrops of Sierra de la Cara Cura. B) General aspect of marine deposits in Río Seco de la Cara Cura section. C) General aspect of fluvial deposits in Río Seco del Altar section. Shcs: hummocky cross-stratified sandstones; Fl: laminated mudstones.

Table 2
Facies associations of the Bardas Blancas Formation.

FA	Sedimentologic features	Paleontological content	Interpretation
1	Fm and Fl (tabular beds with gradational lower contact) interstratified with Sm and Sh (tabular and lenticular beds with erosive base).	*Chondrites* in Fm and Fl. *Skolithos* in Sm and Sh. In a few levels, isolated bivalves from genus *Pholadomya*, *Trigonia*, *Grammatodon*, and *Camptonectes*. More frequently, shelly fauna is lacking.	Fallout of suspended fine material during fair-weather periods (Fm and Fl). Sm and Sh reflect the waning flow deposits of storm-generated currents. *Skolithos* indicates improvements in oxygen content during storms. Lower transition zone to outer shelf settings.
2	Shcs in sharp based sheet-like bodies, overlaid by Sh and Fl. Shcs and Sh can appear replaced by Sm. Water-scape structures in Shcs.	Sandstones with *Skolithos*,*Palaeophycus*, *Planolites*, *Thalassinoides*, *Taenidium*, *Gyrochorte*, *Chondrites*, fodinichnia and pascichnia indet. Tabular and lenticular shell beds with complex internal structures and shell lags.	Storm sedimentation in lower shoreface–upper transition zone settings. Trace fossils (mixed *Skolithos-Cruziana* ichnofacies) and shell beds characterize storm-dominated settings.
3	Vertical amalgamation of Shcs and Sh. Interstratification with lenticular and lentiform Gmm and SGp matrix-supported orthoconglomerates. Water-escape structures and convolute stratification appear in Shcs.	Paleontologic content similar to FA2, but shell beds are more abundant.	Amalgamation of storm-event deposits in middle to lower shoreface-settings. Gravel deposits could be related with exceptional floods at the mouth of distributary systems flowing into the sea.
4	Matrix-supported orthoconglomerates (Gmm) or with planar cross-stratification or normal grading (Gp and Gg) interstratified with tabular beds of Sh, Shcs and Sg.	*Chondrites* in sandstone beds and in the sandy matrix of conglomerates. Scarse shell beds.	Fan delta deposits interstratified with shoreface facies.
5	Planar cross-stratified conglomerates (Gp) interstratified with pebbly sandstones with low angle stratification (SGl) and laminated mudstones (Fl).	Wood fragments.	Gp and SGl correspond to transverse bars in channel-belt deposits. Fl corresponds to overbank facies.

storm events (Dott and Bourgeois, 1982; Dumas and Arnott, 2006). Laminated sandstones overlying Shcs can be interpreted as the result of the thinning over hummocks (antiforms) and thickening within swales (synforms) (Dott and Bourgeois, 1982). Massive sandstones may have resulted from abrupt settling of sand from suspension, probably associated with storm-related flows (Collinson and Thompson, 1989). The presence of water-escape structures attests to rapid sand deposition and/or wave impact on the bottom during high-energy events (Massari and Parea, 1988).

It is important to keep in mind that hummocky cross-stratified sandstones (Shcs) can be generated from the disturbance of the water body along density interfaces (internal waves; see Pomar et al., 2012), and could also be deposited as bipartite hyperpycnal flows (De Celles and Cavazza, 1992; Mutti et al., 2003). Massive sandstones and the presence of water-escape structures also would be consistent with this interpretation.

Laminated siltstones would be deposited under fair-weather conditions. Thickness reached by these deposits would be related with long periods of fair-weather in lower settings of the shelf (below fair-weather wave base). It also could be related with deposition during transgressive periods, particularly those which are transitional with facies association 1 seen toward the top of deepening-upward intervals in Río Potimalal area.

Internally highly variable shell beds suggest complex taphonomic pathways. The breakage observed in valves indicates the action of high energy processes as those produced in the foreshore during extensive periods of time by fair-weather waves, since storm events are not strong enough to produce this kind of fragmentation (Davies et al., 1989). Most probable originated above fair-weather wave base and deposited below it, these shell beds can be interpreted as allochthonous concentrations. Preservational features and internal erosive contacts suggest multiple episodes of exhumation and deposition.

Lenticular shell beds can be interpreted as the infill of broad depressions or channels probably produced by storm-generated currents oblique or perpendicular to the coastline. Shell lags could be produced by the winnowing of previous storm deposits during the high energy phase of the storm (Brenchley, 1989; Dott and Bourgeois, 1982), taking into account the preservational features of the valves.

A trace fossil assemblage comprising elements of the *Skolithos* and *Cruziana* ichnofacies occurs in sandstone beds (Shcs, Sh and Sm), corresponding with two stages of colonization controlled by storm events and fair-weather periods (Bressan and Palma, 2009). The former indicates the colonization of storm sands by a community of opportunistic organisms in a post-event, high-stress, physically-controlled environment, while the *Cruziana* ichnofacies characterizes the colonization of low-energy environments as the same storm sands once the environment stabilizes or during fair-weather periods (Pemberton et al., 1992). This association is also known as the mixed *Skolithos-Cruziana* ichnofacies (MacEachern et al., 2008).

This association would develop in lower shoreface–upper transition zone settings. Following the model proposed by Mutti et al. (2000, 2003), this association could be interpreted as distal delta front deposits of flood-dominated deltas, which are similar to storm-dominated shoreface deposits.

5.3. *Facies association 3: middle to lower shoreface/delta front*

5.3.1. *Description*

This facies association is characterized by the vertical amalgamation of hummocky cross-stratified (Shcs) and horizontal laminated sandstone beds (Sh). In Río Potimalal area hummocky beds amalgamate for as much as 9 m in thickness (Fig. 5e). These thicknesses can also be measured in Arroyo Loncoche, where amalgamated deposits frequently include massive sandstone beds (Sm). In Río Seco de la Cara Cura the amalgamation appears only occasionally.

High weathering and amalgamation makes difficult the recognition of first and second order surfaces (following the nomenclature of Dott and Bourgeois, 1982) and the internal lamination. Occasionally, thin siltstone lenses can be interstratified with sandstone beds. Features of hummocky beds and horizontally bedded sandstones are similar to those mentioned previously for facies association 2. A characteristic feature is the presence of convolute stratification, where the deformed horizon can reach more than 1 m in thickness.

