Expanding the spectrum of shallow-marine, mixed carbonate–siliciclastic systems: Processes, facies distribution and depositional controls of a siliciclastic-dominated example

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Associate Editor – Christopher Fielding

ABSTRACT

Most of the present knowledge of shallow-marine, mixed carbonate–siliciclastic systems relies on examples from the carbonate-dominated end of the carbonate–siliciclastic spectrum. This contribution provides a detailed reconstruction of a siliciclastic-dominated mixed system (Pilmatu é Member of the Agrio Formation, Neuquén Basin, Argentina) that explores the variability of depositional models and resulting stratigraphic units within these systems. The Pilmatu é Member regressive system comprises a storm-dominated, shoreface to basinal setting with three subparallel zones: a distal mixed zone, a middle siliciclastic zone and a proximal mixed zone. In the latter, a significant proportion of ooids and bioclasts were mixed with terrigenous sediment, supplied mostly via along-shore currents. Storm-generated flows were the primary processes exporting fine sand and mud to the middle zone, but were ineffective to remove coarser sediment. The distal zone received low volumes of siliciclastic mud, which mixed with planktonic-derived carbonate material. Successive events of shoreline progradation and retrogradation of the Pilmatu é system generated up to 17 parasequences, which are bounded by shell beds associated with transgressive surfaces. The facies distribution and resulting genetic units of this siliciclastic-dominated mixed system are markedly different to the ones observed in present and ancient carbonate-dominated mixed systems, but they show strong similarities with the products of storm-dominated, pure siliciclastic shoreface–shelf systems. Basin-scale depositional controls, such as arid climatic conditions and shallow epeiric seas might aid in the development of mixed systems across the full spectrum (i.e. from carbonate-dominated to siliciclastic-dominated end members), but the interplay of processes supplying sand to the system, as well as processes transporting sediment across the marine environment, are key controls in shaping the tridimensional facies distribution and the genetic units of siliciclastic-dominated mixed systems. Thus, the identification of different combinations of basin-scale factors and depositional processes is key for a better prediction of conventional and unconventional reservoirs within mixed, carbonate–siliciclastic successions worldwide.

Keywords Depositional controls, Lower Cretaceous, mixed carbonate–siliciclastic marine systems, Neuquén Basin, Pilmatu é Member, sequence stratigraphy.
INTRODUCTION

Mixed carbonate–siliciclastic systems are defined as those depositional settings where coeval deposition of carbonate and siliciclastic sediment takes place (Mount, 1984; Goldhammer, 2003), which is in contrast to mixed carbonate–siliciclastic successions in which reciprocal sedimentation (Van Siclen, 1964) results in the formation of high-frequency alternation of pure carbonate and siliciclastic units that represent different depositional systems (Schwarz et al., 2016b). Depositional models for shallow-marine, mixed carbonate–siliciclastic systems, the focus of this study, are far from being understood.

The configuration and evolution of these mixed systems depend heavily on the processes responsible for producing different types of carbonate grains (i.e. skeletal and non-skeletal), as well as the processes supplying siliciclastic sand and mud to a basin (Zonneveld et al., 2001; Coffey & Sunde, 2014; D’Agostini et al., 2015; Zeller et al., 2015; Labaj & Pratt, 2016). Hydrodynamic processes transporting and depositing the sediment within the marine realm control the final mixing. Although facies distribution schemes have been proposed for some modern mixed shelves and ramps in which carbonate sediment prevails (Purdy & Gischler, 2003; Gischler & Lomando, 2005), less studies have reported on modern or Cainozoic, mixed shallow-marine systems in which siliciclastic sediment is dominant, which is commonly mixed with skeletal grains (Saul et al., 1999; Cantalamessa et al., 2005; Vital et al., 2008). However, even more uncommon are reconstructions of siliciclastic-dominated systems from the rock record in which the contribution of non-skeletal grains is important (Coffey & Sunde, 2014). As a result, no previous studies have attempted to show the degree of variability that can exist from carbonate-dominated to siliciclastic-dominated systems, and their resulting stratigraphic patterns, within the spectrum of these mixed systems.

The Pilmatuè Member of the Agrio Formation in the study area (central Neuquén Basin) is a mixed carbonate–siliciclastic unit (Schwarz et al., 2016a), in which both lateral and vertical transitions from pure siliciclastic, to mixed, to pure carbonate rocks are recorded, but with a pre-eminence of siliciclastic sediment. It thus provides an opportunity to reconstruct in detail the depositional systems, their short-term evolution and the resulting stratigraphic (genetic) units produced in mixed systems with a dominance of siliciclastic supply. The aims of this article are therefore to: (i) reconstruct depositional systems and sequence architecture by describing and interpreting facies associations of the unit over a 350 m thick succession and 20 km long transect; (ii) recreate the short-term shoreline evolution and longer term palaeogeographic scenarios; and (iii) discuss controls on the formation of mixed carbonate–siliciclastic systems and their potential variability even within a single basin.

GEOLOGICAL SETTING

The Neuquén Basin is located in west-central Argentina, covering most of the Neuquén Province, and significant parts of Mendoza, La Pampa and Río Negro provinces (Fig. 1A). It is bounded by tectonically stable regions to the north-east (Sierra Pintada System) and south-east (North Patagonian Massif), and its sedimentary record accumulated in a variety of basin styles during the Late Triassic to the early Cenozoic (Legarreta & Uliana, 1991; Howell et al., 2005). The basin, which is one of the most important petroleum provinces of South America, can be divided into two regions: the Andean Thrust and Fold belt with extensive outcrops of Jurassic–Cretaceous strata, and the Neuquén Embayment, with slightly deformed strata in the subsurface.

Between the Tithonian and Hauterivian ages, the Neuquén Basin was a back-arc basin (Fig. 1B) characterized by a ramp-type gradient in the eastern and southern margins (Legarreta & Uliana, 1991; Spalletti et al., 2000), but a more inclined depositional profile towards the emergent magmatic arc (Spalletti et al., 2008). During that interval, long-lived periods of highstand conditions were interrupted by significant events of relative sea-level fall that, in turn, were followed by rapid transgressions (Fig. 2A). Relative sea-level drops triggered partial disconnection of the epeiric sea from the proto-Pacific, as well as the exposure and erosion of large areas of the basin (Howell et al., 2005). Two of these transgressive-regressive cycles were first recognized by Weaver (1931) and Groeber (1946) and comprise parts of the Agrio Formation. The Pilmatuè Member, the focus of this study, represents the older one (Fig. 2A).
The Pilmatué Member of the Agrio Formation is a regionally extensive unit dominated by marine deposits, which accumulated across the Neuquén Basin between the late Valanginian and early Hauterivian (Spalletti et al., 2011). It is a mixed carbonate–siliciclastic unit (Weaver, 1931; Groeber, 1946), and its base marks a deepening with respect to the underlying continental or shallow-marine deposits of the Mulichinco Formation (Schwarz & Howell, 2005). At the top, the Pilmatué Member is abruptly truncated by continental (fluvial and aeolian) deposits of the Avilé Member of the Agrio Formation (Fig. 2A), which represents a second-order lowstand stage (Legarreta & Uliana, 1991; Veiga et al., 2002, 2007).

