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Sedimentology and sequence stratigraphy of a Tithonian–Valanginian carbonate ramp (Vaca Muerta Formation): A misunderstood exceptional source rock in the Southern Mendoza area of the Neuquén Basin, Argentina

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A B S T R A C T

The Vaca Muerta Formation (early Tithonian–early Valanginian) is a rhythmic succession of marls and limestones, cropping out in the Neuquén Basin, west-central Argentina. This lithostratigraphic unit was traditionally interpreted as basinal to slope deposits. Detailed facies analysis allows to differentiate seven facies associations, representing basinal to middle ramp facies of a homoclinal ramp system prograding westward from the eastern margin, and slope facies attributed to a distally steepened ramp system that progrades eastward from the Andean volcanic arc in the west. Two sequence hierarchies are recognized: five third order depositional sequences, and fifteen fourth order high-frequency sequences. Fluctuations in organic matter content within the Vaca Muerta Formation suggest relationship with depositional sequences, finding the highest values associated with transgressive system tracts. This work represents an important advance in the understanding of the sedimentary and stratigraphic evolution of this exceptional unconventional reservoir. Our sequence stratigraphic approach contributes to the understanding of the relationship between organic matter, facies, and sea-level changes.

1. Introduction

The Vaca Muerta Formation consists of dark bituminous shales, marls and limestones deposited as a result of a rapid and widespread Palaeopacific early Tithonian to early Valanginian marine transgression in the Neuquén Basin, west-central Argentina (Legarreta and Uliana, 1991, 1996). This lithostratigraphic unit is widely distributed over an area of 120,000 km^2 (Leanza et al., 1977; Uliana et al., 1977), and is considered to be the most effective source interval in the Neuquén Basin (Mitchum and Uliana, 1985; Uliana and Legarreta, 1993; Cruz et al., 2002). Actually, more than 75% of discovered hydrocarbons in Argentina were generated in this Late Jurassic–Early Cretaceous source rock (Uliana et al., 1999). Remaining reserves and production data associated with petroleum systems indicate that about 50% of hydrocarbons comes from the Vaca Muerta Formation, which shows a prevalence of oil over gas (Legarreta et al., 2005).

The Vaca Muerta Formation has some of the best characteristics for shale-gas/oil systems, with high average total organic carbon (TOC) levels (>4.0%), moderate depth (~2400 m) and overpressured conditions (Boyer et al., 2011; Giusiano et al., 2011).

Previous works on the Vaca Muerta Formation are relevant to this study, particularly those which cover palaeontological aspects and sedimentological interpretations of economic importance for hydrocarbon exploration. Early regional stratigraphical studies were conducted by Weaver (1931), Groeber (1946, 1953), Marchese (1971), Leanza (1973), Leanza et al. (1977), Gulisano et al. (1984), Mitchum and Uliana (1985), and Legarreta and Gulisano (1989), who interpreted the Vaca Muerta Formation as basin and slope facies.

Sedimentological studies were carried out mostly in the south of the basin (Neuquén sector) by Spalletti et al. (2000), Scasso et al. (2005),

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and Kietzmann and Vennari (2013), whereas in the north (Mendoza sector) important advances have been made by Kietzmann (2011), Kietzmann and Palma (2011), and Kietzmann et al. (2008, 2011a).

The Upper Jurassic–Lower Cretaceous sequence stratigraphic framework has been based on seismic data (Gulisano et al., 1984; Mitchum and Uliana, 1985; Legarreta and Gulisano, 1989; Legarreta and Uliana, 1991), and calibrated with the global chart of third-order eustatic sea-level variations by Legarreta and Uliana (1991, 1996).

The aim of this study is to improve the understanding of the paleoenvironmental evolution of the Vaca Muerta Formation succession integrating sedimentological outcrop information of nine localities, south of Mendoza province (Fig. 1), an area of special relevance for this type of unconventional gas reservoirs. Based on detailed outcrop data we propose a new sequence stratigraphic scheme, which is compared with previous schemes based on seismic data and outcrop information. Also we attempt understand the relationship between organic matter, facies, and sea-level changes.

2. Geological setting

2.1. The Neuquén Basin

The Neuquén Basin was a retro-arc basin developed in Mesozoic times in the Pacific margin of South America (Legarreta and Uliana, 1991, 1996). Its stratigraphy was defined by Groeber (1946, 1953) and Stipanicic (1969), who recognized three sedimentary cycles, i.e. *Jurásico*, *Ándico* and *Riograndico*. This scheme was updated by Legarreta and Gulisano (1989), who emphasized the importance of eustatic changes in the development of depositional sequences (Fig. 2).

Different tectonic regimes (Legarreta and Uliana, 1991, 1996) exerted a first-order control in basin development and sedimentary evolution. An extensional regime was established during Late Triassic–Early Jurassic, and was characterized by a series of narrow, isolated depocenters controlled by large transcurrent fault systems filled mainly with continental deposits of the Precuyo Group (Manceda and Figueroa, 1993; Vergani et al., 1995; Giambiagi et al., 2008).

Thermal subsidence with localized tectonic events characterized the Early Jurassic to Late Cretaceous interval (Vergani et al., 1995). Depocenters were filled by continental and marine siliciclastic, carbonate and evaporitic sediments (Cuyo, Lotena, and Mendoza Groups).

Marine sequences developed throughout the basin during Late Jurassic–Early Cretaceous, are included in the Mendoza Group (Stipanicic, 1969) or Mendoza Mesosequence (Legarreta and Gulisano, 1989) (Fig. 2). Legarreta and Gulisano (1989) divided the Mendoza Mesosequence into three main shallowing-upward sedimentary cycles: Lower Mendoza Mesosequence (lower Tithonian–lower Valanginian), Middle Mendoza Mesosequence (lower Valanginian), and Upper Mendoza Mesosequence (lower Valanginian–lower Barremian).

A compressive deformation regime was established during the Late Cretaceous, and continued throughout the Cenozoic, although alternating with extensional events (Ramos and Folguera, 2005; Ramos, 2010). This Andean deformation resulted in the development of a series of N–S-oriented fold and thrust belts (Aconcagua, Marlargüe and Agrio fold and thrust belts) where excellent outcrops of the Mesozoic successions are exposed (e.g. Giambiagi et al., 2003; Ramos and Folguera, 2005; Ramos, 2010).

2.2. The Lower Mendoza Mesosequence

The Lower Mendoza Mesosequence includes a Tithonian–Valanginian broad shallowing-upward sedimentary cycle (Fig. 2), in which most distal

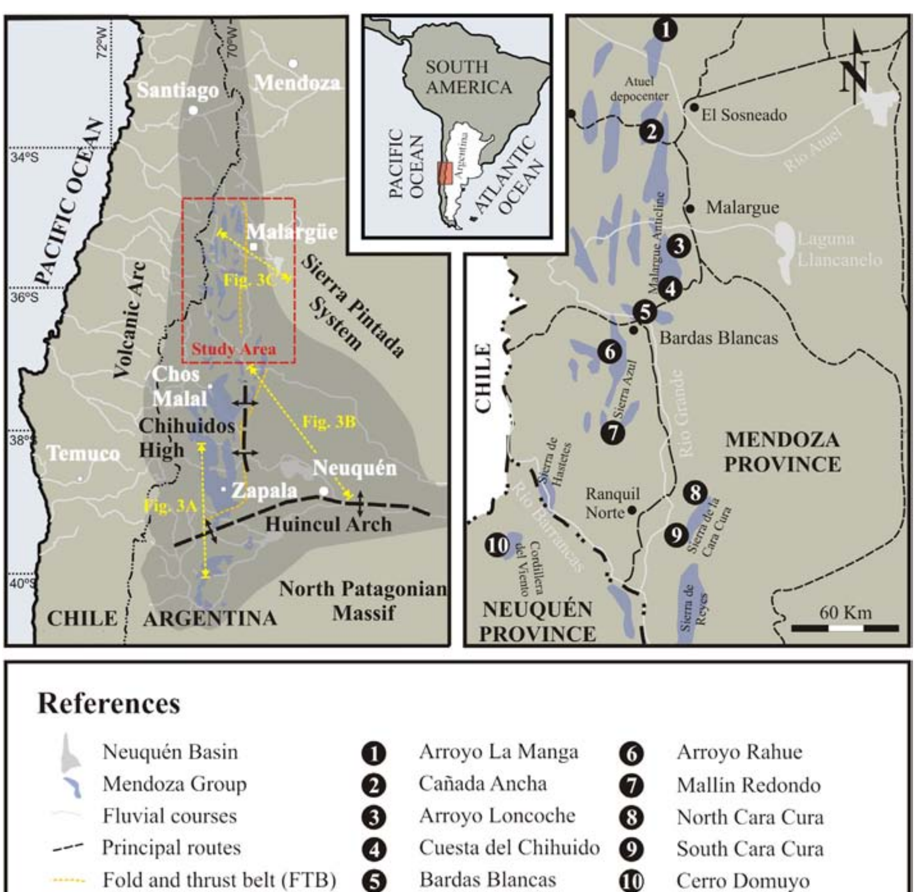

Fig. 1. Location map of the Neuquén Basin showing main geological features and studied localities.

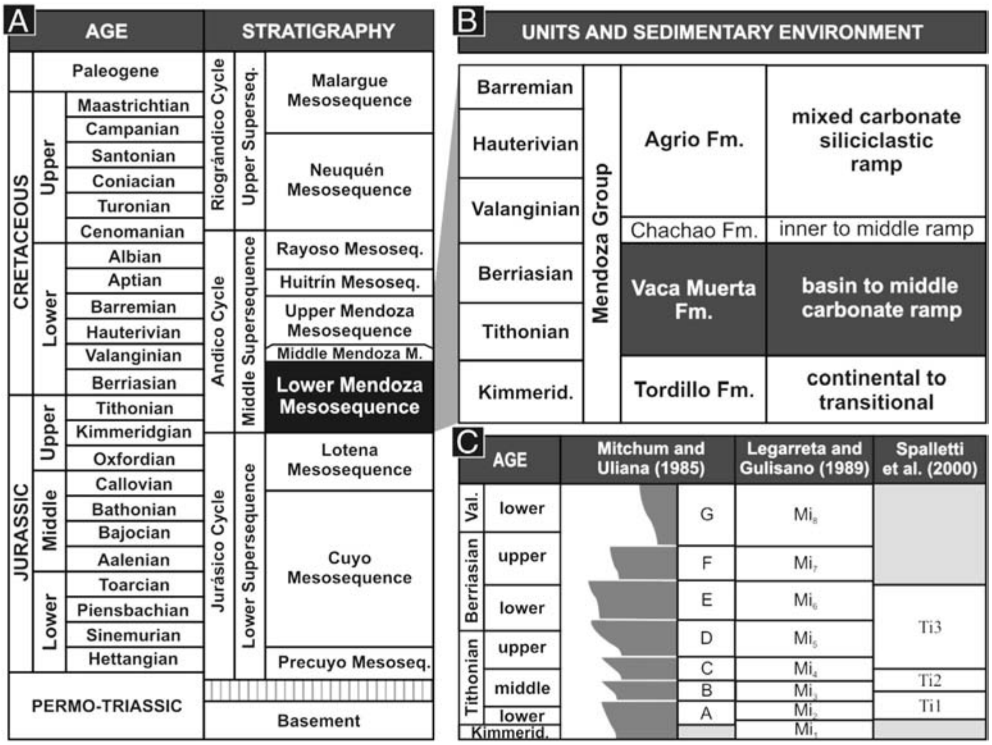

Fig. 2. A) Stratigraphic chart for the Neuquén Basin (after Legarreta and Gulisano, 1989). B) Lithostratigraphic subdivision and environmental interpretations of the Mendoza Mesosequence in Mendoza Province. C) Depositional sequences identified by Mitchum and Uliana (1985) and Legarreta and Gulisano (1989) through seismic stratigraphy studies, and by Spalletti et al. (2000) in outcrops from the south of the Neuquén Basin.

facies are included into the Vaca Muerta Formation. This interval was studied with some detail in the southern sector of the basin (Neuquén Province), where it was divided into nine depositional sequences (Mi_1–Mi_9). The Lower Mendoza Mesosequence shows a general sigmoidal geometry, and thickness reaching 2000 m (Gulisano et al., 1984; Mitchum and Uliana, 1985; Legarreta and Gulisano, 1989; Legarreta and Uliana, 1991) (Fig. 3).

In the southern part of the Neuquén Basin the Lower Mendoza Mesosequence includes the basinal deposits of the Vaca Muerta Formation (early to middle Tithonian), which to the south-southeast change to mixed carbonate-siliciclastic nearshore deposits of the Carrin Cura Formation (lower part of the middle Tithonian) and Picún Leufú Formation (middle Tithonian–lower Berriasian), and to continental deposits of the Bajada Colorada Formation of Tithonian–Berriasian age (Leanza, 1973; Spalletti et al., 2000; Leanza et al., 2011) (Fig. 3A).

In the central part of the Neuquén Basin, also known as Neuquén embayment due to the morphology of the paleocoast (Fig. 1), the Lower Mendoza Mesosequence consists of basinal deposits of the Vaca Muerta Formation (early to upper Tithonian), which to the east change to shoreface deposits of the Quintuco Formation (upper Tithonian–lower Valanginian), and to sabkha deposits of the Loma Montosa Formation (lower Valanginian), forming a mixed carbonate-siliciclastic depositional system (Gulisano et al., 1984; Mitchum and Uliana, 1985; Carozzi et al., 1993) (Fig. 3B). Westward the Vaca Muerta Formation includes slope facies (Huncal Member), and in the Chilean territory pass into shallow marine/volcanic deposits (Charrier, 1985; Leanza et al., 2011; Kietzmann and Vennari, 2013).

In contrast, in the southern Mendoza area the Lower Mendoza Mesosequence consists of divergent sequences, with a maximum thickness of 500 m towards the center of the basin (Legarreta and Gulisano, 1989). It includes basinal to middle carbonate ramp deposits of the Vaca Muerta Formation (early Tithonian–early Valanginian) and middle to inner ramp oyster-deposits of the Chachao Formation (early Valanginian) (Fig. 2), which form a homoclinal carbonate ramp system (e.g. Carozzi et al., 1981; Mitchum and Uliana, 1985). Westward undated tidal to continental mixed deposits have been recognized and correlated with the Vaca Muerta and Chachao Formations, receiving the name of Lindero de Piedra Formation (Legarreta et al., 1981) (Fig. 3C).

In the Mendoza area the Chachao Formation received much more attention than the Vaca Muerta Formation. Detailed descriptions can be found in Mombru et al. (1978), Carozzi et al. (1981), Legarreta and Kozlowski (1981), Palma and Angeleri (1992), Palma (1996), Palma and Lanés (2001), and Palma et al. (2008). New data are provided here for a better understanding of the relationship between both units, and their sedimentary environments.

Sedimentary differences between the southernmost Neuquén area, the Neuquén embayment and the Mendoza area are related to variations in siliciclastic input due to latitudinal position (Volkheimer et al., 2008) and tectonic reactivation of large Late Triassic–Early Jurassic halfgrabens (Marchese, 1971; Orchuela et al., 1981). Two large structures were active during Late Jurassic–Early Cretaceous times, generating several unconformities in the sedimentary record, and particularly the "intravalanginian uncorformity" between the Vaca Muerta and Mulichinco Formations (Vergani et al., 1995). One structure is known as Huincul High (Fig. 1), an outstanding E–W morpho-structural feature that divides the Neuquén Basin into two, and reaches its present configuration during this period. The other large structure developed parallel to the Andean axis is known as Chihuidos High (Maretto and Pángaro, 2005).