Shell deposits comprise beds which are in contact with first and second order surfaces of hummocky cross-stratified sandstones. Their attributes are similar to those described for facies association

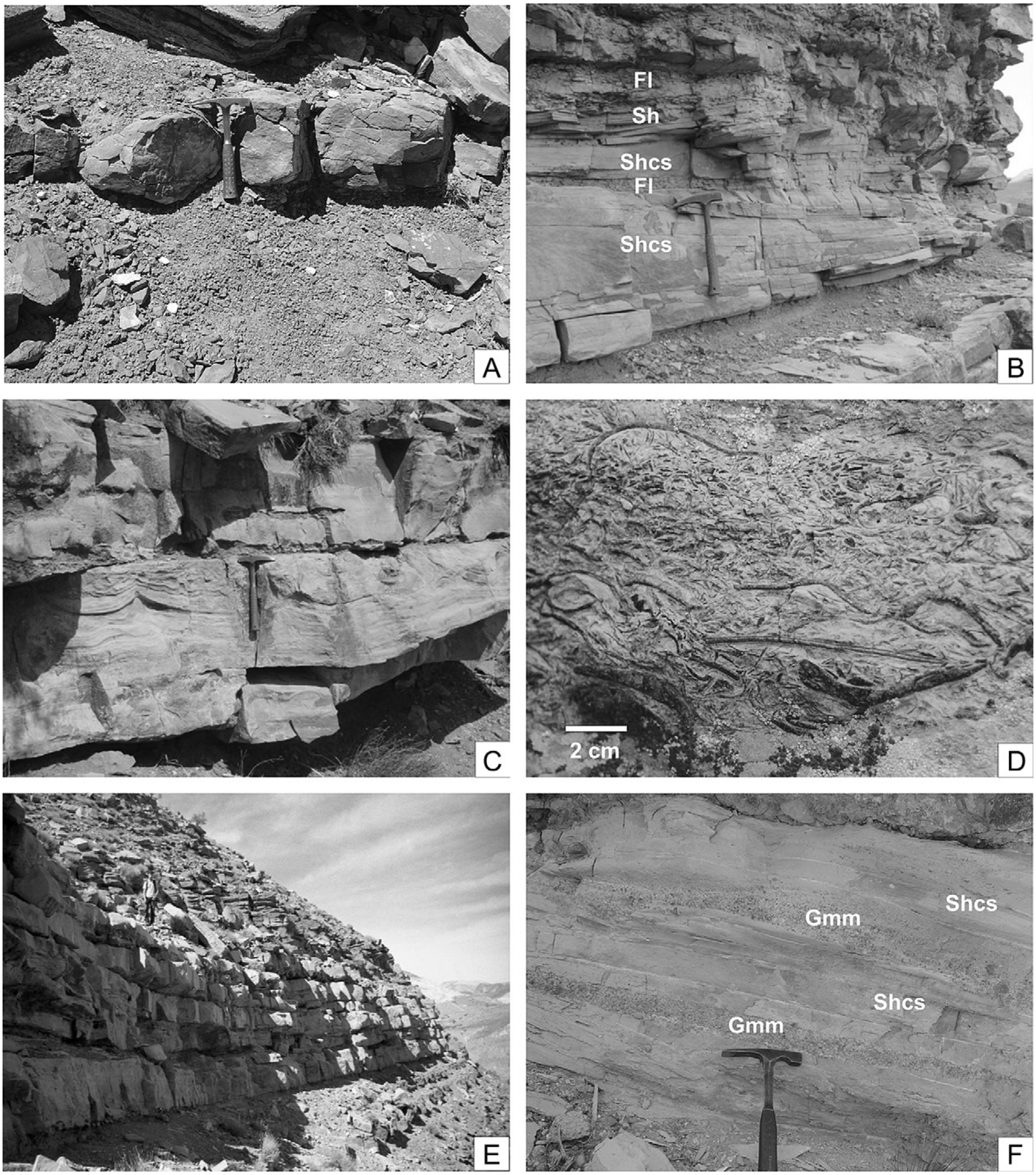

Fig. 5. A) Detail of facies association 1 in Arroyo La Vaina B) Detail of facies association 2 in Arroyo La Vaina. C) Detail of water escape structure in hummocky cross-stratified sandstones of facies association 3 in Arroyo La Vaina. D) Detail of shell bed interstratified with hummocky cross-stratified sandstones of facies association 2 in Río Potimalal. E) General aspect of facies associations 1 and 3 in Río Potimalal, note sharp contact between facies associations. F) Lenticular massive matrix-supported orthoconglomerates interbedded with hummocky cross-stratified sandstones in Arroyo Loncoche section. Fl: laminated mudstones; Sm: massive sandstones, Shcs: hummocky cross-stratified sandstones; Sh: horizontally bedded sandstones; Gmm: massive gravels.

2 although the frequency of the concentrations is higher, particularly in Río Potimalal and Arroyo La Vaina. In Arroyo Loncoche and Río Seco de la Cara Cura shell beds are extremely scarce and represented by thin deposits.

In Río Potimalal area a diverse range of trace fossils include *Skolithos*, *Thalassinoides*, *Planolites*, *Palaeophycus*, *Chondrites* and grazing structures. Biogenic structures are poorly preserved in the other sections preventing the ichnogenus assignation, being recognizable a variety of horizontal trace fossils corresponding to locomotion and feeding activities.

Lenticular to lentiform massive matrix-supported orthoconglomerates (Gmm) and planar cross-stratified pebbly sandstones (SGp) appear interbedded between hummocky cross-stratified sandstones in Arroyo Loncoche section (Fig. 5f). Deposits are 5 cm to one-clast thick, in the pebble size-range. They are sharp-based and occasionally fine upwards into pebbly sandstones, and can have thin shell beds at the top, composed by monotypic pectinid associations characterized by disarticulated valves with whole margins, concordant to stratification and without preferential orientation in plant view.

5.3.2. Interpretation

This facies association represents frequent storm events in shallow settings (Dott and Bourgeois, 1982), developing above the fair-weather wave base in the shoreface (Reading and Collinson, 1996), as suggested by amalgamated cross-stratified hummocky beds and the lack or scarcity of mudstone deposits, which would be related with high energy during storm events.

Shell beds can be interpreted as those described in the facies association 2 and their abundance would be associated with a proximal expression of these shell beds storm-related.

Gravel deposits (Gmm, SGp) associated with hummocky cross-stratified sandstones can be interpreted as exceptional floods at the mouth of distributary systems flowing into the marine environment. The sandy matrix points to the proximity of fluvial distributary mouths (Hart and Plint, 1995). The well preserved shell pavements would be produced by the winnowing of local communities and rapid burial related with high sedimentation rates.

This association would show up in middle to lower shoreface settings. However, in the Arroyo Loncoche section an alternative explanation would be found in flood-dominated deltaic systems (e.g., Mutti et al., 1996, 2003). In such sedimentary systems, fluvial floods generate sediment-water mixtures that enter in seawaters as density-driven underflows or hyperpycnal flows, resulting in massive or graded medium to fine sandstone deposits, and graded fine sandstones with HCS (Mutti et al., 2000, 2003). This interpretation is supported by the presence of conglomerate facies (Gmm, SGp), and massive sandstones (Sm) between the classical shoreface deposits with HCS.

Presence of thick intervals with convolute stratification suggests episodes of seismic activity (e.g., Ringrose, 1989; Rodríguez-Pascua et al., 2000), which could be related with tectonic reactivations of half-grabens. Amalgamation would lead to the underestimation of surface features, as the abundance of horizontal trace fossils and erosive marks.

5.4. Facies association 4: mouth bars/fan delta deposits

5.4.1. Description

This association occurs in the base of Río Potimalal and Arroyo La Vaina sections, and in the lower half of the Arroyo Loncoche and Río Seco de la Cara Cura. It is dominated by matrix-supported orthoconglomerates, which are massive (Gmm) or can display planar cross-stratification (Gp) (Fig. 6a) or normal grading (Gg). Clasts are rhyolitic or basaltic, prolate to equidimensional in shape, and range in size from gravel to cobble. Matrix is composed by medium to coarse grained sand.