The Pilmatué Member was included in studies addressing basin-wide palaeogeographic reconstructions (Legarreta & Gulisano, 1989; Legarreta & Uliana, 1991, 1999) and in detailed palaeontological studies (Aguirre-Urreta et al., 2005; Lazo, 2006), but the palaeoenvironmental and sequence-stratigraphic evolution of the unit has only been broadly outlined (Lazo, 2007; Spalletti et al., 2011). Detailed reconstructions of depositional systems have become available recently for southern regions of the basin (Schwarz et al., 2016c; Veiga & Schwarz, 2017), but not for the study area in its central sector (Fig. 1).

In this region of the Neuquén Basin, the Pilmatué Member comprises up to 700 m of marine deposits and is dominated by basinal shale and offshore mudstone, with subordinate shallow-marine siliciclastic sandstone and mixed (carbonate–siliciclastic) sandstone (Schwarz et al., 2016a). Time-equivalent marginal-marine and continental deposits are more abundant to the east in the Neuquén Embayment (Lower Centenario Member; Digregorio & Uliana, 1980), but this transition is poorly understood. In the northern sector of the basin (Mendoza Province), the Pilmatué Member is mostly composed of basinal and offshore carbonate mudstone and marl (Sagasti, 2005).

An ammonite biostratigraphic framework has been erected for the Pilmatué Member (Aguirre-Urreta et al., 2005, 2011), indicating that the unit spans from the late Valanginian to the early Hauterivian (Fig. 2B). Four ammonite zones are identified in this unit: *Pseudofavrella angulatiformis*, *Holcoptychites nequensis*,...
**STUDY AREA AND METHODS**

The study area is located in the central sector of the Neuquén Basin, near the town of Chos Malal, between 37°42’S and 37°28’S, and 69°59’W and 70°05’W (Figs 1 and 3). This region represents the eastern limit of the Agrio Fold and Thrust Belt, and the Pilmatué Member crops out along three anticlines that collectively represent a continuous, accessible and poorly vegetated outcrop, which is ca 25 km long and up to 8 km wide (Fig. 3). Only in the northernmost 4 km of the area is the stratigraphic section not fully exposed (Fig. 4).

In the study area, the lower half of the Pilmatué Member is exclusively composed of fine-grained lithologies, including grey shale and marl, greenish mudstone and sandy mudstone. The upper half of the unit is characterized by fine-grained deposits interbedded with coarsening-upward, decametre thick intervals comprising muddy sandstone, fine-grained sandstone, mixed sandstone–carbonate deposits and skeletal

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**Variability of carbonate–siliciclastic systems**

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carbonate (Fig. 4). This section, up to 350 m thick, is the focus of this study. Northward of the study area (central and northern part of Curaco anticline), sandstone packages are almost absent, suggesting a general proximal–distal trend in that direction (Fig. 4). Biostratigraphically, the study interval comprises the lower Hauterivian ammonite zones, from the Holcoptychites neuquensis Zone at the base, to the Weavericeras vacaense Zone in its upper contact with the Avilé Member (Fig. 4). The Hauterivian age at the base of the study interval was recently confirmed by a U-Pb dating of 130·0 ± 0·8 Ma (Schwarz et al., 2016a).

The studied succession was investigated by logging 20 key sections, typically less than 2 km apart (Figs 3 and 4). Shorter supplementary sections were measured to capture rapid lateral facies transitions. Sedimentological data were recorded in each section (texture, sedimentary structures and palaeocurrents). Ichnofaunal, macrofaunal and taphonomic information was also collected. Bioturbation intensity was characterized using the Bioturbation Index (BI) defined by Taylor & Goldring (1993). Key stratigraphic surfaces (mostly transgressive surfaces; Fig. 4) were walked out and mapped laterally in the field. Measured sections and outcrop mapping were combined with correlations based on high-resolution aerial photographs of the outcrops (Fig. 5). The photographs provided a continuous view of the succession along the main exposures. Interpretation of macrofossil associations followed previous palaeoecological studies on the Pilmatué Member in the southern sector of the basin (Lazo, 2007).

![Fig. 3. Simplified geological map of the studied area; the Pilmatué Member is exposed in three north–south oriented anticlines. The 20 sedimentological sections of the unit analysed in this contribution are shown. PL: Puesto Ladrillo, S15: South 15, PM: Puesto Mardone, LR: Loma Rayoso, CD: Cóndores, AN: Anfiteatro, PR: Puesto Riquelme, EC: El Cierre, SZ: Solorza, RN: Río Neuquén, QG: Quebrada Grande, QC: Quebrada Chica, PA: Puesto Abandono, EA: El Abra, SE: San Eduardo, PL: Puesto Leiva, CC: Cerro Curaco, PH: Puesto Habitado, EC: Escuela Curaco, PG: Puesto González. The inset (right side) shows the projection of all the sections in a south–north-oriented transect, which is used to reconstruct the general stratigraphy of the unit (shown in Fig. 4).](image)

![Fig. 4. Summary stratigraphic cross-section of the Pilmatué Member in the Loma Rayoso-San Eduardo region. Biostratigraphic subdivisions after Schwarz et al. (2016a). The datum horizon is the regionally extensive transgressive surface marking the base of the Agua de la Mula Member of the Agrio Formation. Shoreface-offshore tongues are here defined as parasequences and numbered using arbitrary number from PS220 to PS520. The transgressive surfaces bounding these parasequences at their bases are labelled consequently (for example, PS220 is bounded by transgressive surface TS220).](image)
Petrographical analysis of 70 thin sections helped to characterize the sedimentary texture and composition of individual beds. Percentages of siliciclastic and carbonate components, as well as grain-size distributions, were estimated using visual comparative charts (cf. Scholle & Ulmer-Scholle, 2003).