3. Age and temporal framework

Upper Jurassic–Lower Cretaceous biostratigraphy in the Neuquén Basin is well defined on the basis of ammonites (cf. Aguirre-Urreta et al., 2011; Riccardi, 2008; Riccardi et al., 2000, 2011), and to a lesser extent on bivalves, brachiopods, and microfossils, such as foraminifers, calcareous nannofossils, radiolarians and dinoflagellates (Quattrocchio et al., 1996; Bown and Concheyro, 2004; Ballent et al., 2004, 2011). Other elements of tethyan affinity have been recognized, such as the typical Tithonian saccocomid microcrinoids (Kietzmann and Palma,

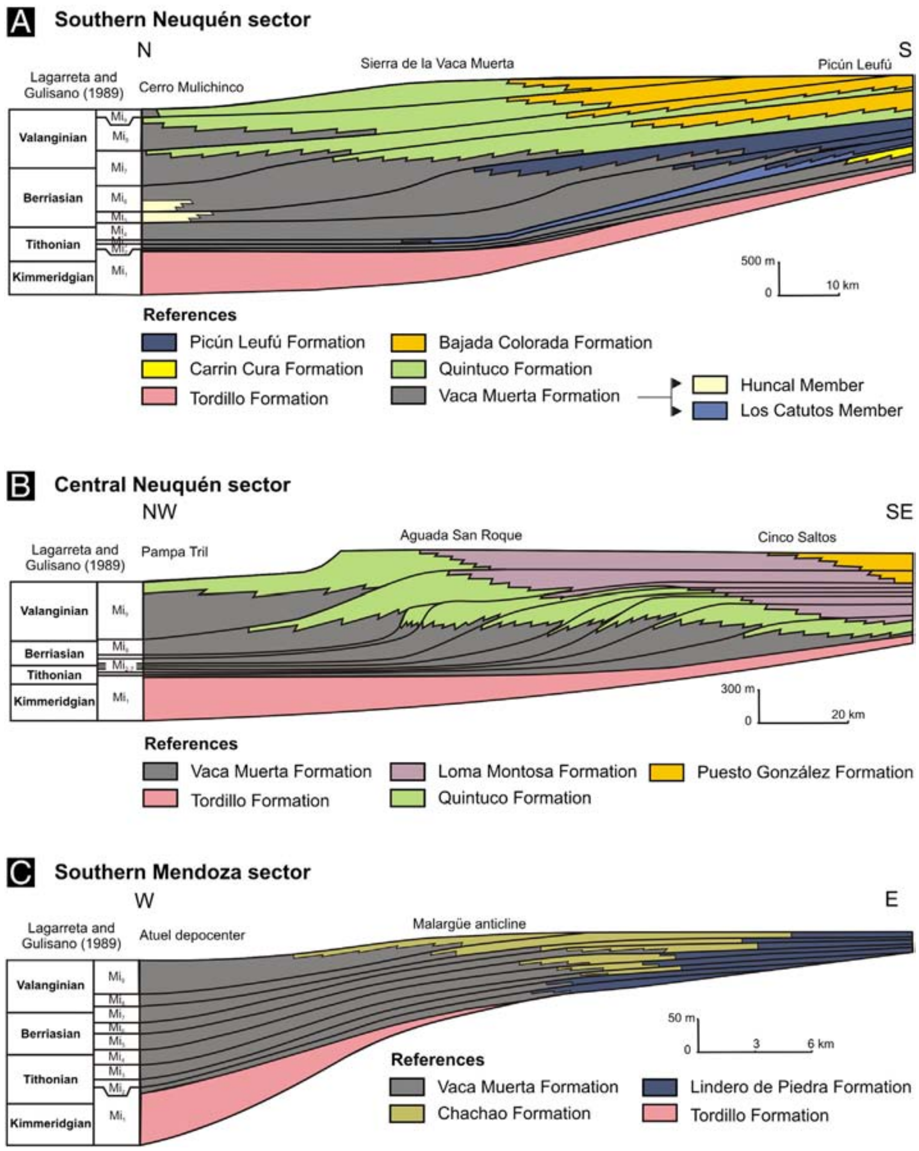

Fig. 3. Schematic sections of the Lower Mendoza Mesosequence in the different sectors of the Neuquén Basins, showing lithostratigraphic relationships, sequence geometries and nomenclature of Legarreta and Gulisano (1989). A) South–north transect of the southern Neuquen Basin sector, showing a general sigmoidal geometry (modified from Legarreta and Gulisano, 1989). B) Southeast–northwest transect of the central Neuquen Basin sector, showing a general sigmoidal geometry (modified from Mitchum and Uliana, 1985). C) East–west transect of the southern Mendoza sector of the Neuquen Basin, showing a divergent prisms geometry (modified from Legarreta and Gulisano, 1989).

2009b), as well as calpionellids and calcisphaeres (Fernández-Carmona and Riccardi, 1998, 1999; Kietzmann et al., 2011b), although are still under study (Fig. 4). Additionally new stratigraphic knowledge based on cyclostratigraphic studies (Kietzmann, 2011; Kietzmann et al., 2011a) provides new facies correlation and improve orbital scale calibration of ammonite zone.

Ammonite data from the entire studied sedimentary sections point out that the Vaca Muerta Formation was deposited from the lower Tithonian (*Virgatosphinctes mendozanus* Zone) to lower Valanginian (lowermost part of the *Olcostephanus* (*O.*) *atherstoni* Zone) (Figs. 4, 5).

4. Methodology

Detailed sedimentological sections of the Vaca Muerta Formation were measured and described bed-by-bed in ten localities of the southern Mendoza sector of the Neuquén Basin, along the Malargüe fold and thrust belt. They include the Arroyo La Manga (170 m), Cañada Ancha (350 m), Arroyo Loncoche (316 m), Cuesta del Chihuido (185 m), Bardas Blancas (230 m), Arroyo Rahue (340 m), Mallín Redondo (130 m), Cara Cura (340 m) and Cerro Domuyo (522 m) sections (Fig. 5). Carbonate and siliciclastic facies were analyzed taking into account bed geometry, lithology, sedimentary structures, fossil content and taphonomic features. Facies were supplemented by petrographic observations based on more than 600 thin sections. We use here a facies code consisting in three letters: First letter refers to texture/lithology (using italic for carbonate lithologies), second letter to main components (in subscript), and third letter to sedimentary structures (Tables 1 and 2). Divisions of sedimentary environments within the carbonate ramp are based in Burchette and Wright (1992).

Time constraints were based on ammonite biozones following the scheme proposed by Riccardi (2008), which represents the biozonation with better temporal resolution, and has proved to be the most practical for field recognition (Fig. 4).

Sequence stratigraphic framework is based on the identification of flooding surfaces, which were identified using juxtaposition and dislocation of facies. In fact, the position of the Vaca Muerta Formation in the sedimentary system does not allow the recognition of sequence boundaries as subaerial exposure surfaces in the sense of Van Wagoner et al. (1990). Nonetheless, stacking pattern and facies tendency are used to recognize sequence stratigraphic trends, where flooding surfaces can be

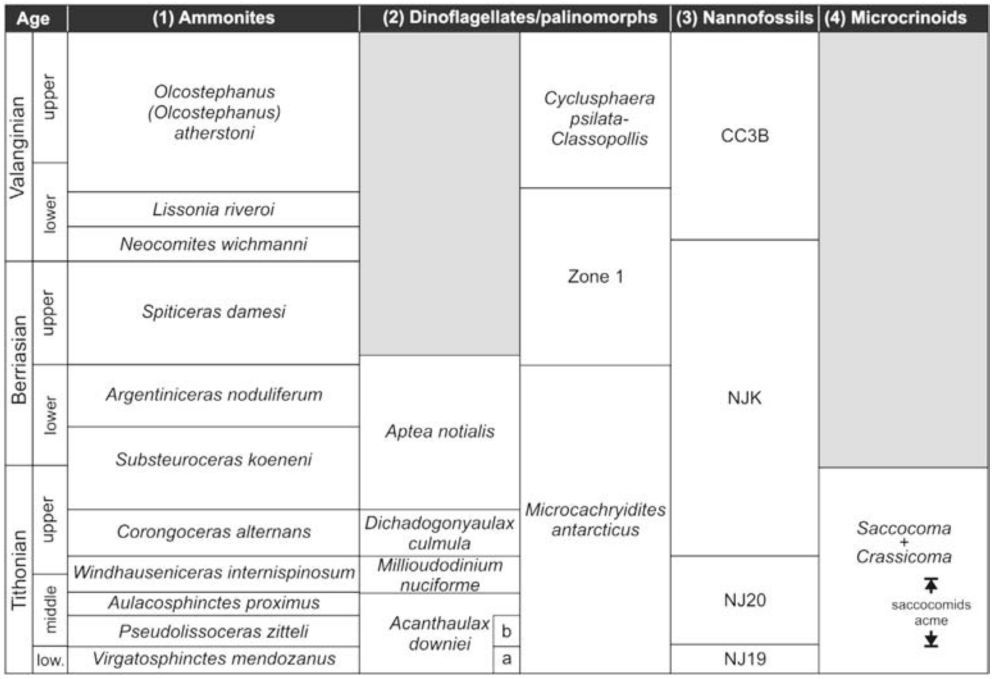

Fig. 4. Tithonian–Valanginian biostratigraphic subdivision in Neuquén Basin. (1) Ammonite biozones after Riccardi (2008) and Aguirre-Urreta et al. (2011). (2) Dinoflagellates and palinomorph Biozones after Quattrocchio et al. (1996). (3) Standard nannofossil biozones after Ballent et al. (2004, 2011). (4) Sacoccomid microcrinoid distribution after Kietzmann and Palma (2009b) and Kietzmann et al. (2010a).

interpreted as correlative conformities of subaerial exposure surfaces, forming coplanar surfaces (e.g., Embry and Johannessen, 1992; Lindsay et al., 1993). Toc values were measured in about 100 marls samples (Arroyo La Manga, Arroyo Loncoche and Arroyo Rahue sections), in order to examine the relationship between organic matter, sedimentary facies and depositional sequences.

5. Facies analysis

The Vaca Muerta Formation consists of different facies, which were combined into seven facies associations representing a carbonate ramp depositional system within a middle to distal outer ramp setting. These facies associations are present throughout the entire southern Mendoza area, although in the southwest there are slope facies of another depositional system, related to the configuration of the Andean volcanic arc. Facies features and their sedimentary interpretation are summarized in Tables 1 and 2.

5.1. Facies association 1: Oyster auto-parabiostrome dominated middle ramp

5.1.1. Description

Facies association 1 is represented by low-angle cross-stratified and massive poorly stratified bioclastic rudstones and floatstones (R_bl, R_bm/g and F_bm) interbedded with bioclastic marls (Mr_b) and laminated or bioturbated wackestones (W_bh, W_bb). Subordinated centimeter thick lapillite deposits (Lm, Lg) also occur. The marl/limestone ratio is ~1:1. This facies association is poorly represented in the Vaca Muerta Formation, although it has been recognized in Arroyo Loncoche, Cuesta del Chihuido, and Cara Cura sections (Fig. 5). These oysters accumulations form auto-parabiostromes (sensu Kershaw, 1994) which are up to several meters thick and have a conspicuous lateral continuity (Figs. 5, 6). Bioclasts include also aragonitic bivalves, serpulids, gastropods, echinoderms, sponge spicules and ammonites. Besides these, dasycladacean algae as well as ostracods, ophiuroid ossicles, brachiopods, foraminifera and calcisphaeres appear sporadically. This facies is also rich in crustacean microcoprolites, which form most of the micritic matrix.

Rudstones and floatstones consist of oyster concentrations composed mainly of *Aetostreon latissimum* and/or *Liostrea* sp. They are typically tabular massive or graded beds ranging from 15 to 25 cm in thickness, showing transitional to erosive bases, although some beds have low-angle cross-stratification. At the base most oyster are articulated and keep in life position. Towards the top the packing becomes denser, increasing the degree of disarticulation and fragmentation, and the proportion of ammonites and serpulids, which have random arrangement.

The top of the individual beds are frequently bioturbated by *Thalassinoides*, including *Thalassinoides suevicus* (Rieth), which form extended galleries of up to 50 cm long, and *Thalassinoides paradoxicus* (Woodward), with galleries of 5–20 cm in depth and passive bioclastic infilling.

Laminated wackestones (W_bh) are generally bioturbated on top by *Taenidium*, *Diplocraterion*, *Rhizocorallium* and/or *Thalassinoides*. They include small disarticulated ostracods, ophiuroid ossicles, dasycladacean algae, calcisphaeres, crustacean microcoprolites, as well as epistominid and textularid foraminifera (Fig. 6). Bioturbated wackestones (W_bb) are similar in textures, but highly bioturbated by *Thalassinoides* forming large galleries with boxwork type structures.

Bioclastic marls (Mr_b) are rich in oyster in life position, serpulids and rynchonellid brachipods.

5.1.2. Interpretation

Bioclastic rudstones (R_bm/g) and floatstones (F_bm) are probably related to bottom remobilization occurring during major storms, as suggested by erosive bases, high fragmentation of bioclasts, shell nests and random shell orientations, so they could be interpreted as proximal tempestites.

Low-angle cross-stratified deposits (R_bl) are interpreted as accretionary bioclastic bars probably related to storm-induced unidirectional flows (e.g. Bádenas and Aurell, 2001; Flügel, 2004). Presence of steinkerns is typically associated with fluctuating sedimentation rates, reworking and redepositional processes, within the winnowing zone (Flügel, 2004). Moreover coexistence of endobenthic and epibenthic organisms is also evidence of alternation in hydrodynamic and energy conditions (Kietzmann and Palma, 2009a).

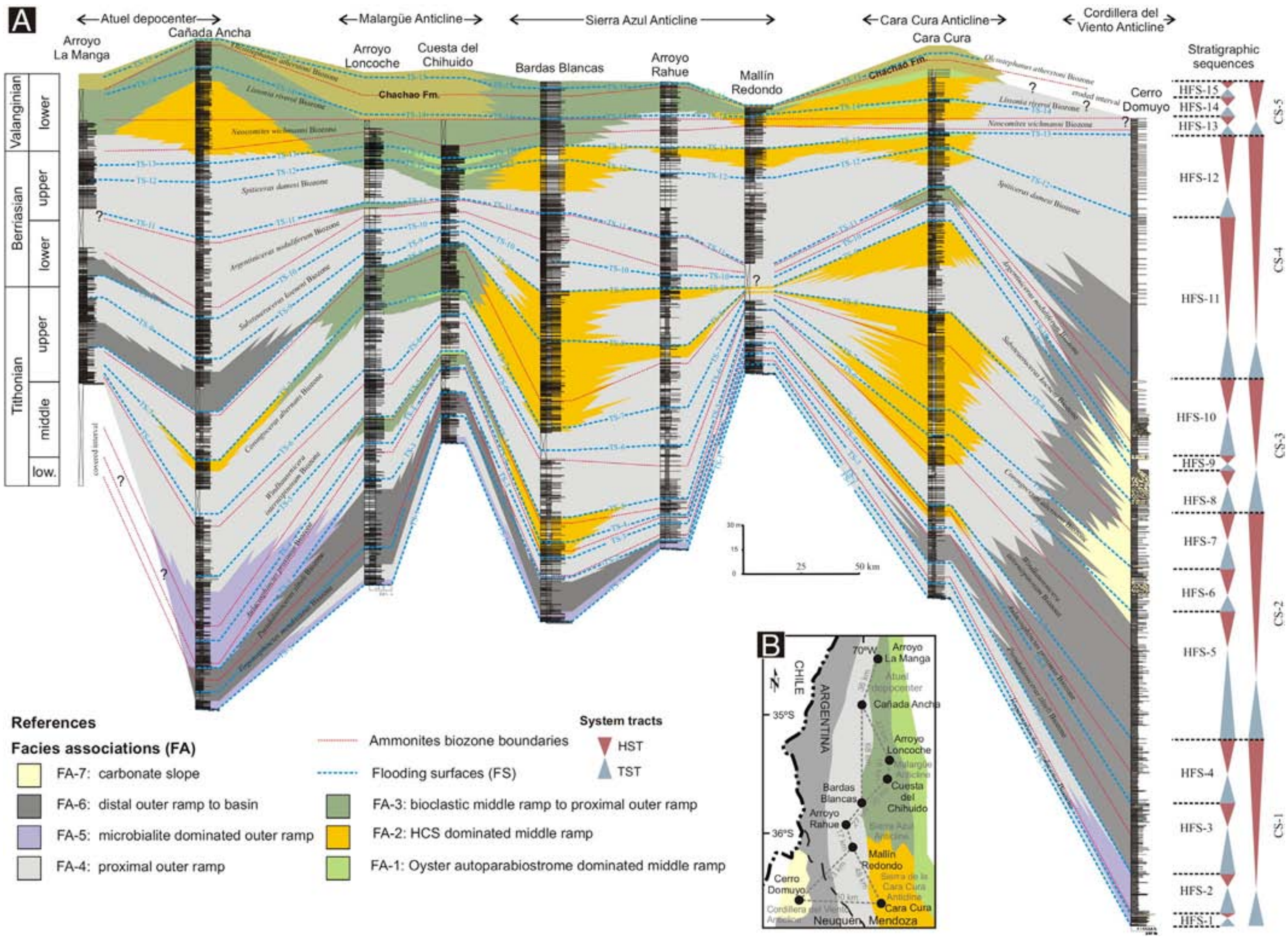

Fig. 5. A) Studied sections of the Vaca Muerta Formation in southern Mendoza, Neuquén Basin, showing correlation of facies associations, ammonite biozones, transgressive surfaces, high-frequency depositional sequence (HFS), composite depositional sequence (CS), and their transgressive system tract (TST) and highstand system tract (HST). B) Map shows geographical distribution of sections and paleogeographical facies distribution for late Tithonian–early Berriasian.