Deposits are sharp-based with tabular geometry varying in thickness between 5 and 120 cm, they are composed by the amalgamation of graded packages thinner than 30 cm, with erosive

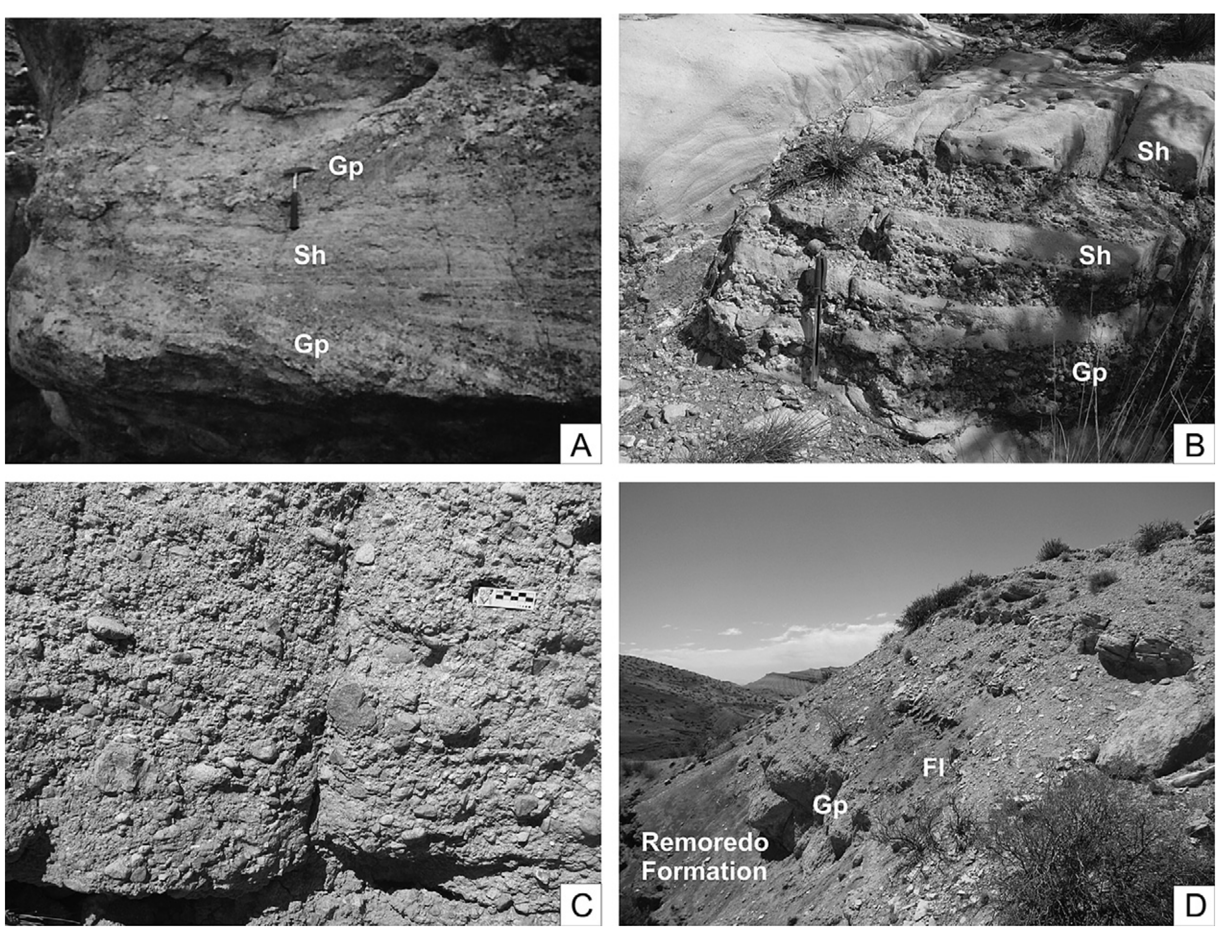

Fig. 6. A) Detail of planar cross-stratified gravels (Gp) and horizontally bedded sandstones (Sh) of facies association 4 at the base of Río Potimalal section. B) Detail of massive gravel deposits (Gmm) interstratified with horizontally bedded sandstones (Sh) of the facies association 4 in Arroyo Loncoche; C) transverse bars deposits (Gp) in Río Seco del Altar; D) General aspect of facies association 5 in Río Seco del Altar with transverse bars deposits (Gp) and overbank facies (Fl).

base and sharp upper contacts. These gravel deposits reach tens of meters of lateral extension.

Conglomerates appear interstratified with horizontally stratified (Sh) and hummocky cross-stratified sandstones (Shcs) (Fig. 6b), and less frequently with graded sandstones (Sg). Massive sandstones (Sm) are medium to coarse grained, sharp based, with water-escape structures and symmetric ripples on the top. These beds can exhibit millimetric levels rich in shell detritus. Graded sandstones are fine to medium grained and develop as sharp-based centimetric tabular deposits while Sh and Shcs beds are similar to those described in facies association 2.

Trace fossils are scarce, appearing *Chondrites* in sandstone beds, but also occur locally in the sandy matrix of conglomerate facies.

5.4.2. Interpretation

Gravel facies can be interpreted as longitudinal bars (Gmm, Gg) and transverse bars (Gp) and can be considered as deposits formed in braided channel belt deposits. The interstratification with facies association 3 in the lower part of the Arroyo Loncoche section indicates a relationship between the gravel deposits and the hummocky cross-stratified sandstones suggesting that the deposition were related with a nearshore marine environment.

Facies association 4 can be interpreted as fan delta deposits interstratified with marine shoreface deposits in the immediate vicinity of a gravelly river mouth (e.g., Ethridge and Wescott, 1984; Massari and Colella, 1988; Postma, 1990; Hart and Plint, 1995). According with this interpretation, the presence of hummocky cross-stratified, horizontally bedded and graded sandstones would be related with storm events, as well as the shell detritus deposits.

These kinds of facies were described also as flood-dominated mouth bars deposits by Mutti et al. (2003). Horizontally stratified (Sh) and graded sandstones (Sg) could be interpreted as the deposits of flows which underwent expansion at river mouth followed by a sudden gravitational collapse of their coarse-grained sediment load in the absence of substantial traction, generating hyperpycnal flows at the river mouth. Hummocky cross-stratified sandstones (Shcs) could be deposited as bipartite hyperpycnal flows (De Celles and Cavazza, 1992; Mutti et al., 2003) from the disturbance of the water body along density interfaces (internal waves; see Pomar et al., 2012).

5.5. Facies association 5: fluvial systems

5.5.1. Description

It develops in Río Seco del Altar section, although similar deposits are observed in the south of the Malargüe Anticline. This association is composed by planar cross-stratified conglomerates (Gp) (Fig. 6c) which appears interstratified with pebbly sandstones with low angle stratification (SGl) and laminated mudstones (Fl) (Fig. 6d).

The conglomerates (Gp) are formed by fine-medium gravels. Clasts are prolate to equidimensional in shape rounded to subangular. Matrix is clast-supported, locally matrix-supported, composed by medium sandstones to sabulitic sandstones. Deposits have erosive base and exhibit lenticular geometry, varying in thickness between 20 and 60 cm.