**FACIES ASSOCIATIONS**

Seven facies associations were identified and interpreted in the early Hauterivian succession of the Pilmatué Member. Three siliciclastic and two mixed facies associations show systematic vertical transitions and are interpreted to represent different conditions across a shelf to shoreface depositional system: basin (i.e. distal shelfal setting without adjacent slope; BA); offshore (OF); offshore-transition (OT); lower shoreface (LS); and upper shoreface (US) facies associations (Fig. 6; Table 1). Two additional facies associations are dominantly composed of gravel-size skeletal fragments and are here collectively termed as shell beds (Table 1): shoreface shell beds (SSB) and offshore shell beds (OSB).

**Basin (BA)**

*Description*

This facies association is composed of fissile, dark grey to black shale (Fig. 7A). Although fissility is ubiquitous (BI 0 to 1), a structureless appearance is observed locally. Apart from ammonites, macrofossils are not present in the shale, but microfossils such as foraminifera and radiolarians are frequent (Table 1).

*Interpretation*

This association is interpreted as the product of settling from suspension on a low-energy, poorly oxygenated sea floor, most likely in a siliciclastic–carbonate basinal setting located well below storm-wave base (Spalletti et al., 2001).

**Offshore (OF)**

*Description*

This facies association comprises coarsening-upward intervals with massive, siliciclastic mudstone at the base that grade upward to structureless siltstone (Fig. 7B). Macrofossils are uncommon, but articulated specimens of shallow-burrowing bivalves such as *Cucullaea* sp.
Fig. 6. Selected sedimentological sections from the Pilmatué Member in the Loma Rayoso-Sand Eduardo region, showing key facies, facies associations (except basinal association), stacking patterns and bounding surfaces. Interpreted genetic units (i.e. parasequences and bedsets) are indicated in one case as an example. *Bivalve (undetermined)* refers to all the bioclasts that come from endobenthic and semi-endobenthic organisms that are not oysters.
Table 1. Description and interpretation of facies associations recognized in the Pilmatué Member. A: articulation degree; F: fragmentation degree; D: distribution; BI: bioturbation index (1 to 6); l: low; m: moderate; h: high. Epibenthic macrofossils: *Ceratostreon* sp. (oyster), *Parsimonia* sp. (serpulid), *Columastrea* sp. (coral). Endobenthic macrofossils: *Eriphyla* sp., *Cucullaea* sp. and *Steimanella* sp. are shallow-burrowing bivalves; *Panopea* sp., *Ptychomya* sp. and *Pholadomya* sp. are deep-burrowing bivalves. Semi-endobenthic macrofossils: *Pinna* sp. and pectinids are byssate bivalves, and *Aetostreon* sp. is a reclined oyster.

| Facies association | Lithology | Sedimentary structures; thickness | Trace fossils; fossils | Taphonomy | Interpretation. Depositional setting |
|--------------------|-----------|-----------------------------------|------------------------|-----------|-------------------------------------|
| Basin (BA)         | Dark grey to black siliciclastic and carbonate shale | Fissility, uncommon structureless; <95 m thick | Typically barren (BI 0 to 1); ammonites, foraminifera, radiolarians | A: h, F: l | Settling from suspension on a low-energy, poorly oxygenated sea floor. Mixed siliciclastic–carbonate basinal setting |
| Offshore (OF)      | Light grey to greenish siliciclastic mudstone and siltstone | Massive, subordinate lamination; <35 m thick | *Thalassinoides*, *Chondrites* (BI 5 to 6); *Cucullaea* sp., *Eriphyla* sp., *Steimanella* sp. | A: h-m, F: l, D: in situ or parallel to bedding | Settling from suspension on a low-energy, well-oxygenated sea floor. Siliciclastic offshore |
| Offshore-transition (OT) | Mudstone and siltstone interbedded with very fine-grained sandstone, rare rip-up muddy clasts | Dominant lenticular and wavy bedding with cross-lamination and symmetrical ripples (beds <0.05 m thick), subordinate hummocky cross-stratification (sets <0.2 m thick), rare gutter casts and parting lineation; <9 m thick | Resident (BI 3 to 6); *Palaepolyphycus*, *Thalassinoides*, *Teichichnus*, *Planolites*, *Asterosoma*, *Rosselia*, *Ophiomorpha*, opportunistic (BI 1 to 3); *Ophiomorpha*, *Gyrochortes*, *Panopea* sp., *Eriphyla* sp., *Steimanella* sp., *Pinna* sp. | A: h-m, D: pockets and stringers of *Pinna*, frequently in life position | Alternation of settling from suspension and sandy distal storm events, below fair-weather wave base and above storm base, *Cruziana* ichnofacies suite. Transition zone from offshore to shoreface |
| Lower shoreface (LS) | Very fine and fine-grained sandstone, rare rip-up clasts and gravel and sand-size shells | Dominant isotropic and anisotropic hummocky cross-stratification, subordinate swaley cross-stratification, current-ripple cross-lamination, small symmetrical 3D ripples, rare parting lineation and gutter casts; <9 m thick | *Ophiomorpha*, *Skolithos*, *Palaepolyphycus*, *Arenicolites*, *Gyrochortes*, *Rosselia* (BI 1 to 6); Rare *Steimanella* sp. | – | Large asymmetrical ripples and hummocks by oscillatory and combined storm-related flows, Wave-induced fair-weather conditions, *Skolithos* ichnofacies suite. Storm-dominated, wave-influenced lower shoreface |
| Facies association | Lithology | Sedimentary structures; thickness | Trace fossils; fossils | Taphonomy | Interpretation. Depositional setting |
|-------------------|-----------|----------------------------------|------------------------|-----------|------------------------------------|
| Upper shoreface (US) | Fine to medium-grained siliciclastic sandstone, rare coarse-grained to pebble-size clasts, common ooids, common to rare gravel to sand-size bioclasts | Trough and planar cross-bedding (sets <0-30 m thick and <2-0 m wide or 0-50 to 1-0 m thick and 2 to 5 m wide), subordinate current-ripple tops; <5 m thick | Ophiomorpha, Arenicolites (BI 0 to 2); Undetermined bivalves, oysters | – | Dune migration under unidirectional currents, resident Skolithos ichnofacies suite. Upper shoreface conditions |
| Shoreface shell beds (SSB) | Ooid-skeletal grainstone-rudstone, abundant sand-size and gravel-size (<150 mm) bioclasts and siliciclastic fine sand, common ooids, common to rare siliciclastic coarse sand to pebbles, rare early-cemented rip-up sandstone clasts, grading to skeletal-ooid packstone | Cross-bedding (sets <0-10 m thick and <0-60 wide) in well-sorted facies, or massive in poorly sorted facies, rare large symmetrical ripples with straight to slightly sinuous and rounded crests; commonly <0-50 m thick, rarely up to 2-0 m thick | Locally abundant Thalassinoides; Ceratostreon sp., Pholadomya sp., Ptychomya sp., Steimanella sp., Trigonia sp., echinoids, gastropods | – | Allochthonous to parautochthonous macrofossil assemblages, intense, infrequent physical reworking near or below fair-weather wave base by wave action and storm-related flows. Shoreface and offshore-transition, during transgressive conditions |
| Offshore shell beds (OSB) | Skeletal, lime mud-rich floatstone, dominant gravel-size bioclasts, less sand-size bioclasts, terrigenous silt, glauconite and ooids | Massive; commonly <0-5 m thick, rarely up to 1-5 m thick | Uncommon Thalassinoides; Ceratostreon sp., Parsimonia sp., Columastrea sp., Eriphyla sp., Cucullaea sp., Panopea sp., Ptychomya sp., Pholadomya sp., Steimanella sp., Aestostreon sp., pectinids, ammonites | A: h-m, F: m-l, D: chaotic, some in life position | Parautochthonous to autochthonous macrofossil assemblages, low net accumulation rates, minimum physical reworking. Offshore, during transgressive conditions |
Offshore-transition (OT)