Table 1
Facies distribution in the Vaca Muerta Formation. References: (MRF) most representative facies, (RF) representative facies, (SF) subordinate facies, (VF) volcaniclastic facies.

				Facies association						
				1: Oyster biostrome dominated middle ramp	2: HCS dominated middle ramp	3: Bioclastic middle to proximal outer ramp	4: Proximal outer ramp	5: Microbialite dominated outer ramp	6: Distal outer ramp to basin	7: Carbonate slope
Facies types	High-energy facies	Cross-stratified bioclastic rudstone	R_bl	RF						
		Bioclastic rudstone	R_bm/g	MRF						
		Bioclastic floatstone	F_bm							
		Multievent bioclastic floatstone/rudstone	RF_bm		RF	MRF	SF			
		HCS grainstrone	G_{pi}HCS		MRF					
		Laminated packstone			RF	MRF	MRF	RF	SF	
		Ripple laminated packstone	P_pr						MRF	
		Fine grained sandy bioclastic packstones	P_{bt}m, P_{bt}h							MRF
		Intraclastic breccias	B_i							SF
	Low-energy facies	Planar microbialite bindstones	B_ml		SF			MRF		
		Bioturbated wackestones	W_bb	SF	RF	SF				
		Laminated wackestone	W_bh	SF		SF	RF			
		Radiolaritic laminated wackestone	W_rh					RF	SF	
		Bioclastic marls	Mr_b	RF	RF	RF				
		Laminated marls	Mrh				RF	RF	RF	RF
VF		Lapillites	Lm/g	SF	SF	SF				SF
		Tuff	Tm/g		SF		SF	SF	SF	SF

Laminated wackestones (W_bh) and marls (Mr_b) were deposited from suspension in a moderate low energy setting, and represent zones unaffected by storm waves or other currents, probably related to fair-weather periods.

Preservation only of lower portions of *Thalassinoides* galleries in bioturbated wackestones (W_bb) suggests recurrent erosive processes related to storm events. On the other hand, *T. paradoxicus* indicates ramp stages with low sedimentation rates allowing early substrate consolidation, and subsequent erosion and passive infilling during storms (Myrrow, 1995).

Presence of burrowing organisms indicates sea floor aerobic conditions. The trace fossil assemblage is indicative of the *Cruziana* ichnofacies, which characterizes low-energy environments, colonized by deposit feeders and also by mobile carnivores, omnivores and suspension feeders (Pemberton et al., 1992; MacEachern et al., 2008).

Facies association 1 is interpreted as deposits of a well-oxygenated middle ramp, between the storm-wave base and the fair-weather wave base.

5.2. Facies association 2: HCS dominated middle ramp

5.2.1. Description

Facies association 2 is represented by an alternation of low-energy facies similar to those of facies association 1, including bioclastic marls

Table 2
Facies in the Vaca Muerta Formation, with summarized lithological description and sedimentary interpretation.

Facies type	Code	Sedimentary structures — trace fossils	Geometry — contacts — color — thickness	Particles types — taphonomy	Interpretation of sedimentary processes	Occurrence in sedimentary environment
Cross-stratified bioclastic rudstone	R_bl	Low angle cross-stratification	Tabular — transitional to erosive bases — gray to brown — 15 to 25 cm	Oysters are dominant (*Aetostreon latissimum*). *Eriphyla*, *Panopaea*, rotularid serpulids, ammonites and rynchonellids are also common. Pellets and steinkerns are common. — Articulation of valves is high, fragmentation and abrasion are low. Evidence of bioerosion or encrustation are rare	Accretionary bioclastic bars above the storm wave base. Fluctuating sedimentation rates, reworking and redepositional processes, within the winnowing zone. Coexistence of endobenthic and epibenthic organisms evidence alternating hydrodynamic and energy conditions	Middle ramp (facies association 1)
Bioclastic rudstone	R_bm; R_bg;	Massive, normal graded — *Thalassinoides*	Tabular — transitional to erosive bases — gray to brown — 15 to 20 cm	Oysters are dominant (*Aetostreon latissimum*, *Liostrea*). *Eriphyla*, *Panopaea*, rotularid serpulids, ammonites, rynchonellids and calcisphaeres are also common. Pellets and steinkerns are common. — Articulation of valves is high, fragmentation and abrasion are low. Evidence of bioerosion or encrustation are rare	Alternating hydrodynamic and energy conditions. Reworking associated with storm oscillatory flows.	Middle ramp to proximal outer ramp (facies associations 1, 2 and 3)
Bioclastic floatstone	F_bm	Massive — *Thalassinoides*	Tabular — sharp and erosive bases — gray to brown — 10 to 25 cm	Pelloidal matrix. Oysters (*Aetostreon*, *Deltoideum*, *Liostrea*), *Eriphyla*, Lucina, *Grammatodon*, rotularid serpulids, ammonites, gastropods, steinkerns, echinoderms, and calcisphaeres. — Low degree of articulation, fragmentation and abrasion. Scarce evidence of bioerosion or encrustation	Related with bottom remobilization during major storms (proximal tempestites).	Middle ramp to proximal outer ramp (facies associations 1, 2 and 3)
Multi-event bioclastic floatstone/rudstone	RF_bm	Massive, normal graded — exhumed *Thalassinoides* galleries with passive infilling	Tabular — sharp and erosive bases — gray to brown — 10 to 40 cm	Peloidal Matrix. Abundant oysters (*Aetostreon*, *Deltoideum*, *Ceratostreon*), epifaunal and infaunal bivalves (pectinids, trigonids, *Lucina*, *Eriphyla*, *Cucullea* and *Grammatodon*). Rynchonellids, gastropods, serpulids (*Rotularia*), ammonites, nautiloids, belemnites, epistominid foraminifera, calpionellids and calcisphaeres. Some also includes calcareous algae and pumiceous fragments. Chaotic distribution of bioclast, ammonites often imbricated. — Articulation and fragmentation are low. Oysters with bioerosion. At bases shells are concordant and convex-down, while to de top are frequently convex-up, oriented perpendicular to stratification or stacked forming nets	Related with bottom remobilization occurring during major storms (proximal tempestites).	Middle ramp to proximal outer ramp (facies associations 2, 3 and 4)
HCS grainstones	GpiHCS	Hummocky cross-stratification — *Helminthopsis*, *Planolites* and *Chondrites*	tabular Sharp and erosive bases Gray to brown 20 to 60 cm	Rich in micritic intraclasts and crustacean microcoprolites. Bivalve fragments, gastropods, benthic foraminifera (*Epistomina*, *Lenticulina*, *Siphovalvulina* and *Pseudocyclammina*), gastropod internal molds and small bone fragments are common. — Remains of *Saccocoma*, calpionellids and calcisphaeresare also common	Accretionary hummocks generated from storm-related oscillatory flows with a small unidirectional component.	Middle ramp (facies association 2)
Bioturbated wackestones	W_bb	Massive, horizontal lamination — well-developed boxwork-type *Thalassinoides* galleries (exhumed)	Tabular — sharp irregular contacts — brown to gray — 20 to 45 cm	Disarticulated infaunal bivalves, shells and internal molds of gastropods, echinoderm and *Saccocoma* remains, ammonites, epistominid foraminifera, calpionellids, calcisphaeres, and abundant pellets.	Deposition from suspension (fall-out and resuspended sediments by storms) in a moderate low energy setting. Lower portions of *Thallasinoides* galleries are preserved. Recurrent erosive processes related with storm events	Middle ramp to proximal outer ramp (facies associations 1, 2 and 3)
Ripple laminated packstone	P_pr	Ripple lamination. Occasionally sole marks and hummocky-like cross stratified structures	Tabular — sharp and erosive bases — dark Gray to black — 5 to 10 cm	Peloids, well sorted in fine sand size. Scarce infaunal bivalves and echinoderm fragments. Silt size terrigens (quartz and plagioclase) are abundant.	Storm-generated turbidity flows	Distal outer ramp to basin (facies association 6)

Laminated packstone	P_{pi}h	Horizontal lamination — rare *Thalassinoides*	Tabular — bases are sharp and sometimes irregular — gray to brown — 210 to 30 cm	Peloidal (crustacean microcoprolites) or intraclastic. Well sorted in medium sand size. Subangular to angular micritic clast. Ammonites, articulated and disarticulated bivalves, lingulid brachiopods, gastropods, saccocoma concentrations, calpionellids and calcisphaeres.	Pelloidal accumulations come from unroofing of crustacean galleries. Intraclastic packstones associated with intermittent erosion processes and transport from bottom currents	Middle ramp to basin (facies association 2, 3, 4, 5 and 6)
Planar microbialite bindstones	B_{m}l	Millimeter-scale microbial lamination. Roll-up structures are common — rare *Thalassinoides Planolites*, *Chondrites*, *Lumbricaria*	Tabular — sharp irregular contacts — gray to black — 10 to 60 cm	Defined by alternating layers of translucent calcite, often internally showing irregular sub-horizontal, and fine-grained wackestones with foraminifers, radiolarians, calcisphaeres, and small peloids, or peloidal packstones with foraminifers, radiolarians. Rich in organic matter. Microbialite intraclasts are also present.	Open ocean conditions. Times of low sedimentation rate. The intercalation of peloidal packstones, and roll-up structures, related to episodically storm-related high energy events	Middle to outer ramp (facies association 2 and 5)
Laminated wackestone	W_{b}h	Horizontal lamination — *Taenidium*, *Diplocraterium*, *Rhizocorallium Thalassinoides*	Tabular — sharp and planar — brown — 10 to 25 cm	Small disarticulated ostracods, ophiuroid ossicles, dasycladacean algae, crustacean microcoprolites, epistominid and textularid foraminifera, calpionellids and calcisphaeres	Deposition from suspension in a moderate low energy setting. Only the lower portions of the *Thallasinoides* galleries are preserved suggesting recurrent erosive processes related with storm events	Middle to outer ramp (facies association 3 and 4)
Radiolaritic laminated wackestone	W_{r}h	Horizontal lamination	Tabular — sharp and planar — dark gray to black — 20 to 30 cm	Abundant radiolarians. Rare calcisphaeres. Ammonites, aptychi, infaunal bivalves (*Eriphyla* and *Lucina*), and serpulids. None of these elements are in life position. Organic matter content is high (3 to 5%). They contain also some laminae of microbial origin.	Mainly deposited by fall out of fine muddy sediments. Nasselarian/spumellarian ratio suggest a poorly oxigenated setting	Outer ramp to basin (facies association 4, 5 and 6)
Bioclastic marls	Mr_{b}	Horizontal lamination, concretions (early diagenetic, with similar fossil content and textural features of limestones)	Tabular — sharp and planar — brown to gray — 10 to 30 cm	Rich in oyster, serpulids, disarticulated infaunal bivalves, rynchonellid brachiopods, and ammonites	Deposition from suspension (fall-out and resuspended sediments by storms) in a moderate low energy setting	Middle to outer ramp (facies association 1, 2 and 3)
Marls	Mrh	Horizontal lamination, concretions (early diagenetic, with similar fossil content and textural features of limestones)	Tabular — sharp and planar — dark gray to black — 15 to 30 cm	Disarticulated thin-shelled oysters, ammonites and abundant fish scales. Rarely also belemnites, trunks and branches	Deposition from suspension (fall-out and resuspended sediments by storms) in a moderate low energy setting	Outer ramp to slope (facies association 3, 4, 5, 6 and 7)
Fine grained sandy bioclastic packstones	P_{bt}m, P_{bt}h	Massive or poorly developed horizontal lamination	Lentiform — sharp and planar — dark gray to black — 10 to 50 cm	Echinoderm fragments, dasycladacean algae, infaunal bivalves, oolite grainstone intraclasts, and fine sand size terrigenous	Turbidity flows	Slope (facies association 7)
Intraclastic breccias	Bi	Massive	Mantiform — sharp and planar — dark gray to black — 5 to 30 cm	Grain-supported, monomictic. Clast are micritic (radiolaritic wackestones and mudstones), of pebble size, angular to subangular.	Non-cohesive debris-flow deposits	Slope (facies association 7)
Lapillites	Lm, Lg	Massive, inverse graded — *Thalassinoides*.	Tabular — sharp planar — gray to brown — 5 to 15 cm	Abundant pumiceous fragments and fine sand size micritic intraclasts. Scarce dasycladacean algae, crustacean microcoprolites, and subordinately silt size terrigenous	Deposited from floating rafts of air fall pumice, and low density turbidity flows	Middle ramp to slope (facies association 3, 4 and 7)
Tuff	Tm, Tg	Massive, inverse graded — *Rhizocorallium*	Tabular — sharp planar or slightly erosive bases — gray to greenish — 2 to 10 cm	Abundant glass shards and pumiceous fragments	Ash fall and/or low density turbidity flows	Outer ramp to slope (facies association 4, 5, 6 and 7)

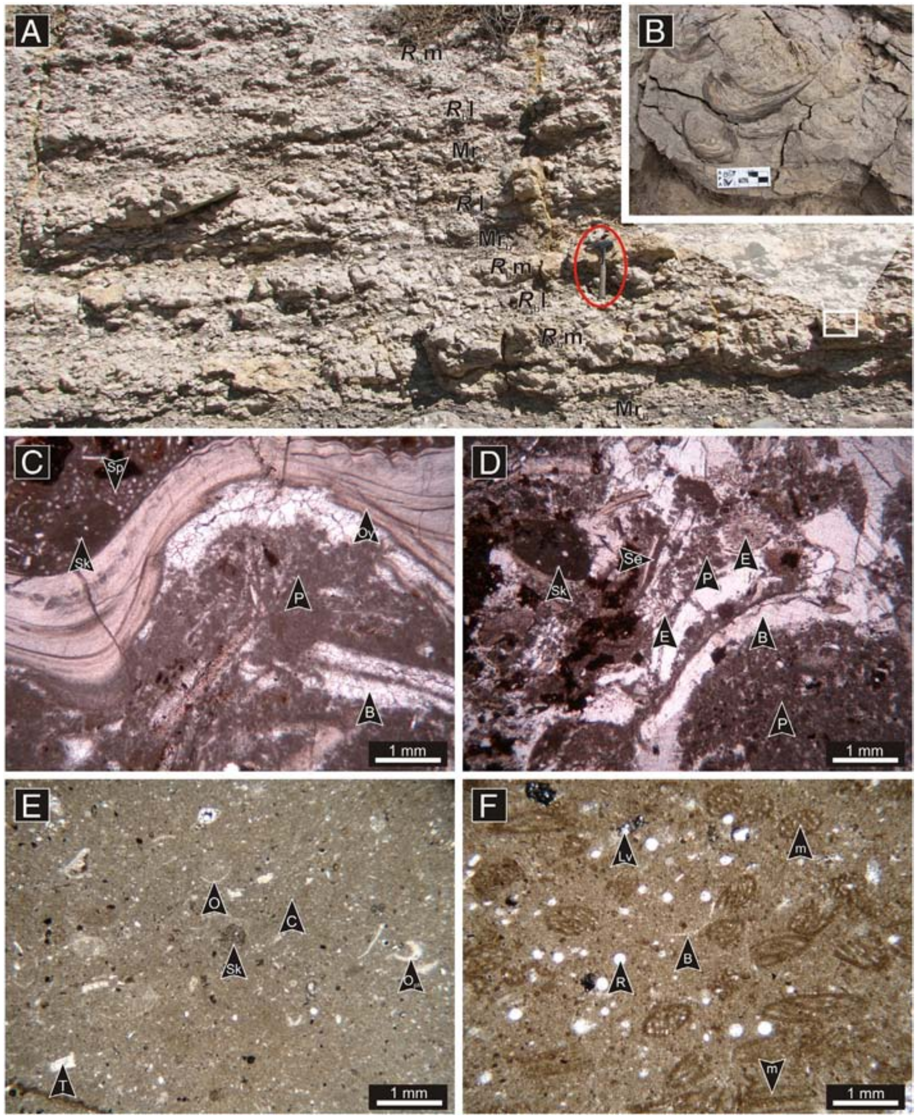

Fig. 6. A) Field exposure of facies association 1 (oyster auto-parabiostrome dominated middle ramp), lower Valanginian, Cara Cura (see hammer as scale and lithofacies code in Table 1). B) Detail of oysters (*Aetostreon latissimum* Lamarck) in bioclastic floatstone/rudstones (R_bm, F_bm). C–D) Thin sections of bioclastic floatstone/rudstones (R_bm, F_bm), showing a peloidal matrix and fragmented skeletal particles. E–F) Thin sections of laminated wackestones (W_bh). References: (B) recrystallized bivalves, (C) calcisphaeres and/or calpionellids, (E) echinoderms, (Lv) volcanic clasts, (m) crustacean microcoprolites, (O) ostracods, (O_{ph}) ophiurids, (Oy) oysters, (P) peloids, (R) radiolarians, (Se) serpulids fragments, (Sk) *steinkerns* (internal molds of gastropods), (Sp) sponge spicules, (T) terrigens.