Pebbly sandstones (SGl) are coarse to sabulitic sandstones with less than 10% of gravel sized particles of rounded to subangular rhyolitic volcanites and rip-up clast. Deposits have lenticular geometry, with irregular base. Thickness varies between 30 and 50 cm.

Mudstones can reach 4 m in thickness. Wood fragments are common (Fig. 6d), including pieces of 4 m in length and 50 cm in diameter.

5.5.2. Interpretation

Deposits with planar cross stratification (Gp) and low angle stratification (SGl) are interpreted as transverse bars in channel-belt deposits. The presence of significant thicknesses of laminated mudstones with remains of trunks, as well as the absence of bioturbation and marine fossils, allows us to interpret mudstone deposits (Fl) as overbank facies.

The association of gravelly and sandy bar deposits with overbank facies can be interpreted as gravelly/sandy braided fluvial systems. Such thicknesses in overbank deposits are rare in this kind of fluvial systems (Miall, 1996). However, these fluvial systems probably reflect variations in erosion rates and the generation of relief, indicating variations in tectonic activity in the area. It is striking the thin thickness of the fluvial deposits, suggesting an extremely low preservation potential and the lack of accommodation during sedimentation of coarse-grained facies. This would suggest that at that time, the river systems acted as sediment transfer zones (e.g., Mutti et al., 1996).

5.6. Sedimentary environment

The Bardas Blancas Formation is characterized mostly by marine sedimentation in upper shoreface to outer shelf settings (Fig. 7). The main evidence for a storm signature is the development of coarse hummocky cross-stratified deposits (FA 2–3). Trace fossils associations and highly reworked shell concentrations also point to marine environments dominated by storm events. In Arroyo Loncoche, Río Potimalal, Arroyo La Vaina and Río Seco de la Cara Cura sections, fan delta deposits are present while fluvial deposits characterize the succession in Río Seco del Altar.

As mentioned before, preservational features of shell beds made difficult the systematic study of the specimens because of the high fragmentation and recrystallization of the valves. Additionally, the strong cementation prevented the recovery of the material. All this leads to an underestimation of the paleontological diversity in this unit. The fossil fauna in FA 1 to FA 3 is characterized by marine mollusks, including some bivalves, gastropods and cephalopods (belemnites), and occasionally by brachiopods. The absence of fossils in gravel deposits (FA 4) is common in coarse high energy environments (Hart and Plint, 1995).

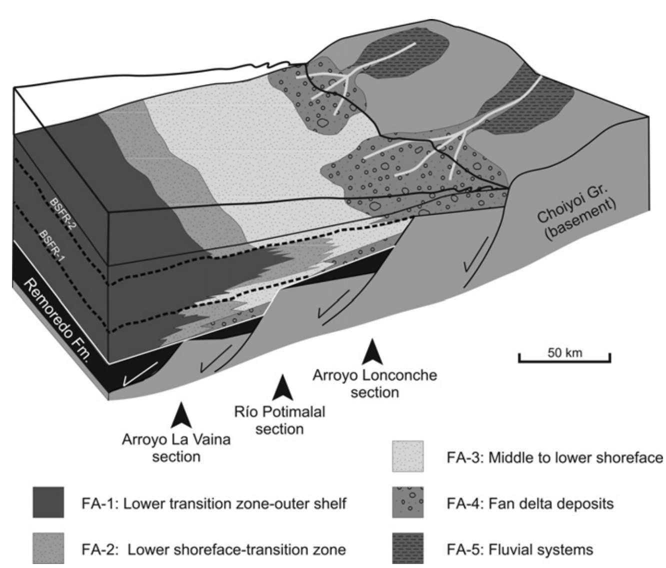

Fig. 7. Schematic block diagram showing the distribution of facies association of the Bardas Blancas Formation throughout a NE–SW transect.

The fauna recovered in mudstone facies mentioned in FA 1 includes infaunal bivalves in situ from the genus *Pholadomya*, indicating well oxygenated bottom waters (Ekdale and Mason, 1988). Occasionally, mudstone beds lack of any shelly fauna. This occurs with *Chondrites* as the only evidence of faunal activity, indicating interstitial waters anaerobic and aerobic or dysaerobic bottom water conditions (Ekdale and Mason, 1988). These levels appear to the top of deepening-upward intervals recognized in Río Potimalal and Arroyo La Vaina sections suggesting restrictions in water circulation during the last stages of transgressive events.

Shelly fauna in FA 2–3 appear as shell beds composed by highly reworked fragmented valves originated in foreshore and shoreface settings and deposited in the upper transition zone and the lower shoreface. These concentrations are well developed in both sections in Río Potimalal area. They are represented only occasionally in Arroyo Loncoche section and are almost completely lacking in Río Seco de la Cara Cura. In base of their internal complexity and their taphonomic and sedimentologic attributes, these shell beds can be interpreted as multievent concentrations (*sensu* Kidwell, 1991) and a few correspond to event concentrations (*sensu* Kidwell, 1991).

In spite of low preservation and scarcity of trace fossils, specimens provide relevant information. The presence of elements from the *Skolithos* ichnofacies and *Cruziana* ichnofacies in the same bed in storm sandstones (FA 2–3) let recognize the development of the mixed *Skolithos-Cruziana* ichnofacies (MacEachern et al., 2008) supporting the interpretation given to those deposits. Bioturbation indexes vary between 1 and 2 (virtually undisturbed lamination and less than 10% of disturbation, respectively, *sensu* Droser and Bottjer, 1986). These values can be assigned to changes in energy levels and oxygen availability (Bressan and Palma, 2009). In a first stage, pioneers would colonized storm beds (elements of the *Skolithos* ichnofacies) followed by the activity of a community exploiting a low-energy environment once normal conditions returned (elements of the *Cruziana* ichnofacies).

Taking into account vertical and lateral variation of facies and changes in ichnofacies distribution, there may have been local variation in physical or chemical conditions related to a complex coastal geomorphology with deltaic headlands or distributary mouths, resulting in different levels of suspended sediment concentration and salinity.

Some evidence, such as the abundance of massive beds, the intercalation of gravelly beds in purely marine environments, the presence of water-escape structures and remains of tree trunks, and the shortages of marine invertebrates in certain intervals, suggests that the Bardas Blancas Formation could have been deposited in the context of flood-dominated deltaic systems (Mutti et al., 1996, 2003). In such sedimentary systems, delta-front facies are similar to storm-generated shoreface deposits because of the abundance of HCS, so it may be difficult to distinguish accurately the unquestionably marine environment from those influenced by processes of the delta front.

Fluvial floods generate sediment-water mixtures that enter in seawaters as density-driven underflows, or hyperpycnal flows, resulting in massive or graded medium to fine sandstone deposits, and graded fine sandstones with HCS (Mutti et al., 2000, 2003). However, most ancient flood-dominated fluvio-deltaic systems can only be viewed in terms of catastrophic processes that were able to transport large amounts of gravel, sand and mud to delta-front and shelfal setting (Mutti et al., 1996). Then, in a complex association of marine and delta/fan delta systems like the Bardas Blancas Formation, a cautious view avoiding the abuse of the hyperpycnal flow model could be a vision closer to reality.