Description
This facies association is composed of heterolithic deposits, muddy sandstone and subordinate hummocky cross-stratified sandstone (Fig. 6; Table 1). Heterolithic deposits are mostly composed of siltstone interbedded with lenticular sandstone that has cross-lamination and symmetrical rippled tops (Fig. 7C); they range from mud-dominated to sand-rich heterolithic intervals with moderate bioturbation (BI 3 to 4), typically forming metre-scale coarsening-upward successions. In contrast, the muddy sandstone is heavily bioturbated (BI 5 to 6), with up to 35% disseminated mud (Fig. 7D).

The trace fossil assemblage in these facies includes Asterosoma, Ophiomorpha, Palaeophycus, Planolites, Rosselia, Teichichnus and Thalassinoides. Macrofossils are not common, but when present, they are mostly represented by moulds of deep-burrowing and shallow-burrowing bivalves, mostly articulated and locally in life position (Fig. 7D). Sandstone beds with hummocky cross-stratification (HCS) are interbedded both within heterolithic strata and bioturbated muddy sandstone (Fig. 7E). The beds show parting lineation, and both symmetrical and asymmetrical small ripples (sensu Dumas et al., 2005) can occur on top of the beds.

Ophiomorpha and Gyrochortes are common in these HCS beds, which have low to moderate bioturbation index (BI 1 to 3). Ripple crests both in heterolithic deposits and HCS beds (Fig. 7E) are oriented mostly east–west with preferential northward migration in asymmetrical forms.

Interpretation
The large proportion of mudstone layers, as well as the mud fraction within muddy sandstone beds, suggest that bottom energy conditions were frequently low enough to allow mud deposition and preservation in this setting (Morris et al., 2006; Schwarz et al., 2016b). Sandy beds are related to storm-generated flows, and both symmetrical and asymmetrical small ripples probably formed under purely oscillatory or combined flows (Myrow & Southard, 1996; Dumas et al., 2005). Most of the silt and very fine sand, however, was subsequently mixed with mud due to intense bioturbation. This is supported by the diverse deposit feeding dominated trace fossil assemblage, interpreted to represent a Cruziana ichnofacies (MacEachern et al., 2007a). Storm-surge flows carrying larger volumes of sand created hummocky bedforms under combined, high-velocity flows (Myrow & Southard, 1996; Dumas et al., 2005) and their final deposits escaped complete homogenization.

This facies association is interpreted to represent a storm-dominated offshore–shoreface transition, between storm-wave base and fairweather wave base (Reading & Collinson, 1996), with storm-generated flows preferentially oriented from south to north (i.e. shore-normal to...
the shoreline). Metre-scale coarsening-upward intervals may record shallowing-upward events (Walker & Plint, 1992) or a gradual increase in storm regime (Hampson & Storms, 2003).

**Lower shoreface (LS)**

**Description**

This facies association grades vertically from the OT facies association and comprises the amalgamation of sandstone beds having variable physical sedimentary structures, as well as intensely bioturbated sandy packages (Fig. 6; Table 1). Beds of very fine-grained sandstone with HCS are dominant (Fig. 7F), in some cases associated with horizontal lamination, low-angle lamination or swaley cross-stratification. Sandstone beds with ripple cross-lamination are less abundant, and they typically have tops with slightly asymmetrical or symmetrical ripples. Cross-lamination orientation is variable, but southward migration dominates. Bioturbation index is low to moderate (BI 1 to 4) in these cross-stratified facies. Burrowing intensity varies from high to very high (BI 4 to 6) in the bioturbated sandstone facies, and HCS or ripple cross-lamination is faintly preserved. *Ophiomorpha* is dominant in the bioturbated facies (Fig. 7G), together with subordinate *Arenicolites*, *Gyrochortes*, *Palaeophycus*, *Rosselia* and *Skolithos*, which can also be present in all of the facies. Isolated shells of endobenthic bivalves (*Steimanella* sp.) are uncommon.

**Interpretation**

The amalgamated sandstone packages are interpreted to reflect a lower shoreface setting, where sand was mostly transported and deposited by storm-related flows and fair-weather waves, but mud, if ever deposited, was not preserved (Walker & Plint, 1992). The HCS-dominated packages are related to storm-generated, off-shore-oriented currents that most commonly created and preserved hummocky bedforms under combined flows. However, plane bed conditions under combined flows were also generated, probably suggesting relatively more energetic flows (Arnott, 1993; Perillo *et al.*, 2014). Protected areas or time intervals with less storm activity favoured aggradation of onshore migrating ripples under fair-weather conditions. This situation was commonly associated with intense biogenic reworking by a filter-feeder dominant *Skolithos* ichnofacies assemblage (MacEachern *et al.*, 2007a).

**Upper shoreface (US)**

**Description**

This facies association is mostly composed of fine-grained, cross-stratified, siliciclastic sandstone and mixed carbonate-siliciclastic sandstone (Fig. 6; Table 1). In the siliciclastic sandstone, cross-sets range from small scale (<0.30 m thick and <2.0 m wide; Fig. 7H) to larger sets up to 1 m thick and 5 m wide. Mixed sandstone commonly occurs as subordinate lenses within the siliciclastic sandstone, typically in the lower part of the troughs of cross-bed sets; they are characterized by the unusual concentration of gravel-size bioclasts, in some cases together with siliciclastic coarse material (coarse sand to fine pebble). However, mixed sandstone also exists as discrete intervals up to 2 m thick of better sorted sand-size material that is mostly ooids, bioclasts and terrigenous grains (Fig. 7I). In this mixed facies, trough cross-sets are typically of small scale (<0.20 m thick and <1.5 m wide). Bioturbation is usually absent to low (BI 0 to 2) in all the facies of this association, and is represented by sparse *Ophiomorpha* and *Skolithos*. Palaeocurrent direction from trough axes shows a wide variation, but northward to eastward directions predominate (mean to the north-east). Current ripples are commonly associated with cross-bedded sets, but they show a wide range of crest orientations.