(Mr_b) and bioturbated wackestones (W_bb), and high-energy facies, including hummocky cross-stratified grainstones (G_{pi}HCS), laminated packstones (P_{pi}h), and massive to graded bioclastic floatstones/rudstones (RF_bm). There are also occasional planar microbialite (*B*m) tuffs (Tm, Tg) and lapillite (Lm, Lg) beds (Fig. 7). The marl/limestone ratio is ~1:1. Facies association 2 is very well exposed in the upper part of the Cañada Ancha section, as well as in the Bardas Blancas and Cara Cura sections (Fig. 5). This facies association is more common than traditionally accepted for the Vaca Muerta Formation, and in some sections is the most frequent (e.g. Kietzmann and Palma, 2011).

Bioturbated wackestones (W_bb) occurs in nodular beds with abundant *T. suevicus*, forming large galleries with boxwork type structures. Trace fossils are exhumed galleries, preserving only the lower levels. Bioclastic marls (Mr_b) are well laminated and rich in oyster fragments. Particles in low-energy facies are dominated by pellets (crustacean microcoprolites), while bioclasts are usually infaunal bivalves, gastropods, echinoderms, *Saccocoma* remains, ammonites, foraminifera, calcisphaeres and radiolarians.

The hummocky cross-bedding grainstones (G_{pi}HCS) can grade laterally in horizontal lamination. Wavelengths range from 25 to 150 cm (Fig. 7A–D). These facies are rich in micritic intraclasts and crustacean microcoprolites, and contains bivalve fragments, gastropods, phosphatized gastropod steinkerns, benthic foraminifera. Trace fossil are represented by *Helminthopsis*, *Planolites*, and *Chondrites*.

Laminated packstones are peloidal or intraclastic (P_{pi}h). Fossil content include ammonites, articulated and disarticulated bivalves, lingulid brachiopods, gastropods, phosphatized gastropod steinkerns, which are chaotically distributed or deposited commonly in discrete levels.

Bioclastic floatstones/rudstones (RF_bm) consist of multi-event concentrations rich either in oysters and other bivalves, rynchonellids, gastropods, serpulids, ammonites, nautiloids, belemnites, epistominid and agglutinated foraminifera, calpionellids, calcisphaeres, and/or calcareous algae and pumiceous fragments (Fig. 7E–F). Deposits are characterized by a chaotic distribution of bioclasts. Bioturbation is rare but can occur as exhumed galleries of *Thalassinoides* and *Planolites* tubes filled with sediments similar to those of the surrounding matrix.

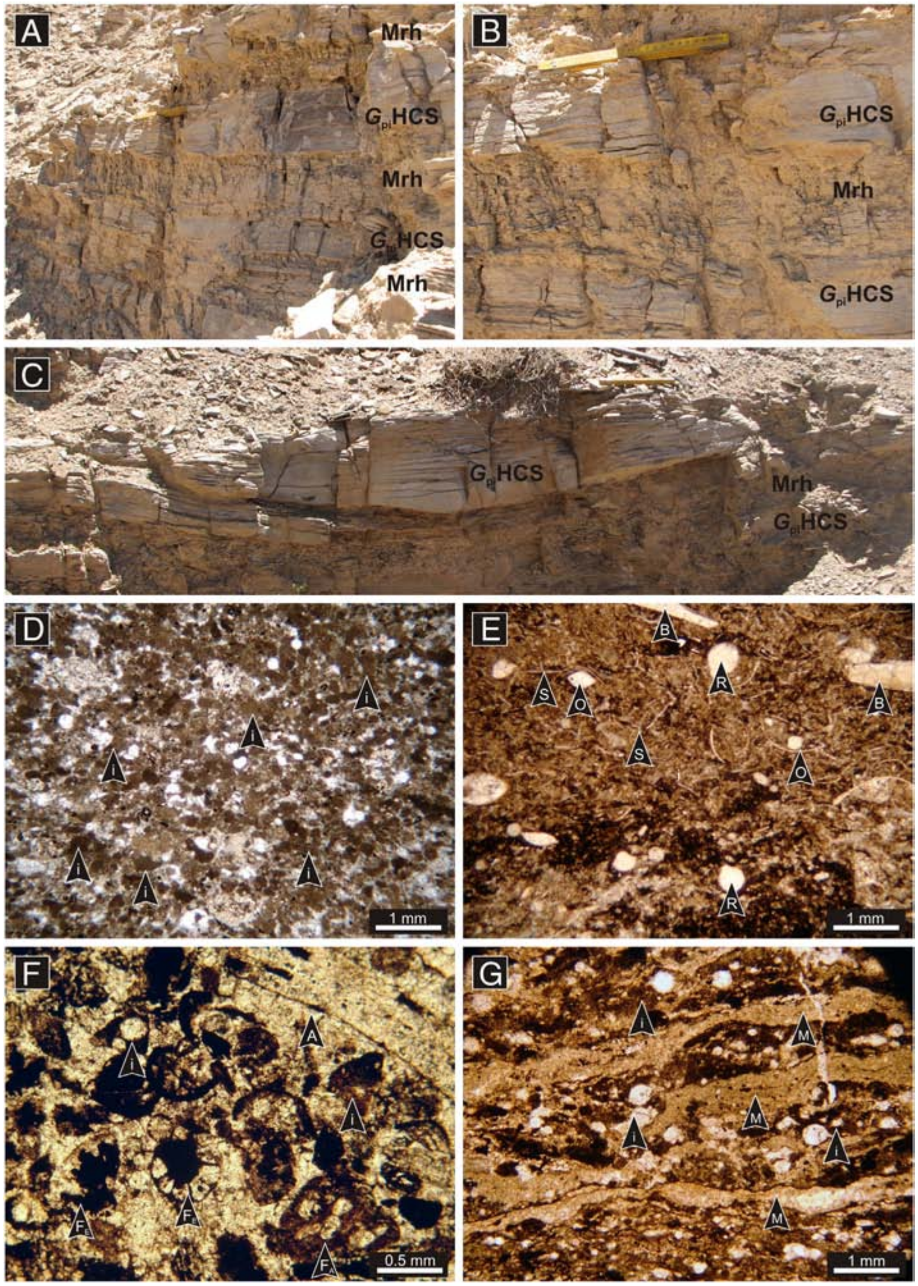

Fig. 7. A–C) Field exposure of grainstones with hummocky cross-stratification of facies association 2 (HCS dominated middle ramp), middle Tithonian, Cara Cura and Bardas Blancas sections (see lithofacies code in Table 1). D) Intraclastic grainstones forming HCS deposits (G_{pi}HCS). E–F) Thin bioclastic packstones and rudstones (RF_{b}m) forming single concentrations of ostracods, saccocomid microcrinoids, and/or foraminifera. G) Microbial laminae alternating with peloidal or intraclastic packstones (B_{m}l). References: (A) dasycladacean algae, (B) recrystallized bivalves, (F_A) agglutinated foraminifera, (F_E) epistominid foraminifera, (i) intraclast, (M) microbial laminae, (O) ostracods, (R) radiolarians, (S) sacoccomid microcrinoid ossicles.

Planar microbialites (*B*m) form laterally persistent beds with thicknesses of several decimeters. The most evident feature is a conspicuous horizontal to sub-horizontal lamination of submillimeter- to millimeter-scale of rich organic matter micritic laminae and fine-grained peloidal wackestones or packstones with foraminifers, radiolarians and calcisphaeres (Fig. 7G). Some laminae are rich in microbialite intraclast accumulations and roll-up structures.

Lapillite deposits are centimeter thick, massive or graded (Lm, Lg), with sharp and planar bases. They are composed by coarse sand to granule size pumiceous fragments. Tuff (Tm, Tg) are centimeter thick tabular gray to greenish carbonates beds of crystalline appearance. They consist of a crystalline calcite mosaic, with crystals of several millimeters, but particles consists of abundant glass shards and pumiceous fragments.

5.2.2. Interpretation

Hummocky cross-stratified grainstones (G_{pi}HCS) are interpreted as deposits of accretionary hummocks generated from storm-related oscillatory flows with a small unidirectional component, while massive to graded bioclastic floatstones/rudstones (RF_{b}m) represent bioclastic tempestites originated by turbidite-like gravity flows (e.g. Monaco, 1992; Molina et al., 1997; Kietzmann and Palma, 2011).

Bioturbated wackestones, laminated packstones, and marls indicate deposition after reworking of the seafloor by action of storm waves. Pelloidal accumulations come probably from the unroofing of crustacean galleries. Indeed, the sea floor would have similar characteristics to those of the Bahamas or the Florida Keys (e.g. Warme, 1967; Tedesco and Wanless, 1991), where callianassids generate an irregular topography composed of conical mounds connected with large horizontal

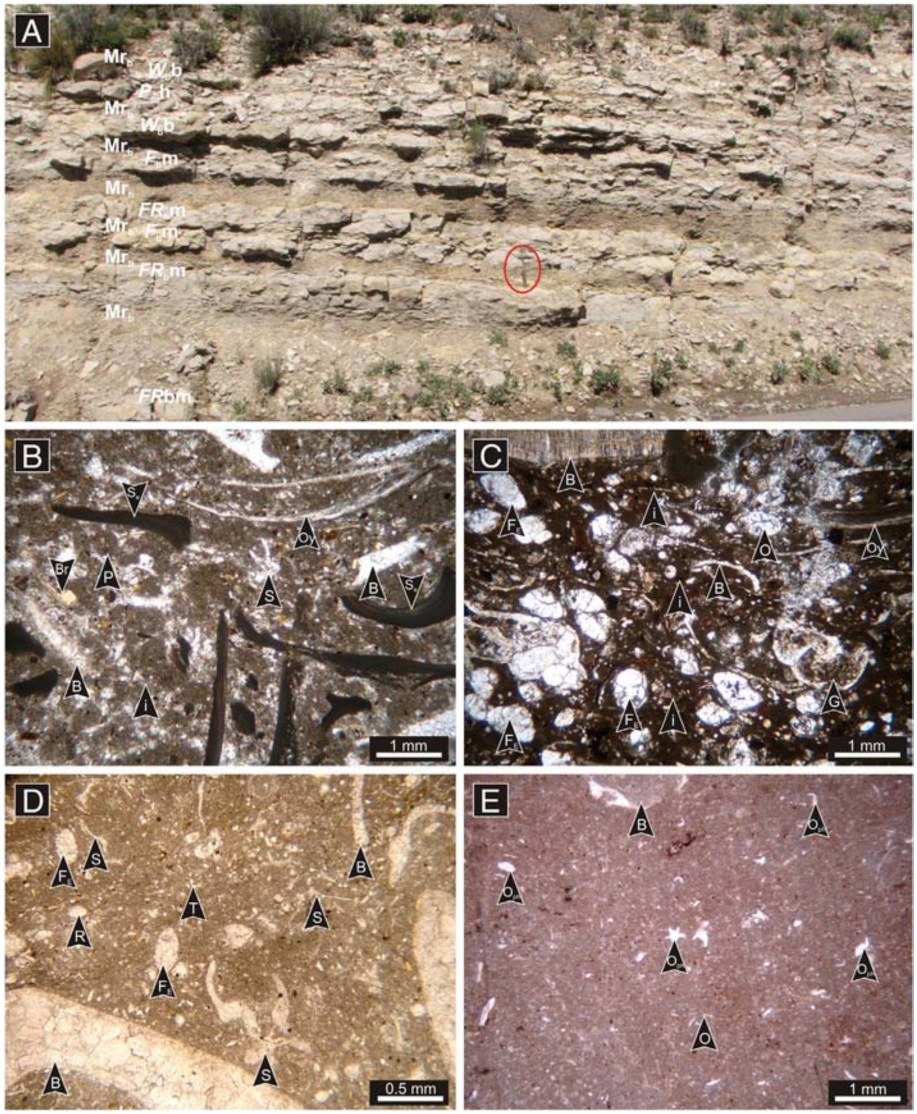

Fig. 8. A) Field exposure of facies association 3 (bioclastic middle ramp to proximal outer ramp), middle Tithonian, Cuesta del Chihuido section (see lithofacies code in Table 1). B) Bioclastic rudstones/floatstone (RF_bm) showing abundant fragments of serpulids and bivalves in a peloidal matrix. C) Bioclastic rudstones/floatstone (RF_bm) showing abundant epistomid foraminifera, bivalve fragments, and intraclasts. D) Bioturbated wackestones (W_bb) containing abundant bivalve fragments, saccocomid microcrinoids, foraminifera, and terrigens. E) Laminated wackestones (W_bh) with ophiurid remains and articulated bivalves. References: (B) bivalves (in general), (Br) brachiopods, (F_E) epistominid foraminifera, (i) intraclasts, (O) ostracods, (O_{ph}) ophiuroid ossicles, (Oy) oysters, (P) peloids, (S) sacoccomid microcrinoid ossicles, (S_e) serpulid fragments, (T) terrigens.

burrow systems. Low energy waters should have favored proliferation of crustaceans, which are responsible for the pelletization of large quantities of muddy sediments, occurring in the substrate or in suspension (Pryor, 1975).

Microbialite beds indicate periods of low sedimentation rate, allowing proliferation of microbial mats in a relative low energy setting, episodically affected by storm-related high energy events. Similar deposits were described by Schieber (1998, 1999) from the Mid-Proterozoic Belt Supergroup of Montana, as well as from the Upper Devonian Sonyea Group of New York.

Tuff deposits were probably deposited from non-cohesive low density turbidites, while massive and inverse graded lapillite facies deposited probably from floating rafts of air fall pumice. Trace fossils indicate alternating energy regimes and a relatively well oxygenated substrate. The association of *Taenidium*, *Thalassinoides*, *Diplocraterion* and *Rhizocoralliun* is indicative of the *Skolithos* ichnofacies, which suggests colonization of storm beds by a community of opportunistic organisms in a post-event, high-stress, physically controlled environment. On the other hand, the association of *Helminthopsis*?, *Planolites*, *Chondrites* and *Thalassinoides* is indicative of the *Cruziana* ichnofacies, which characterizing low-energy environments, and suggesting substrate colonization during fair-weather stages (Pemberton et al., 1992).