6. Sequence stratigraphic analysis

Based in the excellent outcrops quality, the Río Potimalal and Arroyo La Vaina localities have been chosen as reference sections for this interpretation. Stacking patterns in these sections are representative of most of the stacking patterns of Bardas Blancas Formation. For several kilometers this unit outcrops in Río Potimalal area showing the same stacking patterns as well as in the type locality Bardas Blancas, a little town approximately 17 km northeastern Río Potimalal section. The stacking patterns are poorly defined in Arroyo Loncoche and in Río Seco de la Cara Cura localities. Then, the analysis of these sections is prevented by the bad quality of the outcrops, which include extensive intervals covered by detritus. These sections will be studied in further works.

The sequence stratigraphic analysis will be focus using the transgressive–regressive model (Embry and Johannessen, 1991). Stacking patterns of Bardas Blancas Formation in marine settings exhibit a general retrogradational arrangement. The facies associations in Río Potimalal area combined to form transgressive–regressive sequences which start with one extensive deepening-upward and shallowing-upward interval (Fig. 2a), but deepening and shallowing-upward intervals are thinner and poorly developed toward the top of these outcrops.

In base of facies analysis and the recognition of stratigraphic surfaces, four transgressive–regressive sequences (T-R sequences) have been defined (Fig. 2a). Major stratigraphic breaks can be recognized separating the four transgressive–regressive sequences. Each transgressive system tract has a maximum regressive surface (Catuneanu, 1996; Helland-Hansen and Martinsen, 1996) in its base, marking the change from shoreline regression to subsequent transgression. These bounding discontinuities develop in sandstones of FA 3 separating prograding strata (regressive system tract) below from retrograding strata above (transgressive system tract).

Each sequence exhibits a maximum flooding surface (Frazier, 1974; Posamentier et al., 1988; Van Wagoner et al., 1988) marking the end of the shoreline transgression and indicating the limit between the transgressive system tract and the regressive system tract. In the studied unit this surface separates retrograding strata of the FA1 (top of the transgressive system tract) below from prograding strata of the FA2 (base of the regressive system tract) above.

The analysis of the regressive system tract shows an abrupt change from mudstones and sandstones from the transition zone below (FA 2) to thick amalgamated sandstones from the middle/lower shoreface above (FA 3). This change corresponds to an erosive basal surface that can be recognized not only in the Río Potimalal area, but also in the type locality mentioned before. This surface can be interpreted as a surface of forced regression (Hunt and Tucker, 1992). According to Posamentier and Morris (2000) the presence of a significant zone of separation between successive shoreface deposits, the erosive base and the recognition of this surface for long distances are features that support this interpretation. Both, normal and forced regressive intervals, show a progradational trend. This trend is interrupted by the maximum regressive surface which separates one transgressive–regressive sequence from the next.

Sequences are better developed in Arroyo La Vaina section, the westernmost outcrop analyzed, where the deeper deposits of FA 1 are thicker and maximum flooding surfaces and maximum regressive surfaces are more easily recognizable. The proximity between this section and Río Potimalal section (800 m) let correlate both successions in base of stacking patterns and lead to the recognition of the same four transgressive–regressive sequences in Río Potimalal section.

7. Discussion

Paleogeographic reconstruction of this unit is difficult to perform due to the limited availability of biostratigraphic data. It is not possible to establish the age of the base in most of the studied sections owing to the difficulty to obtain useful biostratigraphic data from the coarse-grained deposits present in the lower half of this unit. Nevertheless, the age of the base was established by Sanci (2005) for one section in the Río Potimalal area as lower Toarcian (*Dactylioceras hoelderi* Association Zone) while the top can be established as lower Bajocian in Río Potimalal area and in Arroyo Loncoche (*Malarguensis* Standard Zone and *Singularis* Standard Zone). Biostratigraphic data are still missing in Río Seco de la Cara Cura and in the continental deposits of Río Seco del Altar.

However, the sedimentary information provided in this paper allows some interpretations of environmental evolution of the Bardas Blancas Formation. Differences in thickness between the lower part of the studied sections, twice as thick in Arroyo Loncoche section than in Río Potimalal area, show that the accommodation space related to the previous half graben structures, was one of the main controls on the sedimentary deposition. This would be related with the stepwise transgression mentioned by Gulisano (1981).

The first marine transgression occurred in Río Atuel area during the Late Triassic-Jurassic times from the northwest and spreads to the south (Riccardi and Iglesia Llanos, 1999; Lanés, 2005), reaching earlier the area of Arroyo Loncoche (Valenciana Depocenter). That is the reason why the higher thickness for the Bardas Blancas Formation is reached in this locality.

During the Toarcian the Bardas Blancas Formation was characterized by shallow coastal marine deposits and the progradation of continental distributary systems from higher areas. Probably related to the previous topography, non-marine facies successions were typically thinner (a few meters) and much more laterally variable than marine successions, commonly changing their features over a few hundred meters to a few kilometers.

The reduced thickness of the mouth bars at the base of the Arroyo Loncoche, Río Potimalal and Arroyo La Vaina sections and the lack of gravity deposits suggest that fan deltas were developed in a low gradient shelf (Ethridge and Wescott, 1984; Postma, 1990). Mouth bars can be deposited in shallow basins with less than 3° dip (Orton, 1988; Postma, 1990) which allow the friction of the effluents against the bottom (Kleinspehn et al., 1984; Massari and Colella, 1988; Reading and Collinson, 1996). In a faulted-block topography such conditions control the sedimentation in the gentle sloping areas of the hanging wall just opposite to the main fault (Massari and Colella, 1988; Gawthorpe and Colella, 1988). By the Aalenian, the facies show greater uniformity across the study area, with the development of a typical marine facies succession, characterized mostly by marine sedimentation in upper shoreface to offshore settings.

The presence of large-scale deformational structures related to forced-regressive deposits in the T-R sequence 2 in Río Potimalal and Arroyo La Vaina sections, probably suggests short periods of tectonic activity or reactivation of the previous structures, which have generated the rapid progradation of coastal facies within a generally transgressive condition in the basin.

The interplay between extensional tectonics at the Andean margin of the Pacific Ocean and sea-level fluctuations has been considered as the main factor determining the sedimentary evolution of the basin in the Early-Middle Jurassic (Legarreta et al., 1993; Lanés, 2005; Giambiagi et al., 2008; Lanés et al., 2008). The retrogradational arrangement recognized in Bardas Blancas Formation has been observed previously by Legarreta and Uliana (1996) for the Mendoza area of Neuquén basin. They mentioned this as a consequence of underbalanced conditions of deposition and a low influx of sediments. The retrogradational arrangement mentioned here is related to a widespread transgressive period that led to the overlapping of the basinal facies of the Tres Esquinas (in Mendoza province) and Los Molles Formation (in Neuquén province) on the nearshore deposits of the studied unit (Gulisano et al., 1984; Legarreta et al., 1993).

The analysis of the distribution of facies at the different sections studied indicates a deepening of the basin toward the southwest during the Aalenian-Bajocian. This is evidenced by the development of continental deposits to the east, in Río Seco del Altar and the marine setting southward and westward from this locality. The westward deepening is also evident in the Río Potimalal area, observing the abundance of mudstones among Río Potimalal and Arroyo La Vaina localities.