**Interpretation**

This facies association reflects the development of relative permanent unidirectional currents that formed subaqueous dunes in an upper shoreface setting (Walker & Plint, 1992; Clifton, 2006). These bedforms were probably produced in bar troughs and/or rip channels, and preferential concentration of gravel-size bioclasts and terrigenous sand and pebbles was present at the base of these depressions. Low bioturbation suggests unstable, mobile substrates uncommonly colonized by a proximal *Skolithos* ichnofacies suite. Abundant sand-size bioclasts and ooids in this upper shoreface facies suggest fairly continuous mixing of *in situ* produced carbonates together with siliciclastic grains.

**Shoreface shell beds (SSB)**

**Description**

These shell beds are thin with erosional bases, and they comprise two distinct facies (Table 1). One facies type is characterized by small-scale cross-bedded, oolitic–skeletal grainstone (Fig. 8A
Fig. 8. Main attributes of the shell-bed facies associations. (A) Shoreface shell beds (SSB) showing erosional basal surface (white dashed line) and small-scale trough cross-bedding. Note the concentration of gravel-size bioclasts and terrigenous granules to pebbles (as shown in inset). (B) Thin section photograph (cross-polarized light) of this cross-bedded facies showing the abundance of carbonate grains that characterize these shell beds (bioclasts, ooids and aggregates), together with variable proportions of sandstone, rip-up clasts and siliciclastic coarse-grained material. (C) Thin section photograph (plane-polarized light) of the additional facies included in the SSB facies association. Note the presence of lime mud and lower proportion of siliciclastic material. (D) This muddier facies is typically massive, but the tops can be moulded into large symmetrical ripples that are overlaid (and preserved) by OT or OF deposits. (E) Plan view of the offshore shell-bed (OSB) facies association. This bed is dominated by a high proportion of articulated bivalves belonging to the endobenthic-dominated facies, such as *Cucullaea* sp. (c), *Eriphyla* sp. and *Ptychomya* sp. (p). The epibenthic oyster *Ceratostreon* (Ce) is a subordinate component in this facies, in this example attached to an ammonite (am). (F) Thin section photograph (plane-polarized light) of a bed belonging to OSB. Note the high proportion of carbonate mud and large bioclasts suggesting deposition in low-energy settings and low fragmentation. Legend: a – aggregate; b – bivalve; e – echinoid plate; m – micrite (lime mud); o – ooid; q – quartz. Lens cap is 4.5 cm in diameter, pencil is ca 14 cm in length, and field book is 18 cm long.
and B). Fragmented, gravel-size bioclasts are locally abundant (forming skeletal rudstone) and articulated bivalves are absent. Rip-up clasts of underlying fine-grained sandstone are locally present. The second facies type, which can grade vertically from the previous one, is characterized by skeletal–oolitic packstone, with significant proportion of lime mud (Fig. 8C). In this facies, sand-size grains are associated with abundant and less fragmented gravel-size bioclasts. The fossil association is dominated by oysters and endobenthic bivalves (Table 1), and articulated specimens are locally present. Large symmetrical to slightly asymmetrical ripples are commonly preserved at the top of these carbonate beds (Fig. 8D). In addition to carbonate components, siliciclastic coarse-grained grains and pebbles are commonly concentrated in the two facies (Fig. 8A and B). This facies association overlies LS or US facies associations, and grades vertically to offshore shell beds (described below) or OF and OT facies associations (Fig. 6).

Interpretation
Truncation of underlying sandstone and concentration of coarse siliciclastic and carbonate in thin beds suggest that these shell beds are related to phases of marine erosion and concomitant low supply of terrigenous sand. Additionally, when both facies are present, vertical trends indicate a gradual reduction in hydrodynamic energy. Thus, these shell beds are interpreted as transgressive deposits mantling transgressive ravinement surfaces (Nummedal & Swift, 1987; Naish & Kamp, 1997). The cross-bedded facies, with abundant relict, well-sorted material and lack of mud suggest the generation of transgressive lags (Cattaneo & Steel, 2003) in a shoreface setting with dune development. Conversely, the second facies, with abundant lime mud and large symmetrical ripples, which probably formed by the passage of strong oscillatory flows onto the shelly sea floor (Dumas et al., 2005; Cummings et al., 2009), would suggest a proximal offshore-transition setting (i.e. below but near the fair-weather wave base). In this later facies, shell taphonomy points both to relict fragments, but also new benthic associations that colonized the sea floor during transgression.

Offshore shell beds (OSB)

Description
This association also occurs in thin beds and includes two skeletal-dominated facies, which are characterized by preserved macrofossils surrounded by a lime mud matrix (i.e. skeletal floatstone; Table 1). One end-member facies is dominated by epibenthic bivalves, more commonly cemented oysters (Ceratostreon sp.), and the other end member is enriched in endobenthic (shallow-burrowing and deep-burrowing) bivalves (Fig. 8E). When the two facies are in the same stratigraphic interval, the epibenthic-dominated one is replaced northward (i.e. distally) by the other one. Fragments of corals, serpulids, free-lying and endobyssate bivalves and ammonoids are components of both facies. In general, articulation and bioerosion are high in these fossils, whereas fragmentation, orientation of shells and rounding are low. The matrix is dominated by lime mud, with subordinate terrigenous silt and sand-size bioclasts (Fig. 8F). Glauconite is locally common. These shell beds overlie fine-grained deposits of OF or OT facies associations (Fig. 6), and they grade vertically into the BA or OF facies associations.

Interpretation
Taphonomic attributes and composition of fossil associations in both facies suggest parautochthonous to autochthonous assemblages and normal marine salinities (Fürsich, 1995). Shell taphonomy also suggests that all of the macrofossils lived during the generation of the shell beds. The two facies are interpreted to represent a low-energy, well-oxygenated sea floor, characterized by high biogenic carbonate production and minimal terrigenous supply. These shell beds are interpreted to represent offshore conditions and maximum condensation during transgression (Abbott, 1998). Colonization by epibenthic versus endobenthic-dominated communities could have been controlled by rates of carbonate production and sea floor aggradation, as suggested by Schwarz et al. (2016b), but other parameters such as nutrient availability and/or water depth could also have played a role.