Facies association 2 is interpreted as deposited above the storm-wave base in a well-oxygenated middle ramp.

5.3. Facies association 3: bioclastic middle ramp to proximal outer ramp

5.3.1. Description

Facies association 3 is characterized by the alternation of similar low-energy facies to previous facies association, including bioturbated wackestones (W_bb), laminated wackestones (W_bh), bioclastic marls (Mr_b) and laminated marls (Mrh), and high-energy facies, made up of bioclastic rudstones/floatstones (RF_bm), and laminated packstones (P_{pi}h) (Fig. 8A). Subordinated centimeter thick lapillite deposits (Lm, Lg) also occur. The marl/limestone ratio is ~2:1. This facies association is well represented in the Arroyo Loncoche and Cuesta del Chihuido sections, as well as in the lower Valanginian of the Arroyo La Manga and Cañada Ancha sections (Fig. 5).

Bioturbated wackestones (W_bb) are similar to those of previous facies association, but is appears in lower abundance. Laminated wackestones (W_bh) are have sharp contacts, and tops are usually bioturbated. Bioclasts are scattered and none of these elements are in life position. They include ammonites, aptychi, infaunal bivalves, serpulids, and brachiopods. In the Tithonian interval microfossils includes ostracods, bentonic foraminifera (*Epistomina*, *Lenticulina* and *Textularia*), *Saccocoma* and *calcisphaeres* (Fig. 8D). In the Berriasian–Valanginian interval become more common the association of ophiuroids, dasycladacean algae, *Epistomina* and ostracods (Fig. 8E).

Marls (Mr_b, Mrh) are well laminated. Bioclastic marls contain some thin-shelled oyster, disarticulated infaunal bivalves, serpulids, and fish scales. Thin sections of concretions contained therein show the same textural characteristics of laminated packstones or wackestones. Organic matter content is high, reaching up 2 to 4%. Bioclastic rudstones/floatstones (RF_bm) consists of massive, normal graded multi-event concentrations or inverse graded single concentrations. Bases are usually erosive, but bed tops are sharp or transitional. Valves show chaotic distribution, imbrication, convex-up disposition, and development of stacking and nets, and are usually perpendicular to the stratification.

Laminated packstones (P_{pi}h) are have sharp bases. They are dominated by peloids or by micritic intraclastos, which range from fine to medium sand size. Fossils include ammonites, articulated and disarticulated bivalves, gastropods, phosphatized gastropod steinkerns, which are chaotically distributed.

Lapillite deposits are massive or graded (Lm, Lg), with sharp and planar bases. They contain coarse sand to granule size pumiceous fragments, and calcareous algae in minor proportions.

Bioturbation can occur in bioclastic floatstones/rudstones, bioturbated wackestones and lapillites, as exhumed galleries of *Thalassinoides* with passive filling. In contrast, laminated wackestone beds are usually bioturbated by *Diplocraterion*, *Rhizocorallium* and *Thalassinoides*.

5.3.2. Interpretation

As in facies association 2, bioturbated wackestones (W_bb), laminated packstones (P_{pi}h), and bioclastic marls (Mr_b) indicated deposition after reworking of seafloor by action of storm waves (Schieber and Southard, 2009; Schieber et al., 2010). In contrast, laminated wackestones (W_bh)

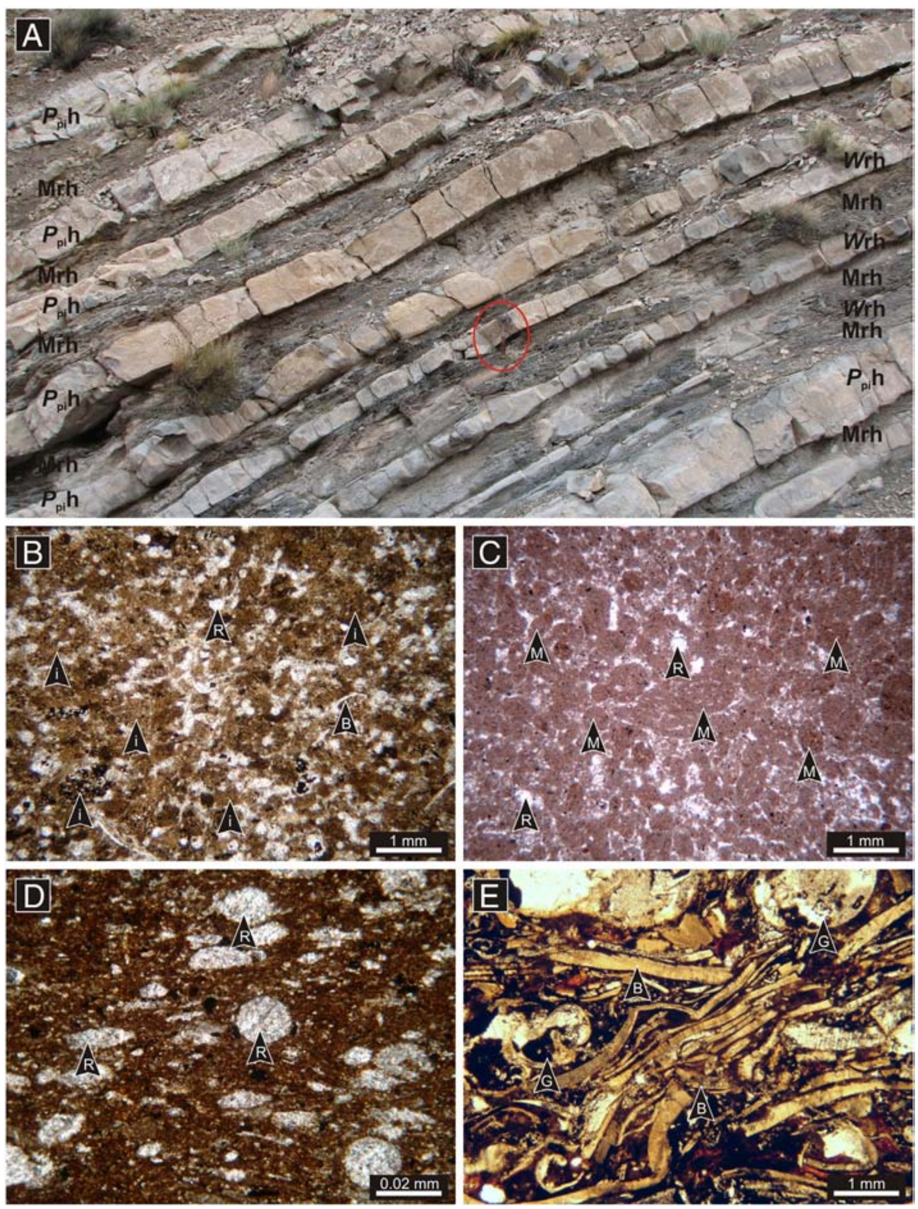

Fig. 9. A) Field exposure of facies association 4 (proximal outer ramp), upper Tithonian, Arroyo Loncoche section (see lithofacies code in Table 1). B) Intraclastic packstones (P_ih) showing abundant rounded to angular micritic intraclasts. C) Peloidal packstones (P_ph) consisting of crustacean microcoprolite accumulations. D) Radiolaritic wackestones (W_rh) showing abundant spumellarid and nassellarid radiolaria. E) Bioclastic rudstones (RF_bm) containing abundant bivalve fragments and gastropods. References: (B) bivalves, (G) gastropods, (i) intraclasts, (M) crustacean microcoprolites (*Palaxius caracuraensis* Kietzmann), (R) radiolarians.

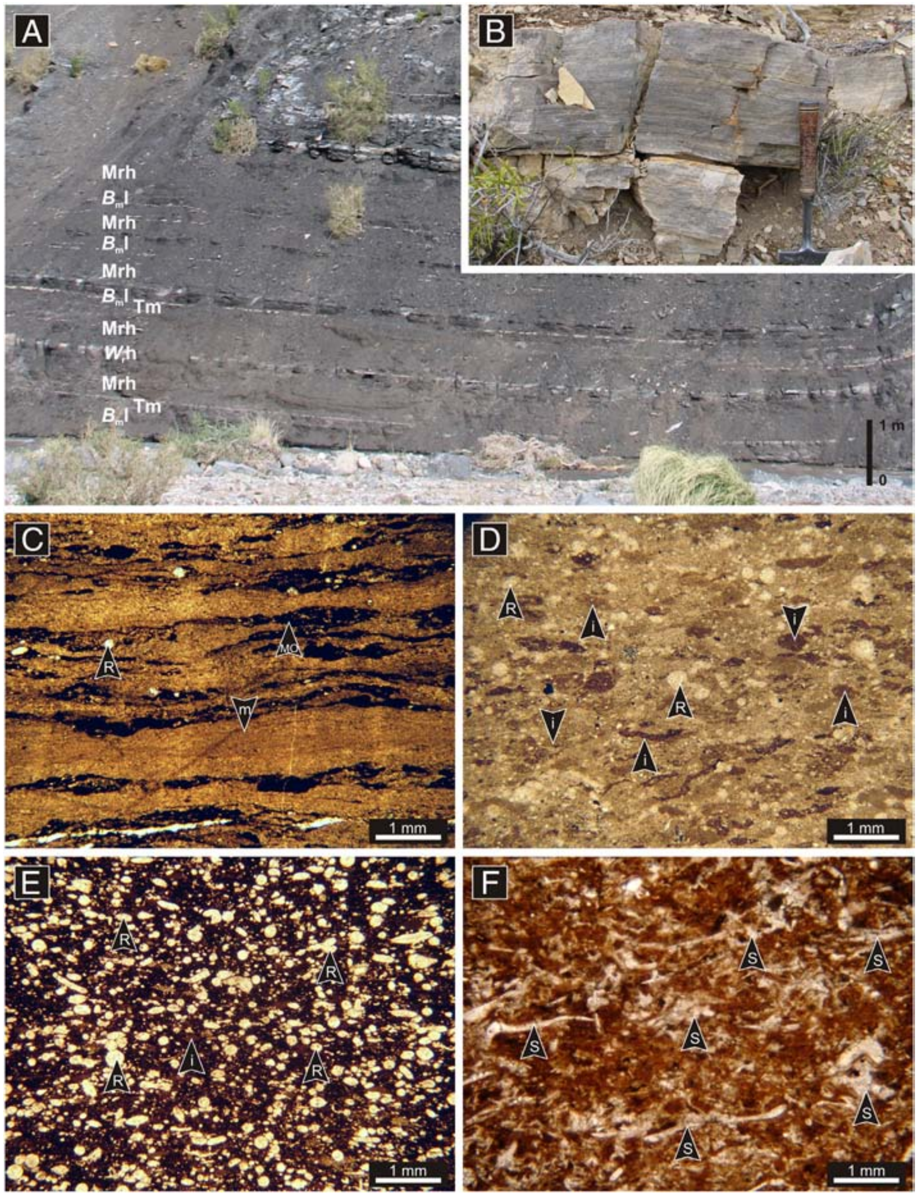

Fig. 10. A) Field exposure of facies association 5 (microbialite dominated outer ramp), middle Tithonian, Cañada Ancha section (see lithofacies code in Table 1). B–C) Field exposure and thin section of planar microbialite facies (B_ml), showing an alternation of microbial induced calcite laminae and organic matter rich laminae. D) Intraclastic packstones (P_ih) with different wackestone intraclasts. E) Radiolaritic wackestones (W_rh) showing abundant radiolaria and pellets. F) Laminated packstones (P_{pi}h) containing abundant saccocomid ossicles. References: (i) intraclasts, (m) microbial laminae, (MO) organic matter, (R) radiolarians, (S) sacoccomid microcrinoid ossicles.

and laminated marls (Mrh) represent a mixture of sedimentary processes including deposition by settling of fine grained suspended material (carbonate mud, radiolarians, calcisphaeres), during fair-weather periods, as well as sedimentary particles put in suspension during storm events. In fact, taphonomic features, along with exhumed *Thalassinoides* galleries with passive infilling, the absence of fauna in life position and the presence of trace fossils seeking a balance with the sediment–water boundary suggest reworking by storm-wave action.

The association of *Thalassinoides*, *Diplocraterium* and *Rhizocoralliun* is indicative of the *Skolithos* ichnofacies, which suggests colonization of storm beds by a community of opportunistic organisms in a post-event, high-stress, physically controlled environment (Pemberton et al., 1992). Trace fossils indicate alternating energy regimes and a relatively well oxygenated substrate.

Massive and inverse graded lapillite deposits are probably deposited from floating rafts of air fall pumice originated in the Andean volcanic arc, whereas that normal graded lapillite were probably deposited from low density turbidites (e.g. Whitham, 1993).

Facies association 3 is interpreted as deposited in a moderate well-oxygenated bioclastic middle ramp to proximal outer ramp setting, immediately below the storm-wave base. High organic matter content in marls suggests that oxygenation conditions were probably not constant, being occasionally dysoxic.

5.4. Facies association 4: proximal outer ramp

5.4.1. Description

Low energy facies are represented in facies association 4 is by radiolaritic laminated wackestones (W_rh) and laminated marls (Mrh), rhythmically interbedded with peloidal and intraclastic laminated packstones (P_{pi}h) and thin graded bioclastic rudstones/floatstones (RF_bm), which represents high energy facies (Fig. 9), Subordinated

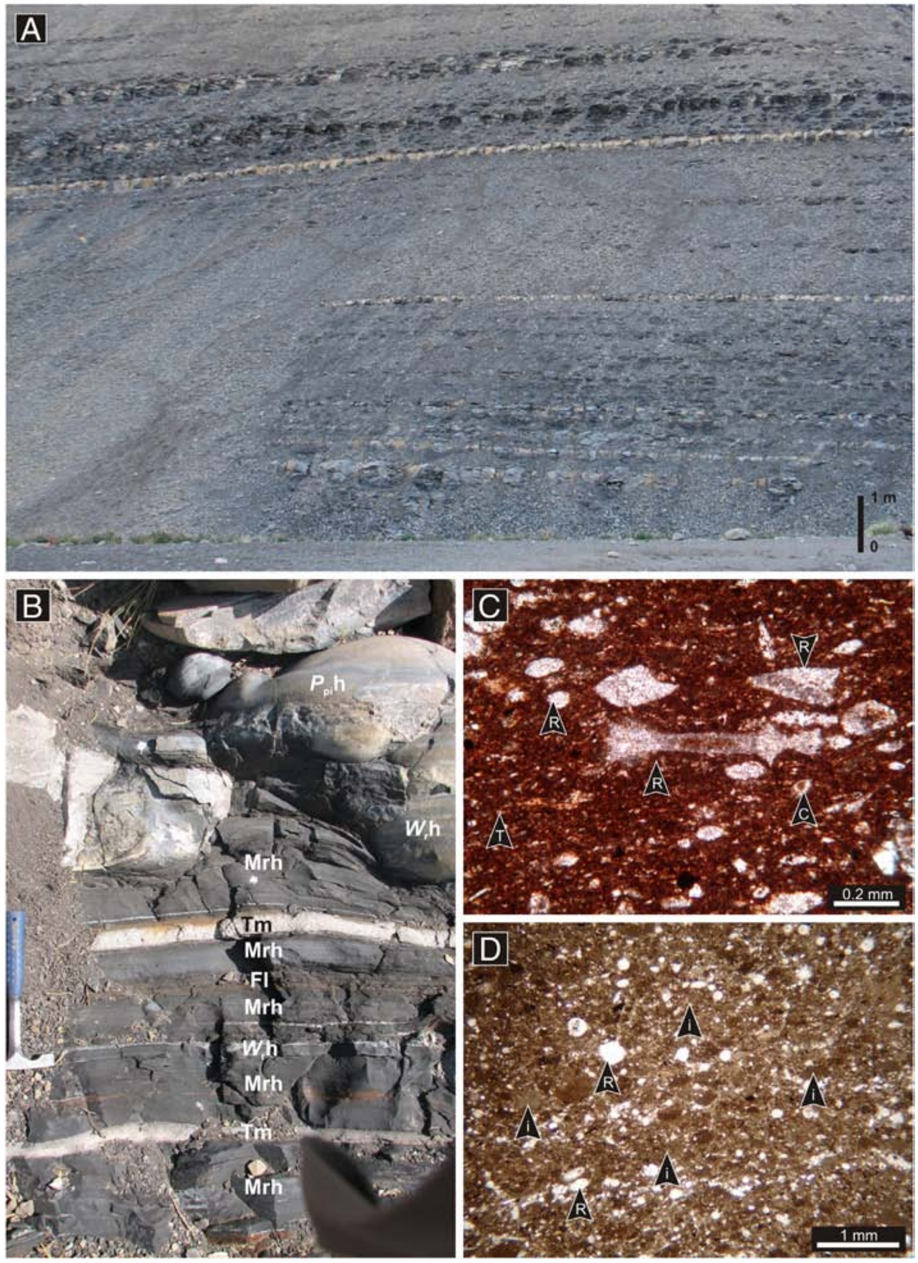

Fig. 11. A) Field exposure of facies association 6 (distal outer ramp to basin), Berriasian, Arroyo Rahue section, showing the alternation of marls with intraclastic packstones (P_ih) and radiolaritic wackestones (W_rh). B) Detail of facies association 6, lower Tithonian, Cañada Ancha section, showing alternation of marls (Mrh), laminated wackestones (W_rh) and pyroclastic deposits (Tm, Tg) (see lithofacies code in Table 1). C) Radiolaritic wackestones (W_rh) showing abundant radiolarians and terrigens. D) Normal graded intraclastic packstone (P_ih) composed by micritic intraclasts and radiolarians. References: (C) calpionellids, (i) intraclasts, (R) radiolarians, (T) terrigens.

lapillite and tuff deposits are also present. The marl/limestone ratio is ~3:1.