8. Conclusions

In most of their localities, the Bardas Blancas Formation is characterized by hummocky cross-stratified, laminated and massive sandstones and massive and laminated mudstones of shoreface to offshore deposits. However, part of these deposits could be interpreted in the context of flood-dominated delta/fan delta systems. Event and multievent concentrations are abundant as well as trace fossils assigned to the mixed *Skolithos-Cruziana* ichnofacies. These features let interpret this unit as a marine shelf dominated by storm events. In eastward localities, this unit is represented by fluvial facies.

In marine settings, the deposits exhibit a retrogradational arrangement related to a widespread transgressive period that led to the overlapping of the basinal facies of the Tres Esquinas and Los Molles Formation on the nearshore/coastal deposits of the Bardas Blancas Formation.

Differences in thickness among the lower part of the studied sections show that the accommodation space related to the previous half graben structures controlled the sedimentary deposition. The stepwise transgression was recorded firstly in the Arroyo Loncoche section during the Toarcian. At this time, the Bardas Blancas Formation was characterized by shallow coastal marine deposits and the progradation of continental distributary systems from higher areas. Probably related to the previous topography, non-marine facies successions were typically thinner and much more laterally variable than marine successions, commonly changing character over a few hundred meters to a few kilometers. The lateral variation of facies among five localities shows a deepening of the basin toward the southwest.

Acknowledgments

This research has been done in the framework of the UBACyT 20020100100801 (Universidad de Buenos Aires) and PIP 5142 (CONICET) projects. The authors are especially grateful to Dr. Riccardi and Dr. Damborenea (Universidad Nacional de La Plata y Museo, Argentina) for the ammonite and bivalve determinations respectively. This is the contribution R-80 of the Instituto de Estudios Andinos Don Pablo Groeber.

References

Arnott, R.W.C., Southard, J.B., 1990. Exploratory flow-duct experiments on combined-flow bed configurations, and some implications for interpreting storm-event stratification. Journal of Sedimentary Petrology 60, 211–219.
Brenchley, P.J., 1989. Storm sedimentation. Geology Today, 133–137.
Brenchley, P.J., Pickerill, R.K., Stromberg, S.G., 1993. The role of wave reworking on the architecture of storm sandstone facies, Bell Island Group (Lower Ordovician), eastern Newfoundland. Sedimentology 40, 359–382.