HIGH-FREQUENCY SEQUENCES (PARASEQUENCES)

Shallowing-upward successions are the dominant motif in the Pilmatuë stratigraphy, and they occur at different scales (Figs 5, 9 and 10). Shallowing-upward packages bounded by stratigraphic surfaces that represent abrupt marine flooding are termed parasequences (sensu Van Wagoner et al.,
Fig. 9. Detailed cross-sections oriented approximately along depositional dip through two selected intervals of the Pilmatué Member, showing lateral and vertical distribution of facies associations within successive parasequences, shell beds associated with transgressive surfaces and intra-parasequence architecture (bedsets). (A) Study succession from PS250 to PS300. (B) Study succession from PS330 to PS380. Datum is assumed horizontal for simplicity. For log locations, see Fig. 3.
1988), but this definition has an intrinsic problem because it relates to the degree of deepening a surface must show to be defined as such (Catuneanu, 2006; Zecchin & Catuneanu, 2013). In this study, flooding surfaces are consistently defined as those that represent at least a vertical shift of two siliciclastic facies associations in any sector of the study area (i.e. BA deposits overlying OT or shallower deposits, OF deposits overlying LS or US deposits, or OT deposits overlying US deposits). As the stratigraphic units include thin shell beds produced during transgression (Figs 6 and 9), the parasequences identified in this study could be better defined as high-frequency sequences following the Zecchin & Catuneanu (2013) suggestion; but for simplicity, they will be termed parasequences herein. Nonetheless, the bounding surfaces are appropriately defined as transgressive surfaces and placed at the base of the shell beds (Fig. 9A and B).

According to this definition, 17 parasequences were identified in the study interval (Fig. 9; Table 2). These units and their bounding surfaces can be confidently correlated across most of the depositional transect, although precise identification is more difficult in distal areas (Fig. 9). Of the 17 parasequences, 13 record shallowing from BA or OF deposits to LS or US deposits, whereas four document solely shallowing within the distal part of the depositional system (Figs 9 and 10; Table 2). The compacted thickness of completely preserved parasequences ranges from 10 to 50 m (mean of 26 m; Table 2).

Individual parasequences in cases form a single coarsening-upward succession, but more commonly they are composed of bedsets that represent shallowing-upward successions of a higher order (Van Wagoner et al., 1990; Hampson, 2000) (Figs 9 and 11). In this study, the bedset boundaries are surfaces across which there is a minor deepening of the system that is considered as a shift in only one facies association (for example, BA deposits overlying OF deposits and OT deposits overlying OF deposits). Following these criteria, individual parasequences comprise two to six bedsets (Table 2) and bedsets are typically from 5 to 10 m thick. Internally, bedsets show shallowing-upward trends from OF to OT deposits in distal parts of the system (Fig. 9), whereas in proximal parts they comprise OT deposits rapidly passing into LS deposits, and eventually grading to US strata (Fig. 11). Albeit rare, a few bedset boundaries are associated with the presence of shoreface shell beds (Fig. 11B and C), which allow them to be mapped over large distances (for example, PS290 in Fig. 9A; and PS340 and PS380 in Fig. 9B).

**PROCESSES, FACIES BELTS AND SHORELINE EVOLUTION**

**Depositional model**

The vertical and lateral relationships between siliciclastic facies associations (OF, OT and LS) and mixed associations (BA and US) of the Pilmatué Member (Fig. 9) allowed reconstruction of the dominant processes and depositional conditions within a siliciclastic-dominated mixed system (Fig. 12A). This system is characterized by a shoreface–basin profile composed of five zones, and is mainly dominated by storm weather and fair-weather wave processes. The basinal setting was characterized by continuous sedimentation of siliciclastic and carbonate mud and by the lack of significant sea floor colonization and/or bioturbation. The latter suggests that reduced oxygen levels at the water–sediment interface and/or lack of nutrients (Fürsich, 1995; Spalletti et al., 2001) were the likely controlling factors inhibiting the development of endobenthic communities. Shoreward, in the offshore setting (Fig. 12A), siliciclastic sedimentation prevailed onto a relatively well-oxygenated sea floor, where bivalves, arthropods and other benthic fauna were able to develop. The fine-grained sediment in this setting could have derived from settling, but its
Variability of carbonate–siliciclastic systems

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origin could be also related to mud resuspension and the generation of wave-supported sediment gravity flows, a sediment-dispersal process recently recorded in modern shelf systems (Hill et al., 2007; Parson et al., 2007) and described in theoretical studies (Kämpf & Myrow, 2014). In this case, mud resuspension for the Pilmatué system could have occurred associated with the passage of major storms recorded in the offshore-transition zone as discrete storm-event beds.

The offshore-transition setting was dominated by recurrent alternation of siliclastic mud and sand deposition. Sand was emplaced by combined flows or pure oscillatory flows that moulded the sea floor with large asymmetrical ripples and hummocks under relatively high velocities, and small ripples when flows where less energetic or original flows were waning. This zone was intensely colonized by endobenthic communities producing, in many cases, a complete homogenization of the original heterolithic deposits.

In the lower shoreface setting, the sandy sea floor was mainly mobilized by onshore shoaling waves that produced symmetrical to slightly asymmetrical ripples. These conditions were episodically interrupted by storm-related, combined underflows that generated large asymmetrical ripples and hummocks, as well as plane bed conditions (Dumas et al., 2005; Perillo et al., 2014). Both fair-weather and storm deposits were largely affected by organisms of a Skolithos ichnofacies assemblage, suggesting that processes that commonly produce benthic environmental stress, such as high sedimentation rates, turbidity, reduced oxygenation and/or salinity changes (MacEachern et al., 2007b), were not common in this part of the system.

The development and migration of dunes was common in the upper shoreface area, the most landward setting recorded in this depositional model. These dunes probably migrated at a low angle with respect to the reconstructed shoreline orientation (for example, to the north-east for an east–west shoreline), suggesting a significant control of longshore currents and the generation of bar-trough systems in this region (Fig. 12A). Littoral drift was probably responsible for the supply of the siliciclastic sand and subordinate pebbles (see Discussion below). The upper shoreface was also an area where contemporaneous mixing of carbonate grains and terrigenous sand took place. Non-skeletal grains (i.e. ooids and aggregates) were probably produced in this region due to high carbonate saturation state and high-energy conditions, as in modern carbonate-dominated ramps and shelves (Gischler & Lomando, 2005; Rankey, 2014) and mixed settings (Michel et al., 2011). However, processes responsible for cross-shelf transport were in general unable to shed siliciclastic and carbonate medium-grained sand (or larger particles) off of the upper shoreface and were consequently stored in that part of the system (Fig. 12A).