Facies association 4 is represented in all studied stratigraphic sections in Southern Mendoza (Fig. 5), and is characterized by marls with high organic matter content, reaching values of 5%.

Radiolaritic wackestones (W_rh) are well laminated. They contain abundant radiolarians (Fig. 9D), including spumellarians and nassellarians with a ratio of 0.8 to 1. Other bioclasts include ammonites, aptychi, and reworked infaunal bivalves, lingularids brachiopods, and occasionally serpulids.

Laminated packstones (P_{pi}h) are composed by well sorted, rounded to angular, fine to medium sand size micritic clasts, which correspond to radiolaritic wackestones or mudstones (Fig. 9B) or by crustacean microcoprolite accumulations (Fig. 9B). Fossils contained in the beds include reworked infaunal bivalves, serpulids, lingulid brachiopods, gastropods, echinoderms, and ammonites. These are filled by pellets, and distributed chaotically or parallel to the stratification. Bioturbation is rare, although at certain levels some *Planolites*, *Palaeophycus* and *Thalassinoides* tubes has been identified.

Thin graded bioclastic rudstones/floatstones (RF_bm) are single or multi event concentrations of bivalves, gastropods, ammonites and foraminifers (Fig. 9E). Beds have sharp erosive bases, ranging in thickness from 2 to 10 cm. The bivalves are disarticulated and highly fragmented, distribution of bioclasts is random or arranged relatively concordant to the bedding plane or stacked.

5.4.2. Interpretation

Fair-weather sedimentation is represented by marls and laminated radiolaritic wackestones, originated mostly from deposition by settling of fine grained suspended material, including planktonic microorganisms

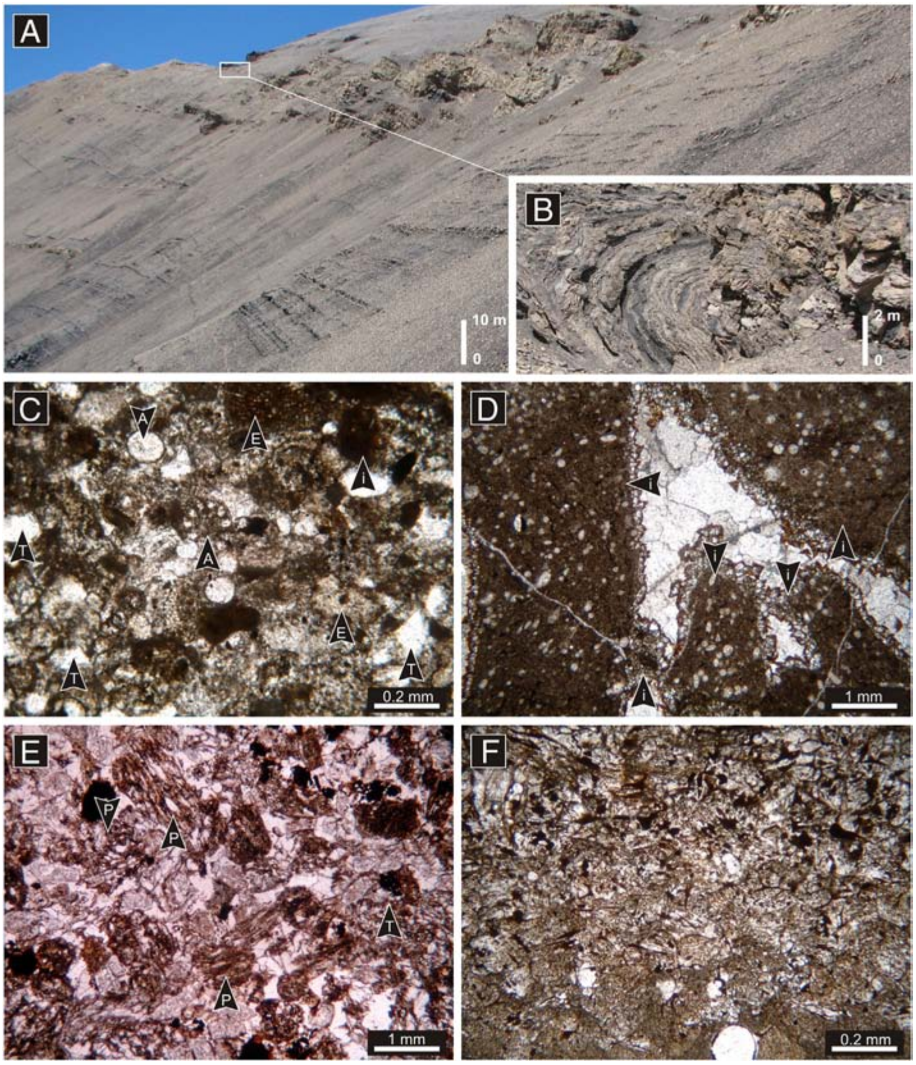

Fig. 12. A–B) Field exposure of facies association 7 (carbonate slope), upper Tithonian–lower Berriasian, Cerro Domuyo section, showing slumped fine grained intervals and lentiform sandy packstones (P_{bt}m, P_{bt}h). C) Sandy bioclastic packstones (P_{bt}m, P_{bt}h) in lentiform sandy interval. D) Intraclastic breccia (B_i) consisting of radiolaritic wackestone intraclasts. E) Lapillite deposits (Lm, Lg) of coarse sand to granule grain size. F) Inverse graded tuff deposits (Tg) consisting of shards and pumiceous fragments. References: (A) dasycladacean algae, (E) echinoderm fragments, (i) intraclasts, (P) pumiceous fragments, (T) terrigens.

and carbonate mud. Also, spumellarian and nassellarian ratio suggests distal open marine waters (see Kiessling, 1996). On the contrary, high energy facies suggest deposition linked to storms. The abundance of peloids and micritic intraclasts, as well as disarticulated and fragmented fossils indicates that these sediments come from reworking of the seafloor during strong storms or storm-induced return flows. In fact, intraclastic packstones show similar textures to the lenticular shale fabric describer by Schieber et al. (2010), which is associated with intermittent erosion processes and transport from bottom currents. Experimental observations show that the erosion of muddy substrates tends to form intraclasts rather than resuspending muddy material, and these are transported by bed-load at relatively low velocities (Schieber and Southard, 2009; Schieber et al., 2010). Thin massive or graded bioclastic rudstones are sedimentary single or multi-event concentrations. Presence of disarticulated and highly fragmented bivalves, with random arrangement, perpendicular orientation or stacking, suggests an origin as storm-generated turbidite-like flows (e.g. Monaco, 1992).

The presence of lucinid bivalves and epistominid foraminifera might suggest low-oxygen conditions, as they were probably chemosymbionts organisms (Sagasti and Ballent, 2002; Taylor and Glover, 2006). Planktonic and nektonic organisms, such as radiolarians, calcisphaeres and ammonite fragmocones also contributed to accumulation of sediments. Trace fossils are related to the *Cruziana* ichnofacies, characterizing low-energy environments, colonized by deposit- and suspension-feeders and also by mobile carnivores (Pemberton et al., 1992; MacEachern et al., 2008).

Facies association 4 is interpreted as deposited below the storm-wave base in a poorly-oxygenated bioclastic outer ramp setting.

5.5. Facies association 5: microbialite dominated outer ramp

5.5.1. Description

Facies association 5 is mainly represented by low energy facies, including planar microbialites (B_ml), radiolaritic laminated wackestones (W_rh) and laminated marls (Mrh), interbedded with laminated packstones (P_{pi}h) and subordinately tuff (Tm, Tg) deposits highly cemented by carbonates (Fig. 10A). The marl/limestone ratio is ~3:1.

Facies association 5 is well represented in the lower part (lower and middle Tithonian) of the Cañada Ancha and Cerro Domuyo sections of the Vaca Muerta Formation (Fig. 5).

Planar microbialite beds (B_ml) consist of thinly laminated, fine-grained limestones, rich in organic matter, which are laterally continuous (Fig. 10B–C). Some of these beds contain soft-sediment deformation structures, which are particularly significant in the basal microbial level of the Vaca Muerta Formation. Those structures include boudins of different sizes and complexity, a variety of folds, normal dm-scale faults, sub-horizontal detachment surfaces and other features, which are part of several larger-scale, complex slump structures (Martín-Chivelet et al., 2011). At the top of these beds, traces fossils such as *Planolites*, *Chondrites*, small forms of *Thalassinoides*, and *Lumbricaria* coprolites can occur. Also evidences of cryptobioturbation are found in microbialite laminae.

Bioclasts in radiolaritic laminated wackestones (W_rh) and laminated packstones (P_{pi}h) include reworked infaunal bivalves, gastropods, echinoderms, ammonites, and radiolarian and epistominid foraminifera. Laminated marls (Mrh) have high organic matter content, reaching values of 5%.

Laminated packstones (P_{pi}h) are composed by well sorted, rounded to angular, fine to medium sand size micritic clasts (Fig. 10D). Fossils contained in the beds include reworked infaunal bivalves, gastropods, echinoderms, *Saccocoma* concentrations and ammonites. These are filled by pellets, and distributed chaotically or parallel to the stratification.

5.5.2. Interpretation

Original biocenosis in this subenvironment had reduced diversity, probably dominated by infaunal organisms, including crustaceans, shallow infaunal bivalves, and benthic foraminifera, whilst ammonites, radiolarian, and calpionellids, and calcisphaeres were present in the water column. Other skeletal components, such as gastropods, saccocomid microcrinoids, ophiuroids, and echinoids, are interpreted as allochthonous to parautocthonous.

Proliferation of microbial mats suggests a poorly oxygenated substrate and a low sedimentation rate. The submillimeter- to millimeter-scale lamination represents a combination of biologically influenced carbonate deposition, and settling of mud and planktonic organisms. Remobilization by bottom currents generated local accumulation of microbial mats fragments, similar to those described by Schieber (1998, 1999) for deep-sea microbial mats. Presence of bioclastic material between microbial laminae probably indicates storm deposition. As suggested by Martin-Chivelet et al. (2011) deformation of the basal microbial level of the Vaca Muerta Formation could be associated with seismic activity at intermediate depths.

Radiolaritic wackestones and marls facies are mainly due to deposition of mud, planktonic organisms, and particles transported during storms, while intraclastic packstones are interpreted as deposition of reworked intraclasts by bottom currents associated with storm events. Tuff deposits were probably originated in non-cohesive low density turbiditic currents.

Trace fossils could be related to the *Cruziana* ichnofacies, which indicates low-energy environments (Pemberton et al., 1992). Presence of *Lumbricaria* has been also cited in dysoxic environments (Savrda and Bottjer, 1986).

Facies association 5 is interpreted as deposited below the storm-wave base in a poorly-oxygenated outer ramp setting.

5.6. Facies association 6: distal outer ramp to basin

5.6.1. Description

Facies association 6 is dominated by dark gray to black well laminated marls (Mrh). Subordinated appear laminated packstones (P_ih), ripple-laminated packstones (P_pr), radiolaritic wackestones (W_rh), and tuffs (Tm, Tg), similar to those of facies association 5 (Fig. 11A–B).

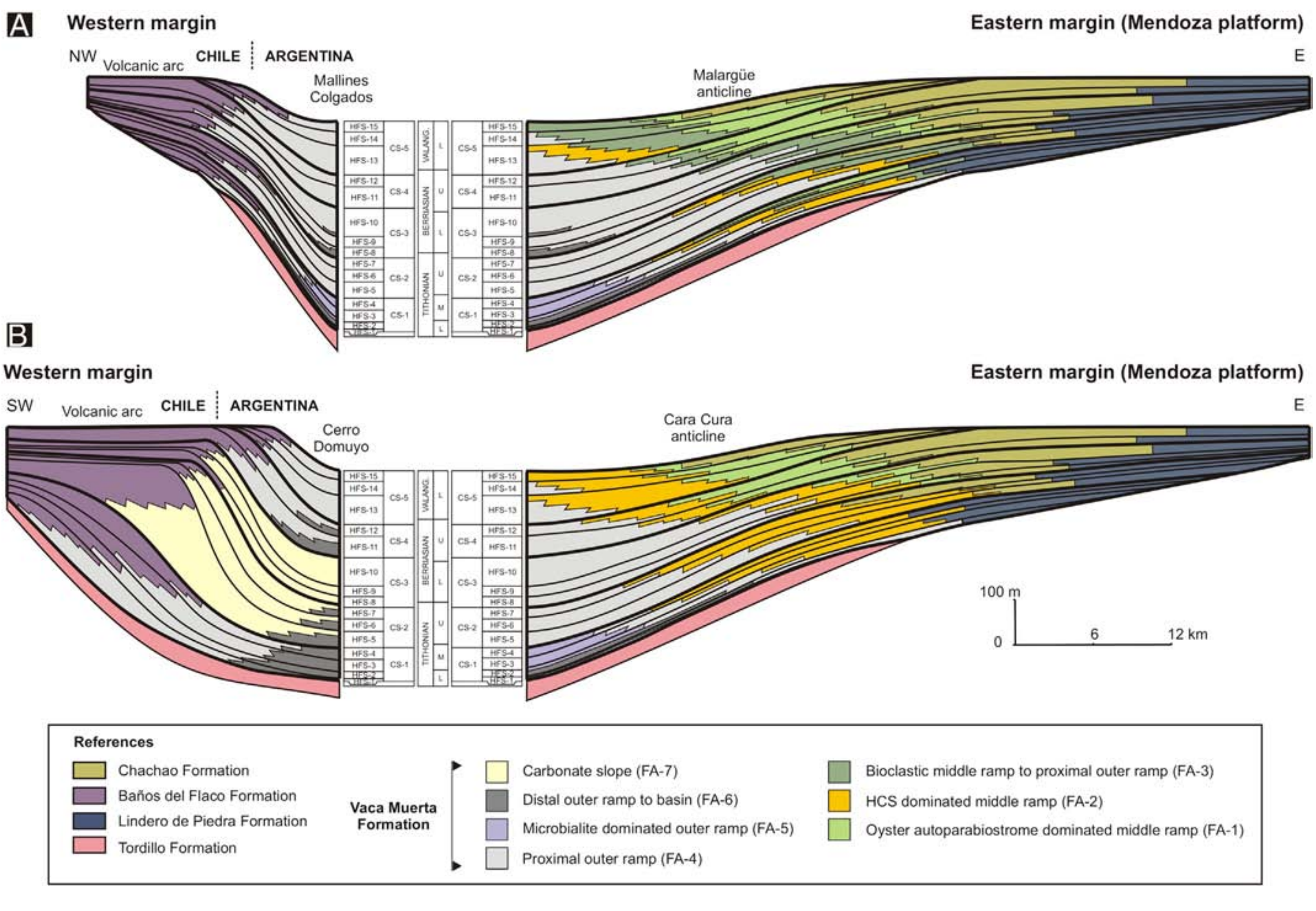

Fig. 13. A) East-northwest schematic section of the Lower Mendoza Mesosequence in the southern Mendoza sector of the Neuquen Basin (35.5°S), showing stratigraphic architecture in western and eastern margins of the basin, and recognized depositional sequences. B) East-southwest schematic section of the Lower Mendoza Mesosequence in the southern Mendoza sector of the Neuquen Basin (36.5°S), showing stratigraphic architecture in western and eastern margins of the basin, and recognized depositional sequences.