Bressan, G.S., 2011. Evolución ambiental, tafonomía e icnología de la Formación Bardas Blancas (Jurásico) en el sector mendocino de Cuenca Neuquina. PhD thesis. Universidad de Buenos Aires.
Bressan, G.S., Palma, R.M., 2008. Tafonomía e icnología de los depósitos de tormenta de la Formación Bardas Blancas (Jurásico Inferior-Medio), Mendoza, Argentina. Ameghiniana 45, 513–528.
Bressan, G.S., Palma, R.M., 2009. Trace fossils from the Lower-Middle Jurassic Bardas Blancas Formation, Neuquén Basin, Mendoza Province, Argentina. Acta Geologica Polonica 59, 201–220.
Cantalamessa, G., Di Celma, C., 2004. Sequence response to syndepositional regional uplift: insights from high-resolution sequence stratigraphy of late Early Pleistocene strata, Periadriatic Basin, central Italy. Sedimentary Geology 164, 283–309.
Catuneanu, O., 1996. Reciprocal architecture of Bearpaw and post-Bearpaw sequences, Late Cretaceous-Early Tertiary, Western Canada Basin, Ph.D thesis. University of Toronto.
Chacra, J., 2007. Evolución paleoambiental, ciclicidad y estratigrafía secuencial en los depósitos de la Fm. Bardas Blancas (Mesosecuencia Cuyo) Cuenca Neuquina-Mendoza. Trabajo Final de Licenciatura. Universidad de Buenos Aires.
Cheel, R.J., Leckie, D.A., 1993. Hummocky cross-stratification. In: Wright, V.P. (Ed.), Sedimentology Review 1. Blackwell Scientific Publications, Oxford, pp. 103–122.
Collinson, J.D., Thompson, D.B., 1989. Sedimentary Structures. Unwin Hyman Ltd., London, pp. 1–207.
Cristallini, E.O., Bottesi, G., Gavarrino, A., Rodriguez, L., Tomezzoli, R.N., Comeron, R., 2006. Synrift geometry of the Neuquén Basin in the northeastern Neuquén Province, Argentina. In: Kay, S.M., Ramos, V.A. (Eds.), Evolution of the Andean Margin: A Tectonic and Magmatic View from the Andes to the Neuquén Basin (35°-39° S Lat). Geological Society of America, pp. 147–161. Special Paper, 407.
Damborenea, S.E., 1996. Palaeogeography of Early Jurassic bivalves along the southeastern pacific margin. In: XIII Congreso Geológico Argentino y III Congreso de Exploración de Hidrocarburos, Actas V, pp. 151–167.
Davies, D.J., Powell, E.N., Stanton Jr., R.J., 1989. Relative rates of shell dissolution and net sediment accumulation – a commentary: can shell beds form by the gradual accumulation of biogenic debris on the sea floor? Lethaia 22, 207–212.
De Celles, P.G., Cavazza, W., 1992. Contrains on the formation of Pliocene hummocky cross-stratification in Calabria (southern Italy) from consideration of hydraulic and dispersive equivalance, grain flow theory, and suspended-load fallaout rate. Journal of Sedimentary Petrology 62, 555–568.
Dessanti, R.N., 1973. Descripción Geológica de la Hoja 29b, Bardas Blancas, provincia de Mendoza. Boletín del Servicio Nacional Minero Geológico 139, 1–70.
Dessanti, R.N., 1978. Descripción Geológica de la Hoja 28b, Malargüe, provincia de Mendoza. Boletín del Servicio Geológico Nacional 149, 1–50.
Digregorio, J.H., Gulisano, C.A., Gutiérrez Pleimling, A.R., Minitti, S., 1984. Esquema de evolución geodinámica de Cuenca Neuquina y sus implicancias paleogeográficas. In: IX Congreso Geológico Argentino, Actas II, pp. 147–163.
Dott Jr., R.H., Bourgeois, J., 1982. Hummocky stratification: significance of its variable bedding sequences. Geological Society of America Bulletin 93, 663–680.
Droser, M.L., Bottjer, D.J., 1986. A semiquantitative classification of ichnofabric. Journal of Sedimentary Petrology 56, 558–569.
Dumas, S., Arnott, R.W.C., 2006. Origin of hummocky and swaley cross-stratification – the controlling influence of unidirectional current strength and aggradation rate. Geology 34, 1073–1076.
Ekdale, A.A., Mason, T.R., 1988. Characteristic trace-fossils associations in oxygen-poor sedimentary environments. Geology 16, 720–723.
Embry, A.F., Johannessen, E.P., 1991. T-R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic-Lower Jurassic succession, western Sverdrup Basin, Arctic Canada. In: Vorren, T.O., Bergsager, E., Dahl-Stamnes, O.A., Holter, E., Johansen, B., Lie, E., Lund, T.B. (Eds.), Arctic Geology and Petroleum Potential. Norwegian Petroleum Society, pp. 121–146. Special Publication 2.
Ethridge, F.O., Wescott, W.A., 1984. Tectonic setting, recognition and hydrocarbon reservoir potential of fan-delta deposits. In: Koster, E.H., Steel, R.J. (Eds.), Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists, Calgary, pp. 217–235. Memoir 10.
Frazier, D.E., 1974. Depositional Episodes: Their Relationship to the Quaternary Stratigraphic Framework in the Northwestern Portion of the Gulf Basin, vol. 74. University of Texas at Austin, Bureau of Economic Geology, Geological Circular, 1–28.
Gawthorpe, R.L., Colella, A., 1988. Fan-delta facies associations in Late Neogene and Quaternary basins of southeastern Spain. In: Nemec, W., Steel, R.J. (Eds.), Fan Deltas; Sedimentology and Tectonic Settings. Blackie and Sons, Glasgow, pp. 91–111.
Gerth, E., 1925. Contribución a la estratigrafía y paleontología de los Andes argentinos. I, Estratigrafía y distribución de los sedimentos mesozoicos en los Andes argentinos. Academia Nacional de Ciencias Actas 9, 7–55.
Giambiagi, L.B., Bechis, F., Lanés, S., Tunik, M., García, V., Suriano, J., Mescua, J.F., 2008. Formación y evolución triásica-jurásica del depocentro Atuel, cuenca Neuquina, Argentina. Revista de la Asociación Geológica Argentina 63, 520–533.
González Pelegri, E., 2011. Análisis sedimentológico-petrográfico y reconstrucción paleoambiental de la Formación Bardas Blancas (Jurásico), Sierra Azul, provincia de Mendoza. Trabajo Final de Licenciatura. Universidad de Buenos Aires.
Groeber, P., 1918. Estratigrafía del Dogger en la República Argentina. Boletín de la Dirección General de Minas, Geología e Hidrología, Serie B 18, 1–81.
Groeber, P., 1946. Observaciones geológicas a lo largo del Meridiano 70°, 1. Hoja Chos Malal. Revista de la Asociación Geológica 1, 177–208.
Groeber, P., 1953. Geografía de la República Argentina II, 1° parte. Sociedad Argentina de Estudios Geográficos GAEA, 1–541.
Gulisano, C.A., 1981. Ciclo Cuyano en el norte de Neuquén y sur de Mendoza. In: VIII Congreso Geológico Argentino, Actas 3, pp. 579–592.
Gulisano, C.A., Gutiérrez Pleimling, A.R., 1994. Field Trips Guidebook B, Neuquén Basin, Mendoza Province. 1–113. In: 4th International Congress on Jurassic Stratigraphy and Geology.
Gulisano, C.A., Gutiérrez Pleimling, A.R., Digregorio, R.E., 1984. Esquema estratigráfico de la secuencia jurásica del oeste de la Provincia de Neuquén. In: IX Congreso Geológico Argentino, Actas I, pp. 236–259.
Harms, J.C., Southard, J.B., Spearing, D.R., Walker, R.G., 1975. Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences. Society of Economic Paleontologists and Mineralogists. Short Course 2.
Hart, B.S., Plint, A.G., 1995. Gravelly Shoreface and Beachface Deposits. International Association of Sedimentologists. Special Publication, 22: 75–99.
Helland-Hansen, W., Martinsen, O.J., 1996. Shoreline trajectories and sequences: description of variable depositional scenarios. Journal of Sedimentary Research 66, 670–688.
Howell, J.A., Schwarz, E., Spalletti, L.A., Veiga, G.D., 2005. The Neuquén basin: an overview. In: Spalletti, L., Veiga, G., Schwarz, E., Howell, J. (Eds.), The Neuquén Basin Argentina: a Case Study in Sequence Stratigraphy and Basin Dynamics. Geological Society of London, pp. 1–14. Special Publications, 252.
Hunt, D., Tucker, M.E., 1992. Stranded parasequences and the forced regressive wedge systems tract: deposition during base level fall. Sedimentary Geology 81, 1–9.
Jaworski, E., 1926. La fauna de Lias Dogger de la Cordillera Argentina en la parte meridional de la Provincia de Mendoza. Academia Nacional de Ciencias de Córdoba. Acta 9, 139–317.
Junken, E.A., 2002. Sedimentación dominada por tormentas en el Bajociano (Jurásico medio): Formación Bardas Blancas, Cuenca Neuquina, Mendoza. Trabajo Final de Licenciatura. Universidad de Buenos Aires.
Kidwell, S.M., 1991. The stratigraphy of shell concentrations. In: Allison, P.A., Briggs, D.E.G. (Eds.), Taphonomy. Releasing the Data Locked in the Fossil Record. Plenum, New York, pp. 211–290.
Kleinspehn, K.L., Steel, R.J., Johannessen, E., Netland, A., 1984. Conglomeratic fan-delta sequences, late Carboniferous-early Permian, western Spitsbergen. In: Koster., E.H., Steel., R.J. (Eds.), Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists, pp. 1–31. Memoir 10.
Lanés, S., 2005. Late Triassic to early Jurassic sedimentation in northern Neuquén basin, Argentina: tectosedimentary evolution of the first transgression. Geologica Acta 3, 81–106.
Lanés, S., Giambiagi, L.B., Bechis, F., Tunik, M., 2008. Late Triassic e early Jurassic successions of the Atuel depocenter: sequence stratigraphy and tectonic controls. Revista de la Asociación Geológica Argentina 63, 534–548.
Legarreta, L., Uliana, M., 1991. Jurassic-cretaceous Marine Oscillations and Geometry of Back-arc Basin Fill, Central Argentine Andes. International Association of Sdimentologists. Special Publication, 12, 429–450.
Legarreta, L., Uliana, M., 1996. The Jurassic sucession in west-central Argentina: stratal patterns, sequences and paleogeographic evolution. Palaeogeography, Palaeoclimatology, Palaeoecology 120, 303–330.
Legarreta, L., Gulisano, C.A., Uliana, M., 1993. Las secuencias sedimentarias jurásico-cretácicas. XII Congreso Geológico Argentino y II Congreso de Hidrocarburos, Relatorio. 87–114.
MacEachern, J.A., Kerrie, L.B., Pemberton, S.G., Gingras, M.K., 2008. The ichnofacies paradigm: high-resolution paleoenvironmental interpretation of the rock record. In: MacEachern, J.A. (Ed.), Applied Ichnology. SEPM, pp. 27–64. Short Course notes.
Massari, F., Colella, A., 1988. Evolution and types of fan-delta systems in some major tectonic settings. In: Nemec, W., Steel, R.J. (Eds.), Fan Deltas: Sedimentology and Tectonic Settings. Blackie and Sons, Glasgow, pp. 103–122.
Massari, F., Parea, G.C., 1988. Progradational gravel beach sequences in a moderate-to high-energy, microtidal marine environment. Sedimentology 35, 881–913.
Miall, A.D., 1996. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer, 598 pp.
Mutti, E., Davoli, G., Tinterri, R., Zavala, C., 1996. The importance of fluvio-deltaic systems dominated by catastrophic flooding in tectonically active basins. Memorie di Scienze Geologiche 48, 233–291.
Mutti, E., Tinterri, R., Di Biase, D., Fava, L., Mavilla, N., Angella, S., Calabrese, L., 2000. Delta-front facies associations of ancient flooddominated fluvio-deltaic systems. Revista de la Sociedad Geológica de España 13, 165–190.
Mutti, E., Tinterri, R., Benevelli, G., di Biase, D., Cavanna, G., 2003. Deltaic, mixed and turbidite sedimentation of ancient foreland basins. Marine and Petroleum Geology 20, 733–755.
Orton, G.J., 1988. A spectrum of middle Ordovician fan deltas and braid plain deltas, North Wales: a consequence of varying clastic input. In: Nemec, W., Steel, R.J. (Eds.), Fan Deltas; Sedimentology and Tectonic Settings. Blackie and Sons, Glasgow, pp. 23–49.
Pemberton, S.G., MacEachern, J.A., Ranger, M.J., 1992. Ichnology and event stratigraphy: the use of trace fossils in recognizing tempestites. In: Pemberton, S.G. (Ed.), Apliccations of Ichnology to Petroleum Exploration. Society of Economic Paleontologists and Mineralogists, pp. 15–118. Core Workshop, 17.
Pomar, L., Morsilli, M., Hallock, P., Bádenas, B., 2012. Internal waves, an under-exploted source of turbulence events in the sedimentary record. Earth-Science Reviews 111, 56–81.