Transgressive conditions favoured the formation of extensive shell beds (Fig. 9) that developed on the underlying regressive deposits (Fig. 12B). An exception is sediment in the basin areas that was never susceptible for benthic colonization; the rest of the sea floor region that was already below fair-weather wave base at the onset of transgression was colonized by bivalve-dominated communities (offshore shell beds). Conversely, the zones that were above fair-weather wave base at the time of transgression underwent erosion and concentration of gravel-size and sand-size material due to wave reworking and ravinement (Nummedal & Swift, 1987; Swift et al., 1991), and high-energy conditions produced well-sorted cross-bedded carbonates (shoreface shell beds; Fig. 12B). Finally, intermediate regions of this carbonate-dominated mixed system favoured the formation of shelly substrates (with variable proportions of lime mud and benthic colonization) in which the passage of storm surges moulded large symmetrical ripples that were occasionally preserved as transgression progressed. Because this contribution focuses on the siliciclastic-dominated mixed depositional system developed during regressive conditions, this transgressive carbonate-dominated system will not be discussed further.

Spatial facies distribution

Coeval sedimentation of carbonate and siliciclastic components in different zones of the regressive part of the Pilmatué depositional system resulted in the development of a mixed, but siliciclastic-rich, storm-dominated environment characterized by three distinctive zones: (i) a mixed distal zone (BA facies association); (ii) a middle siliciclastic zone (OF to LS facies associations); and (iii) a mixed proximal zone (US facies association; Fig. 12A). Moreover, detailed characterization of the facies associations distributions and lateral transitions (Fig. 9) indicates that these zones were individual facies belts that
Table 2. Key attributes recognized in the Pilmatué Member parasequences. The number of bedsets typically varies from proximal to distal settings and is shown as a range in the corresponding column. Grey cells indicate no available data; number in italics represents minimum values. TS: transgressive surface; US dunes: upper shoreface dunes; WA: wave approach; SRNSB: storm-reworked nearshore sandstone belt during maximum regression, a parameter defined by Hampson (2010) that combines LS and OT facies belts.

| No. | PS  | Capping TS | Mean thickness (m) | Facies associations | Number of bedsets | Wave approach and longitudinal currents | Migration direction | Facies-belt width at maximum regression |
|-----|-----|------------|-------------------|--------------------|------------------|----------------------------------------|-------------------|----------------------------------------|
| 1   | PS240 | 240 | 53 | BA, OF, OT | 6 | NE | 4 | 12 | 8 |
| 2   | PS250 | 250 | 43 | BA, OF, OT, LS, US | 3 | US dunes to SW | N | 5 | 2 | 2.5 | 10 | 5 | 4.5 |
| 3   | PS260 | 260 | 22 | (SSB, OFSB), BA, OF, OT | 3 | NE | 4 | 8 | 12 |
| 4   | PS270 | 270 | 16 | BA, OF, OT | 2 | N | 5 | 7 | 12 |
| 5   | PS280 | 280 | 32 | (OFSB), BA, OF, OT | 2 | N | 5 | 8 | 11 |
| 6   | PS290 | 290 | 22 | (OFSB), BA, OF, OT, LS, US | 3-2 | WA from NNW | N | 3.5 | 2 | 3 | 8.5 | 7 | 5 |
| 7   | PS300 | 300 | 46 | (OFSB), BA, OF, OT, LS, US | 4 | WA from NNW, US dunes to NE | WA from NW | N | 16 | 2 | 3 | 3.5 | 5 |
| 8   | PS310t | N/A | 1 | SSB, OF, OT, LS | 1 | WA from NW | WA from NW | N | 5 | 2 | 17 | 7 |
| 9   | PS325 | 325 | 1 | SSB, OF, OT, LS | 1 | | | | | | | |
| 10  | PS340 | 340 | 24 | OFSB, OF, OT, LS | 4-2 | WA from N | N | 4 | 6 | 12 | 10 |
| 11  | PS350 | 350 | 14 | SSB, OFSB, OF, OT, LS | 2 | WA from N | N | 4 | 1.5 | 6 | 10 | 7.5 |
| 12  | PS360 | 360 | 16 | SSB, OFSB, OF, OT, LS, US | 3 | WA from N | N | 4 | 2 | 4 | 12 | 6 |
| 13  | PS380 | 380 | 14 | SSB, OFSB, OF, OT, LS, US | 4-2 | US dunes to NE | NE | 4 | 2 | 4 | 12 | 6 |
| 14  | PS400 | 400 | 32 | SSB, OFSB, OF, OT, LS, US | 5-2 | WA from NNW | N | 13 | 2 | 3 | 6 | 5 |
| 15  | PS420 | 420 | 10 | SSB, OFSB, OF, OT, LS, US | 2-1 | WA from SW | W | | | | | |
| 16  | PS500 | 500 | 48 | OFSB, OF, OT, LS | 1 | WA from SW | W | 2.5 | 3 | 6 | 5.5 |
| 17  | PS520t | N/A | 23 | OFSB, OF, OT, LS | 4-1 | WA from SW, US dunes to NE | W | | | | | |
were roughly parallel to one another and to the inferred coastline (Fig. 13).

In order to refine the reconstruction of this siliciclastic-dominated mixed system, the width of individual belts was quantified wherever possible (Table 2), by using the up-dip and down-dip pinchouts of individual facies associations at the time of maximum regression, combined with the reconstructed shoreline orientation for each parasequence (Fig. 13). The width of the lower shoreface facies belt varied from 2 to 5 km, whereas the offshore-transition facies-belt width ranged from 2 to 6 km. The combination of these two facies belts (LS and OT) has been defined as the ‘storm-reworked nearshore sandstone belt during maximum regression’ for pure siliciclastic systems (Hampson, 2010; Hampson et al., 2011). It is possible to estimate the width of this belt for seven parasequences within the study interval (Table 2). The storm-reworked nearshore sandstone belt was ca 5 km wide in the lower stratigraphic interval (PS240 to PS300) but increased to 6 to 10 km wide in genetic units of the upper stratigraphic interval (PS340 to PS380). The OF facies belt recorded a similar vertical pattern. It ranges from 7 to 12 km wide in the PS240 to PS290 interval (Table 2), but expanded significantly in the PS340 to PS380 interval, having a minimum width that varied from 10 to 17 km among successive parasequences (Fig. 13).