The marl/limestone ratio is ~6:1. This facies association is well represented in the Cerro Domuyo section. It is characteristic in the basal part of the Vaca Muerta Formation (lower Tithonian to the lower part of the middle Tithonian), as well as in the upper Tithonian of the Arroyo La Manga and Cañada Ancha sections (Fig. 5). These intervals are the richest in organic matter, and therefore the main Vaca Muerta Formation source levels (organic matter content reaches values of 7%).

Bioclasts in laminated packstones (P_ih) and radiolaritic wackestones (W_rh) are mainly represented by thin-shelled oysters, abundant fish scales, and articulated fishes, reworked infaunal bivalves, gastropods, ammonites, radiolarian, and epistominid foraminifera, calpionellids and calcisphaeres. In the middle Tithonian interval, these beds are particularly rich in vertebrate remains, including turtles, ichthyosaurs and crocodiles.

Packstones with ripple-lamination (P_pr) are tabular, centimeter thick, and have erosive bases and occasionally sole marks. Fine material is commonly accumulated between foreset laminae. In some cases hummocky-like cross stratified structures appears within them. Paleocurrent measures in this facies indicate southwest directions.

5.6.2. Interpretation

Sedimentation occurred mainly from suspension. However, presence of fine-grained ripple laminated packstones, as well as bioclastic remains such as infaunal bivalves and echinoderm fragments, suggests shallow-water sediment input, probably associated with storm-generated turbidity flows.

The high organic matter content and absence of bottom-dwelling organisms suggest elevated organic productivity or good preservation, and sedimentation in a steady restricted marine environment with poorly-oxygenated bottom waters.

Tuffs were probably deposited from non-cohesive low density turbiditic currents, similar to those described by Whitham (1993) and Scasso (2001) from the Ameghino Formation of Antarctica.

Presence of benthic fauna is extremely limited, including epifaunal oysters and epistominid foraminifera. Spumellarian and nassellarian ratio in radiolaritic wackestones is about 0.8 to 1, suggesting distal open marine waters, but values near 0.5 are also found, suggesting an oxygen-depleted environment (cf. Kiessling, 1996). Similar interpretation follows from the abundance of ammonites, microfossils, and vertebrate remains, indicating an anoxic to dysoxic environment.

Facies association 6 is interpreted as deposited below the storm-wave base in a poorly-oxygenated distal outer ramp to basin setting.

5.7. Facies association 7: carbonate slope

5.7.1. Description

Facies association 7 is composed by slumped fine grained sandy bioclastic packstones (P_{pt}m, P_{pt}h), lapillites (Lm, Lg), tuffs (Tg), intraclastic breccias (B_i), and laminated marls (Mrh) (Fig. 12A–B). This facies association is only recognized in the Cerro Domuyo section, and occurs in an interval called Huncal Member (Leanza et al., 2003). It is composed of slumped lentiform bodies of massive to poorly laminated fine grained sandy bioclastic packstones, developed between two slumped complexes. The marl/limestone ratio is ~1:3.

Fine grained sandy bioclastic packstones (P_{pt}m, P_{pt}h) forms coarsening upward lentiform bodies of 5 to 15 m high and about 1000 m length. Particles include echinoderm fragments, dasycladacean algae, infaunal bivalves, oolite grainstone intraclasts, and terrigens (Fig. 12C).

Slumps are conspicuous and characteristics structures of this facies association. They have thickness of several meters (~1–10 m) and verges to the northeast (Kietzmann and Vennari, 2013), contrasting with other paleocurrent measures in the Vaca Muerta Formation, which have westward paleodirections.

Intraclastic breccias (B_i) are mantiform clast-supported monomictic beccias. Contacts are sharp and planes. Clasts are micritic (radiolaritic wackestones and mudstones) pebble sized, and angular to subangular (Fig. 12D). Thickness of beds increases westward from centimeters to decimeters along about 3 km.

Lapillite deposits are very abundant in this association. They are massive (Lm) or graded (Lg), and consist of abundant pumiceous fragments, fine sand-size micritic intraclasts, dasycladacean algae, crustacean microcoprolites, and subordinately silt size terrigens (Fig. 12E).

Tuff deposits (Tg) are tabular, with sharp planar or slightly erosive basal contacts. They are composed of abundant glass shards and pumiceous fragments in inverse graded layers of 2 to 5 mm thick (Fig. 12F).

Fossil content in laminated marls (Mrh) is scarce and includes belemnites, ammonites, trunks and branches, and fish scales.

5.7.2. Interpretation

Lapillite and tuff deposits are very abundant in this association, suggesting sedimentation in proximity of the Andean volcanic arc. These deposits were probably deposited from rafts of floating pumice, ash falls and/or low density turbidites (cf. Whitham, 1993). The northeast vergence of landslides indicates the proximity of the Cerro Domuyo section to the western margin of the Neuquén Basin during the Late Jurassic, represented by the volcanic arc.

The massive to poorly laminated lentiform bodies composed by fine grained sandy bioclastic packstones and associated with slumped intervals, are interpreted as a grain-dominated slope apron deposited at the toe of the slope (Playton et al., 2010). Presence of echinoderm fragments, dasycladacean algae, oolite grainstone intraclasts, and terrigenous materials, suggests transport from shallower and protected areas.

Grain-supported intraclastic breccias are interpreted as non-cohesive debris-flow deposits, as suggested by their non-erosive bases and lateral increment in thickness. Clast composition suggests that the break of slope was in distal sectors of the depositional system.

Facies association 7 is interpreted as accretionary slope deposits linked probably with a carbonate open shelf or a distally steepened ramp system.

5.8. Sedimentary environment

During early Tithonian to early Valanginian the Neuquén Basin would have behaved as a partially closed basin, bounded on the west by a volcanic island arc and connected with the Pacific Ocean by narrow marine passages (Legarreta and Uliana, 1991; Howell et al., 2005). This configuration allowed the existence of low energy and relatively shallow marine ramps with development of carbonate and mixed carbonate-siliciclastic depositional systems.

Carbonate platform geometry was related to hydrodynamic setting and biological characteristics. In fact, ramp geometries are seen as the products of decreased differentiation of depth-dependent production rates, depth-enhanced carbonate production, and/or strong offshore transport, as well as the lack of frame-building organisms capable of building steep platform margins (Pomar and Kendal, 2008). The last two factors were most probably those controlling facies distribution of the Vaca Muerta carbonate ramp system.

On the eastern margin of the basin a homoclinal carbonate ramp system was developed (Vaca Muerta-Chachao carbonate ramp system), while between volcanic arc in the western margin, a series of carbonate shallow areas generated a distally steepened ramp system (Vaca Muerta-Baños del Flaco carbonate ramp system), which shows its maximum expression with the Huncal Member towards the Neuquen embayment (Fig. 13).

The Vaca Muerta-Chachao carbonate ramp has a shallow facies belt dominated by sedimentologic recliner-oyster accumulations, among which are intercalated isolated branching coral patches and biodetritic mud mounds (Legarreta and Kozlowski, 1981; Palma et al., 2000). This facies belt includes subtidal inner ramp to middle ramp deposits of the Chachao Formation, which grades basinward to middle ramp oyster auto-parabiostromes (FA-1), which were reworked and transported forming bioclastic middle to outer ramp deposits (FA-3).

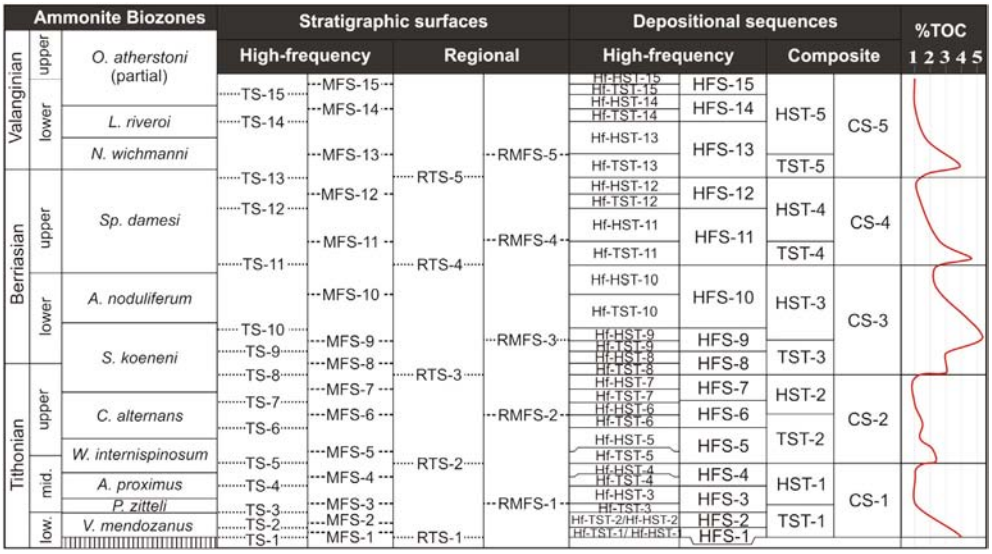

Fig. 14. Summary of stratigraphic sequences recognized in the Vaca Muerta Formation, and total organic carbon data (TOC) from Arroyo Rahue section (Sierra Azul area). References: (TS) transgressive or flooding surface, (RTS) regional transgressive or flooding surface, (MFS) maximum flooding surface, (RMFS) regional maximum flooding surface, (Hf-TST) high-frequency transgressive system tract, (Hf-HST) high-frequency highstand system tract, (TST) transgressive system tract, (HST) highstand system tract, (HFS) high-frequency depositional sequence, (CS) composite depositional sequence.

During fair-weather stages, these shallow areas were dominated by low energy conditions, allowing proliferation of recliner benthic organisms, such as oysters and serpulids, in a sedimentary environment dominated by sedimentation of carbonate mud. In contrast, storm events caused reworking and transport of organisms to distal areas of the carbonate ramp. In fact, these kind of muddy-substrate recliner-oyster reefs originate under low to moderate sedimentation rates (Seilacher et at., 1985; Machalski, 1989). Our data indicate an early Valanginian sedimentation rate between 8 and 30 m/Ma, and taphonomic evidence indicates that oyster accumulations were reworked during high energy events, showing displacement of life-position, disarticulation and even fragmentation. Actually, a continuous low energy sedimentation with intermittent high energy episodes of reworking is probably the most likely mechanism responsible for the formation of this facies belt.

In unfavorable areas for the generation of muddy-substrate recliner-oyster reefs, the ramp was dominated by settling of mud and proliferation of benthic organisms such as crustaceans, gastropods, ophiuroids, saccocomid microcrinoids, rotularid serpulids, as well as infaunal bivalves and brachiopods. Presence of transported, but moderately well preserved, green algae and sponges spicules, suggest low energy conditions and shallow water. Particularly, presence of callianassid crustaceans must have been important, given the abundance of fecal pellets produced by these organisms (Kietzmann and Palma, 2010a,b; Kietzmann et al., 2010b). Probably, the sea floor had an irregular topography, similar to the present day Bahamas platform, with conical mounds connected with extensive horizontal galleries systems (Warme, 1967; Wanless et al., 1988).

During storms, these conical mounds were truncated and flattened by wave activity, forming hummocky-cross stratified beds, and thin bioclastic deposits. Pellets were transported to the outer shelf, where they were concentrated generating pelletoidal muds (Wanless, 1979).

These shallow areas of the carbonate ramp are represented by facies association 2. Similar examples in the sedimentary record are the Betic Middle Jurassic carbonate ramp deposits of Spain (Molina et al., 1997), the Umbria-Marche Middle Jurassic of Italy (Monaco, 1992), and some Paleogene deposits of southwestern Iran (Mohseni and Al-Aasm, 2004), among others.

A second facies belt is represented by facies associations 4, 5 and 6, which represent the distal part of the carbonate ramp, extending from outer ramp to basin. In this sector the carbonate ramp was dominated by settling of mud and planktonic organisms, as well as pellets and bioclasts transported during storms. Proliferation of benthic organisms was much more restricted than in middle ramp. In moderate to well oxygenated sectors the substrate was colonized by shallow infaunal bivalves, recliner-flat-oysters and benthic foraminifera, and callianassids, which contributed to the pelletization of the seafloor.

With exception of some localities where sedimentation was probably controlled by preexisting topographic highs (as in Mallín Redondo section, southern Sierra Azul), the sedimentation rate was of 25 to 35 m/Ma. During Tithonian times low sedimentation rates favored the proliferation of microbial mats in some areas like Cañada Ancha and Cerro Domuyo.

Presence of storm deposits between microbial laminae indicates moderate energy hydrodynamic conditions were of. As suggested by Mata and Bottjer (2009), development of microbial horizons would be favored under transgressive conditions due to a significant decrease in sedimentation rate, and microbial mats could colonize the seabed below the fair-weather wave zone (Schlager, 2005; Álvaro and Clausen, 2006).

The third facies belt is represented by facies association 7, which is interpreted as slope deposits linked probably with an open carbonate shelf or a distally steepened ramp system. The intercalation of slumped deposits and gravity flows with east-northeast paleodirections, indicates establishment of a slope in the western margin of the basin, related to a shallow protected environment developed within the Andean volcanic arc. In the south of the basin, similar facies are represented by the Picún Leufú Formation, which is interpreted as originated in shallow protected areas, with lagoons and oolitic bars (Armella et al., 2007). In Chilean territory, backarc sequences equivalent to the Mendoza Group, i.e. the Lo Valdés and Baños del Flaco Formations, are interpreted as originated in a restricted subtidal environment limited by oolitic barriers (Moreno and Pino, 2002).

6. Sequence stratigraphy

In this paper we present a new sequence stratigraphic framework for the Vaca Muerta Formation, based in the intensive stratigraphic work performed by the authors in southern Mendoza during the last years.

Sequences stratigraphic units were defined in this paper using the recognition of flooding or transgressive surfaces (TS), which are the best developed and less ambiguous stratigraphic surfaces for the positions of the analyzed sedimentary environment. System tracts are defined by stacking pattern and facies tendency.

Based on this analysis, two hierarchies of depositional sequences are recognized, used here as composite depositional sequences (CSs) for high-rank sequences, and high-frequency depositional sequences (HFSs) for those of small scale (Figs. 5, 13). Because of its average duration, high-rank sequences are considered to be equivalent to third order sequences, while low-rank sequences are considered as fourth order sequences (e.g., Kerans and Tinker, 1997).

6.1. First composite depositional sequences (CS-1)

Composite depositional sequences CS-1 starts with the transgressive surface TS-1, which is an important regional surface (RTS-1) where the late Kimmeridgian continental/transitional deposits of the Tordillo Formation are overlapped by microbialite dominated outer ramp deposits of the Vaca Muerta Formation. This basal surface coincides with the basal microbialite level of the Vaca Muerta Formation, which contains ammonites from the lower Tithonian *V. mendozanus* Biozone (Fig. 5), and has been named informally as Las Amarillas level by Martín-Chivelet et al. (2011). The upper limit is determined by the transgressive surface TS-5, which is another surface of regional value recognized throughout the basin (RTS-2) and is located within the uppermost middle Tithonian *Windhauseniceras internispinosum* Biozone (Fig. 14).