Posamentier, H.W., Morris, W.R., 2000. Aspects of the strata architecture of forced regressive deposits. In: Hunt, D., Gawthorpe, R.L. (Eds.), Sedimentary Responses to Forced Regressions. Geological Society of London, pp. 19–46. Special Publication, 172.
Posamentier, H.W., Jervey, M.T., Vail, P.R., 1988. Eustatic controls on clastic deposition I- conceptual framework. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C. (Eds.), Sea Level Changes-an Integrated Approach. SEPM, pp. 110–124. Special Publication, 42.
Postma, G., 1990. Depositional architecture and facies of river and fan deltas: a synthesis. In: Colella, L.A., Prior, D.B. (Eds.), Coarse-grained Deltas. International Association of Sedimentologists, pp. 13–27. Special Publication, 10.
Ramos, V.A., 1999. Rasgos estructurales del territorio argentino. Evolución tectónica de la Argentina. In: Caminos, R. (Ed.), Geología Argentina. Instituto de Geología y Recursos Minerales, pp. 715–784. Anales 29.
Ramos, V.A., 2010. The tectonic regime along the Andes: present-day and Mesozoic regimes. Geological Journal 45, 2–25.
Ramos, V.A., Folguera, A., 2005. Tectonic evolution of the Andes of Neuquén: constraints derived from the magmatic are and foreland deformation. In: Spalletti, L., Veiga, G., Schwarz, E., Howell, J. (Eds.), A Case Study in Sequence Stratigraphy and Basin Dynamics. Geological Society of London, pp. 15–35. Special Publication 252.
Reading, H.G., Collinson, J.D., 1996. Clastic coasts. In: Reading, H.G. (Ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Science, Oxford, pp. 154–231.
Riccardi, A.C., 1984. Las asociaciones de amonitas del Jurásico y Cretácico de la Argentina. In: IX Congreso Geológico Argentino, Actas 4, pp. 559–595.
Riccardi, A.C., 2008. El Jurásico de la Argentina y sus amonites. Revista de la Asociación Geológica Argentina 63, 625–643.
Riccardi, A.C., Gulisano, C.A., 1990. Unidades limitadas por discontinuidades. Su aplicación al Jurásico andino. Revista de la Asociación Geológica Argentina 45, 346–364.
Riccardi, A.C., Iglesia Llanos, M.P., 1999. Primer hallazgo de amonites en el Triásico de la Argentina. Revista de la Asociación Geológica Argentina 54 (3), 298–300.
Riccardi, A.C., Westermann, G.E.G., 1984. Amonitas y estratigrafía del Aaleniano-Bayociano de la Argentina. In: Con un apéndice micropaleontológico. IX Congreso Geológico Argentino, Actas 4, pp. 362–393.
Ringrose, P.S., 1989. Palaeoseismic (?) liquefaction event in late Quaternary lake sediment at Glen Roy, Scotland. Terra Nova 1, 57–62.
Rodríguez-Pascua, M.A., Calvo, J.P., De Vicente, G., Gómez-Gras, D., 2000. Soft-sediment deformation structures interpreted as seismites in lacustrine sediments of the Prebetic Zone, SE Spain, and their potential use as indicators of earthquake magnitudes during the Late Miocene. Sedimentary Geology 135, 117–135.
Sanci, R., 2005. Evolución ambiental y bioestratigráfica de las Formaciones Bardas Blancas y Tres Esquinas (Grupo Cuyo), Cuenca Neuquina, Mendoza. Trabajo Final de Licenciatura. Universidad de Buenos Aires.
Savrda, C.E., Bottjer, D.J., Seilacher, A., 1991. Redox-related benthic events. In: Einsele, G. (Ed.), Cycles and Events in Stratigraphy. Springer-Verlag, Berlin, Heidelberg, pp. 524–541.
Seilacher, A., Aigner, T., 1991. Storm deposition at the bed, facies and basin scale: the geologic perspective. In: Einsele, G. (Ed.), Cycles and Events in Stratigraphy. Springer-Verlag, Berlin, Heidelberg, pp. 249–267.
Spalletti, L., Parent, H., Veiga, G., Schwarz, E., 2012. Amonites y Bioestratigrafía del grupo Cuyo en la Sierra de Reyes (Cuenca Neuquina Central, Argentina) y su significado secuencial. Andean Geology 39, 464–481.
Stipanicic, P.N., 1969. El avance de los conocimientos del Jurásico argentino a partir del esquema de Groeber. Revista de la Asociación Geológica Argentina 24, 367–388.
Uliana, M.A., Biddle, K.T., 1988. Mesozoic-Cenozoic paleogeographic and geodynamic evolution of southern South America. Revista Brasileira Geociencias 18, 172–190.
Van Wagoner, J.C., Posamentier, H.W., Mitchum Jr., R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S. (Eds.), Sea Level Changes-an Integrated Approach. SEPM, pp. 39–45. Special Publication, 42.
Vergani, G.D., Tankard, A.J., Belotti, H.J., Welsink, H.J., 1995. Tectonic evolution and paleogeography of the Neuquén Basin, Argentina. In: Tankard, A.J., Suárez Soruco, R., Welsink, H.J. (Eds.), Petroleum Basins of South America. American Association of Petroleum Geologists, pp. 383–402. Memoir 62.
von Hillebrandt, A., Schmidt-Effing, R., 1981. Ammoniten aus dem Toarcium (Jura) von Chile (Sudamerika). Zitteliana 6, 3–74.
Weaver, C., 1931. Paleontology of the Jurassic and Cretaceous of West Central Argentine. University of Washington, Seattle. Memoir 1, 1–469.
Westermann, G.E.G., Riccardi, A.C., 1979. Middle Jurassic Ammonoid fauna and biochronology of the Argentine-Chilean Andes. Part II: Bajocian Stephanocerataceae. Palaeontographica, A 164, 85–188.
Yrigoyen, M.R., 1991. Hydrocarbon resources of Argentina. Petrotecnia, 38–54. Special Issue.