In the eastern margin the transgressive system tract (TST-1) is clearly retrograding, beginning in almost all stratigraphic sections with microbialite dominated outer ramp deposits (FA-5), grading into proximal outer ramp deposits (FA-4), and then to the distal outer ramp deposits (FA-6), representing a maximum flooding zone (RMFZ-1) located within the lowermost middle Tithonian *Pseudolissoceras zitteli* Biozone. TOC values in the TST-1 reach 4% (Fig. 14).

The highstand system tract (HST-1) is defined by a net progradational strata arrangement characterized in distal positions of the carbonate ramp by the progradation of microbialite dominated outer ramp deposits (FA-5) and proximal outer ramp deposits (FA-4), and proximal outer ramp facies (FA-4), bioclastic middle ramp to proximal outer ramp (FA-3), HCS dominated middle ramp facies (FA-2), and oyster autoparabiostrome dominated middle ramp facies (FA-1) (Figs. 5, 13). TOC values in the HST-1 decrease to 1%.

In the western margin facies remain homogeneous, recognizing the progradational pattern by an increase in carbonate content (Figs. 5, 13). The first composite sequence contains four high frequency sequences (HFS-1 to 4), whose temporal distribution can be seen in Fig. 14.

6.2. Second composite depositional sequences (CS-2)

Composite depositional sequences CS-2 begins with the transgressive surface TS-5 (lower part of the middle Tithonian *W. internispinosum* Biozone). The upper limit is determined by the transgressive surface TS-8 (RTS-3), which is located within the uppermost upper Tithonian *Substeueroceras koeneni* Biozone.

The transgressive system tract (TST-2) is recognized in the eastern margin by a facies deepening, from middle ramp deposits (FA-1, 2 or 3) to proximal outer ramp deposits (FA-4) (Fig. 13). In the western margin the TST-2 is represented by the progradation of carbonate slope deposits (FA-7) related with the generation of a steep slope due to the increase in accommodation space (Kietzmann and Vennari, 2013). TOC values in the TST-2 reach 2.4% (Fig. 14).

The highstand system tract HST-2 in the eastern margin consists of a net progradational strata arrangement from proximal outer ramp deposits (FA-4) to HCS dominated middle ramp deposits (FA-2) in Sierra Azul and Sierra de la Cara Cura anticlines, from proximal outer ramp (FA-4) to bioclastic middle ramp to outer ramp deposits (FA-3) in the Malargüe Anticline, and from proximal outer ramp (FA-4) to HCS dominated middle ramp deposits (FA2) in the Atuel depocenter. In the western margin HST-2 is represented by carbonate slope deposits (FA-7) (Figs. 5, 13). TOC values in the HST-2 decrease to 0.8% (Fig. 14).

Composite depositional sequences CS-2 contains three high-frequency sequences (HFS-5 to 7), whose temporal distribution and facies can be seen in Fig. 14.

6.3. Third composite depositional sequences (CS-3)

Composite sequence CS-3 begins with the transgressive surface TS-8 during late Tithonian (*S. koeneni* Biozone), and ends with transgressive surface TS-11 (RTS-4) in the early late Berriasian (lower part of the *Spiticeras damesi* Biozone) with the progradation of bioclastic middle ramp facies (Fig. 5).

The transgressive system tract (TST-3) is recognized in the eastern margin by a facies deepening, from middle ramp deposits (FA-2 or 3) to proximal outer ramp deposits (FA-4) in most of the studied sections or to distal outer ramp to basin deposits (FA-6) in the Atuel depocenter (Figs. 5, 13). TOC values in the TST-3 reach 5 to 7% (Fig. 14).

The highstand system tract HST-2 in the eastern margin consists of a progradational strata arrangement from proximal outer ramp deposits (FA-4) to HCS dominated middle ramp deposits (FA-2) in Sierra Azul and Sierra de la Cara Cura anticlines, and proximal outer ramp (FA-4) or bioclastic middle ramp to outer ramp deposits (FA-3) in the Malargüe Anticline (Figs. 5, 13). TOC values in the HST-3 decrease to 2% (Fig. 14).

In the western margin the composite sequence CS-3 is represented by carbonate slope deposits (FA-7), which coincides with the Huncal Member (Kietzmann and Vennari, 2013).

Composite sequence CS-3 contains three high-frequency sequences (HFS-8 to 10). Their temporal distribution and facies can be seen in Fig. 14.

6.4. Fourth composite sequence (CS-4)

Composite sequence CS-4 lies between transgressive surface TS-11 (RTS-4) and TS-13 (RTS-5) in the upper Berriasian (*S. damesi* Biozone, Figs. 5, 14).

In the eastern margin the transgressive system tract (TST-4) consists of proximal outer ramp deposits (FA-4), while the highstand system tract (HST-4) shows the progradations of to bioclastic middle ramp-proximal outer ramp facies (FA-3), HCS dominated middle ramp facies (FA-2) and finally to oyster auto-parabiostrome dominated middle ramp facies (FA-1).

The western margin is dominated by proximal outer ramp facies (FA-4) which prograde over distal outer ramp to basin deposits (FA-6). TOC values in the TST-4 reach 4.6% and decrease in HST-4 to 0.9% (Fig. 14).

Composite sequence CS-4 contains two high-frequency sequences (HFS-11 and 12; Fig. 14).

6.5. Fifth composite sequence (CS-5)

Composite sequence CS-5 begins with the transgressive surface TS-13 in the uppermost part of the upper Berriasian (*S. damesi* Biozone), and ends in the lower Valanginian (lower part of the *O. atherstoni* Biozone) with the progradation of the shallow oysters-dominated deposits of the Chachao Formation (Fig. 5). In the more distal positions, as the Bardas Blancas or the Arroyo Rahue sections, the lower part of the *O. atherstoni* Biozone is represented by facies of the Vaca Muerta Formation, and culminates with the regional transgressive surface, that marks the beginning of the Agrio Formation.

In the eastern margin the transgressive system tract (TST-5) consists of proximal outer ramp (FA-4) and bioclastic middle ramp-proximal outer ramp (FA-3) deposits, while the highstand system tract (HST-5) shows the progradations of to bioclastic middle ramp-proximal outer ramp facies (FA-3) or HCS dominated middle ramp facies (FA-2), and finally oyster auto-parabiostrome dominated middle ramp facies (FA-1) or oyster dominated facies of the Chachao Formation (Fig. 5). TOC values in the TST-5 reach 4% and decrease in HST-5 to 1% (Fig. 14).

The western margin is dominated by proximal outer ramp facies (FA-4), but in the Cerro Domuyo section HST-5 is not represented due to erosion.

Composite sequence CS-4 contains three high-frequency sequences (HFS-13 to 15).

7. Discussion

7.1. Sedimentary environment

The sedimentary environment of the Vaca Muerta Formation was traditionally interpreted as basinal to slope deposits, based on seismic interpretations, as well as outcrops and well data in the Neuquén embayment (Leanza, 1973; Leanza et al., 1977; Mitchum and Uliana, 1985; Legarreta and Uliana, 1991, 1996). Similar interpretations were performed for the Mendoza platform (Legarreta et al., 1981; Mitchum and Uliana, 1985; Legarreta and Uliana, 1991, 1996).

The conception that the Vaca Muerta Formation in the Neuquén embayment represents basin-slope facies is due to the sigmoidal geometry of clinoforms on seismic sections, although detailed sedimentological studies were never performed. According to Mitchum and Uliana (1985) data, maximum inclination of clinoform slopes does not exceed 0.6° during the Tithonian–Berriasian. In fact, depositional systems dominated by production of mud-size sediment in the shallow-water zone have a minimum capacity to fill the accommodation of a shallow-water shelf. Storms erode and suspend this fine material, so it is easily shed downshelf and the angle of repose is very low, resulting in a homoclinal ramp depositional profile (Pomar and Kendall, 2008).

Detailed facies analysis presented in this paper, and previous works (Kietzmann et al., 2008, 2011a; Kietzmann and Palma, 2009a, 2011) indicate high lateral and vertical facies variability. The Vaca Muerta Formation in the southern Mendoza sector of the Neuquén Basin is the result of two systems: the westward progradations of a homoclinal ramp and the outermost part of a distally steepened ramp, whose shallow facies were developed in the present Chilean territory to the west.

Early sequential stratigraphic studies on the Tithonian–Valanginian successions of the Neuquén Basin were made by Mombrú et al. (1978), who studied the Chachao Formation deposits using a reef-rimmed shelf model, recognizing three episodes of flooding, culminating with dolomitization and subaerial exposure phenomena. This model was subsequently abandoned by Legarreta and Kozlowski (1981) and Mitchum and Uliana (1985), who interpreted the Chachao Formation as an alternation between ramp and platform geometries with offshore organic banks development at the break of slope. Finally, detailed microfacial and taphonomic studies carried out by Palma (1996) and Palma and Lanés (2001) concluded that deposits of the Chachao Formation are related to a carbonate ramp geometry.

The detailed data presented in this work shows that the deposition of the Vaca Muerta Formation occurred in shallower conditions than previously accepted, in the context of a low-gradient carbonate ramp rather than in an basin-slope environment. This interpretation coincide the idea that rich organic matter systems occurred mostly in shallow environments rather than in deep-water systems.

7.2. Sequence stratigraphy

Seismic sequences of Mitchum and Uliana (1985) were made with low-quality seismic data, but since then no regional studies were performed. These authors defined nine depositional sequences (A to I) for the lower Tithonian–lower Valanginian interval (Vaca Muerta and Chachao Formations): Four tithonian sequences (A to D), two berriasian sequences (E to F) and three lower valanginian sequences (G to I). This set of depositional sequences were included by Legarreta and Gulisano (1989) within the Lower Mendoza Mesosequence (Mi_1 to Mi_9), and assigned to depositional sequences defined by Haq et al. (1987, 1988) (see Fig. 2).

Sequence Mi_1 of Legarreta and Gulisano (1989) include the Tordillo Formation (LST) and the basal part of the Vaca Muerta Formation (TST and HST), whereas the last depositional sequence recognized in the Chachao Formation was incorporated into the Middle Mendoza Mesosequence (Mm_1) by correlation with the Mulichinco Formation, which is separated from the Vaca Muerta Formation by the intravalanginian unconformity (Stipanicic and Rodrigo, 1970; Gulisano et al., 1984).

The sequence stratigraphic framework presented in this paper include five composite depositional sequences and fifteen high-frequency depositional sequences, which are supported by detailed sedimentological and biostratigraphical data. As no field evidence of subaerial exposure are available for the Vaca Muerta Formation that could help to recognize sequence boundaries and/or their correlative conformities, flooding surfaces have proven to be useful for stratigraphic studies. Thus, recognizing the composite depositional sequences, as done in the present work, can be an important subsurface tool for correlation, since flooding surfaces can be detected by gamma rays, and probably could be detected with modern seismic resolution. In fact, the five major progradations (composite sequences) are outlined in the work of Legarreta and Kozlowski (1981), Legarreta et al. (1981) and Legarreta and Gulisano (1989), and are easily recognizable in the field (Spalletti et al., 2000; Kietzmann et al., 2008, 2011a; Kietzmann and Palma, 2009a, 2011).

Regarding the youngest sequences, we found no evidence of an intravalanginian unconformity within the Vaca Muerta Formation. This unconformity was probably tectonically induced, resulting in a basinward shift of proximal marine and continental facies belts (Gulisano et al., 1984; Vergani et al., 1995). But unlike Neuquén Province, where the continental deposits of the Mulichinco Formation directly overlap the Vaca Muerta and Quintuco Formations (Gulisano et al., 1984; Legarreta and Gulisano, 1989), in Southern Mendoza this intravalanginian unconformity is absent. Only in Sierra de la Cara Cura we recognized an intravalanginian unconformity between the Chachao and Mulichinco Formations. This unconformity, however, is not present north of this area, where the Vaca Muerta Formation grades transitionally to the Agrio Formation, as shown in the Arroyo Rahue and Cañada Ancha sections.

7.3. Relevance for the Vaca Muerta shale-gas/oil system

A correct interpretation of the sedimentary environment and the sequence stratigraphic framework of the Vaca Muerta Formation is necessary to understand the Vaca Muerta shale system. Sedimentary environment and diagenesis can control the micro- and/or cryptoporosity type (Slatt and O'Brien, 2011; Loucks et al., 2012), but organic matter distribution could be also controlled by facies changes, fluctuations in productivity/fertility or in sedimentation rate, among other factors (e.g. Passey et al., 2010; Graham, 2012).

The obtained TOC curve shows five intervals with a decreasing trend (Fig. 14), which correlates with the five composite depositional sequences. Each interval starts with a significant increase in TOC values of 4 to 7%, coinciding with the transgressive system tract, and then decreased to 0.8 to 1% coinciding with the highstand system tract.

In composite depositional sequences CS-2 and CS-3 high frequency variations are observed, but more data are needed to ensure that high frequency sequences also exert a control on the total organic content.

These data also show a significant difference with TOC curves from the southern sector of the basin (Urien and Zambrano, 1994; Villar et al., 1998; Cruz et al., 2002), which shows high TOC values (8–12%) in basal part of the Vaca Muerta Formation (*V. mendozanus* and *P. zitteli* Biozones), and then decrease significantly to the Picún Leufú and Quintuco Formations.

Organic matter data from Arroyo Rahue section were chosen as representative of the Vaca Muerta Formation in southern Mendoza

(Fig. 14), because this locality is characterized by a reduced facies variability (mainly facies association 4: bioclastic outer ramp),and therefore it can be inferred a relationship between the organic matter content and see-level fluctuations within a sequence stratigraphic context.

Carbonate ramps responds quickly to changes in sea level (Burchette and Wright, 1992; Handford and Loucks, 1993; Tucker et al., 1993). Transgressive system tracts may become the most important part of a carbonate ramp sequence, due to its low topographic gradient. The rapid flooding of the ramp generates a migration of the carbonate production area to shallow ramp, whereas in the outer ramp the sedimentation rate is significantly reduced, and the environment stays under reduced oxygenation conditions, allowing a significant accumulation of organic matter (e.g. Hardie, 1986; Emery and Myers, 1996). In contrast, during regressive stage carbonate ramps prograde increasing erosion and sediment exportation to distal parts of the environment, diluting and oxidizing organic matter (e.g. Burchette and Wright, 1992; Bádenas et al., 2005).

Therefore the sedimentary evolution of the Vaca Muerta Formation deposits and sequence stratigraphic model should be established to locate possible intervals for the exploration of this exceptional unconventional reservoir of the Neuquén Basin.

8. Conclusions

The Vaca Muerta Formation in the Southern Mendoza sector of the Neuquén Basin is interpreted as the westward progradation of a homoclinal ramp located on the eastern margin of the basin, while on the western margin represents the outermost part of a distally steeped ramp, whose shallow facies were developed in the present Chilean territory.

Based on the identification of flooding surfaces two hierarchies of transgressive–regressive cycles are recognized: five composite depositional sequences, and fifteen high frequency depositional sequences, which together show a regressive trend.

First composite depositional sequence starts in the lower Tithonian (*V. mendozanus* Biozone) with a regional transgressive surface, which overlap late Kimmeridgian continental/transitional deposits by microbialite dominated outer ramp deposits, and ends in the uppermost middle Tithonian (*W. internispinosum* Biozone).

Second composite depositional sequence develops between the middle Tithonian and the uppermost upper Tithonian (*W. internispinosum* to *S. koeneni* Biozones), while composite depositional sequence include upper Tithonian to upper Berriasian deposits (*S. koeneni* to *S. damesi* Biozone).

Fourth composite depositional sequence include the upper Berriasian (*S. damesi* Biozone), while the fifth composite depositional sequence include upper Berriasian to lower Valanginian deposits (*S. damesi* to *Olcostephanus* (*O.*) *athertoni* Biozones), and culminate with the progradation of the shallower oysters-dominated deposits of the Chachao Formation and/or basinal facies of the Agrio Formation.

No evidence of an intravalanginian unconformity was found in the studied area within the Valanginian interval of the Vaca Muerta Formation, which favors an interpretation for its presence in Neuquén province, as a tectonically controlled unconformity.

Fluctuations in organic matter content within the Vaca Muerta Formation suggest their relationship with composite depositional sequences — with the highest values being associated with transgressive system tracts.

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