**Shoreline orientation and migration**

The overall northward progradation of the Pilmatué Member within the study area (Fig. 4) can be refined using the detailed mapping of individual parasequences (Figs 9 and 10), together with the palaeocurrent analysis for each of those units (Table 2). Integration of these data suggests that the migration direction of the shoreline varied through time (Fig. 13). North-eastward progradation direction is reconstructed for PS240, PS260 and PS380, whereas north-oriented progradation is inferred for most of the parasequences (Fig. 13; Table 2). A significant change occurred in the uppermost interval (PS420, PS500 and PS520). The data suggest that progradation took place mostly from east to west during the development of these parasequences (Figs 4 and 10C), and that only the eastern sector of the study area was located in shoreface conditions (PS500 in Fig. 13).

Within parasequences, the up-dip and down-dip pinchouts of US deposits have been used in previous studies as respective proxies for the initial and final position of the shoreline during progradation (Hampson, 2010; Hampson et al., 2011). The width of the preserved facies belt is therefore an estimation of seaward migration of the shoreline. In this study, the down-dip pinchout of US facies is recorded in six parasequences, but the up-dip pinchout is not

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**Fig. 11.** (A) Internal architecture of parasequences, which are commonly formed by metre thick bedsets. In this example, bounding surfaces (white lines) are typically non-depositional discontinuities representing a minor shift in depositional conditions. (B) and (C) bounding surfaces occasionally demarcated by thin concentration of shells. Persons for scale are ca 1·8 m tall. Lens cap is 4·5 cm in diameter.

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observed in any of them due to the lack of exposure (or preservation) of coeval coastal plain deposits. Therefore, in this case, the width of the US facies belt is an indication of the minimum value of shoreline progradation (Table 2). The facies belt reaches a maximum width in PS300 and PS400, suggesting a minimum progradation in the order of 16 km and 13 km, respectively (Figs 9 and 13). For the other four parasequences, a minimum progradation of 3 to 6 km has been estimated (Table 2). In the same way, considering the estimated width of different facies belts (Fig. 13; Table 2), transgressive surfaces topping PS250, PS300 and PS400 suggest significant landward displacement of the shoreline, in the order of 10 km for PS250 (Fig. 9), to more than 20 km for PS325.

**DISCUSSION**

**Variability and controls of mixed carbonate–siliciclastic systems**

Mixed carbonate–siliciclastic systems have been documented from shallow-marine shelves through most of the Phanerozoic (Table 3). Their configuration and evolution depended heavily on the processes responsible for producing and depositing different types of carbonate grains (i.e. skeletal and non-skeletal), as well as the processes supplying siliciclastic sand and mud to the basins (Coffey & Sunde, 2014; Zeller et al., 2015; Labaj & Pratt, 2016; Schwarz et al., 2016b). Although a wide variety of depositional models (Table 3) and resulting stratigraphic patterns are described for these mixed systems, few published examples have explored the attributes and controls of siliciclastic-dominated mixed systems in which the contribution from non-skeletal carbonates is dominant.

A distinctive feature of the depositional system reconstructed for the Pilmatué Member is the high proportion of non-skeletal (i.e. ooids) grains in the upper shoreface facies belt (Figs 12A and 13). A literature review shows that carbonate-dominated mixed systems are common, but ooid contribution to the carbonate factory is rare (Table 3). Even less common are examples in which ooids were formed and deposited within a siliciclastic-dominated system (Coffey & Sunde, 2014; in Table 3). The modern northern coast of Kuwait (western coast of the Arabian Gulf) has been described as a mixed, siliciclastic
dominated marine system (Gischler & Lomando, 2005) which is greatly influenced by the siliciclastic input from the Euphrates and Tigris rivers. However, the terrigenous contribution decreases rapidly southward, and most of the coast of Kuwait becomes a carbonate-dominated system with a high proportion of ooids being generated in the high-energy inner ramp (Gischler & Lomando, 2005; see Table 3). Another example is located in north-western Africa, where Michel et al. (2011) reported the formation of aragonite ooids in isolated bays along the coast of Mauritania, which are mixed in shallow waters (<20 m) with aeolian-derived siliciclastic material and skeletal fragments. Hydrodynamic studies on how the sediment is being mixed in this marine environment, and resulting facies belts patterns, are not available.

In any case, it is worth noting that these two examples of siliciclastic-dominated mixed systems are developed in shallow seas associated with arid continental conditions, where river discharge and sediment supply are associated with isolated entry points, leaving tens to hundreds of kilometres of the remaining shoreline without direct sediment input. Because the Neuquén Basin was a shallow epeiric sea (Howell et al., 2005) located in an arid climate belt during the Early Cretaceous (Scotese, 2000), it is plausible that these conditions could have favoured the development of a similar siliciclastic-dominated, mixed system, away from the major source of siliciclastic supply to the basin. The non-skeletal carbonate production (i.e. ooid formation) could have been aided by the arid climate and the greenhouse conditions that prevailed during the Hauterivian (Föllmi, 2012). In this context, the lack of studies reporting modern mixed systems similar to that inferred for the Pilmatué Member (Table 3) could be due to a bias towards the study of mixed, but carbonate-dominated systems, or a result of the low occurrence of these systems at present.

Siliciclastic-dominated mixed systems versus pure siliciclastic systems

Except for the concurrent contribution of ooids and siliciclastic sand to the upper shoreface, the dominant depositional processes and facies belts reconstructed for the siliciclastic-dominated mixed system of the Pilmatué Member (Figs 12A and 13) do not differ from well-known, shoreface to shelf depositional systems developed in pure siliciclastic marine systems (Walker & Plint, 1992; Reading & Collinson, 1996). Both systems are characterized by storm and fair-weather related transport and deposition, and by the formation of facies belts that are mainly parallel to the shoreline. As a consequence, high-frequency sequences in the Pilmatué Member, and the inferred short-term evolution of shoreline migration (Figs 9 and 13; Table 2), are also markedly similar to the parasequences developed in purely siliciclastic systems (Walker & Plint, 1992; Reading & Collinson, 1996; Hampson & Storms, 2003). Bedsets, a main component of parasequences in siliciclastic systems (Van Wagoner et al., 1990; Hampson, 2000; Hampson et al., 2011; Zecchin et al., 2017), are also common in the siliciclastic-dominated, mixed system reconstructed in this study (Figs 9 and 12A).

The large-scale palaeogeographic scenario reconstructed for the siliciclastic-dominated, mixed system of the Pilmatué Member can also be compared with pure siliciclastic-dominated systems. Due to the arid conditions, large extensions of the shoreline provided little volume of terrigenous sand via direct fluvial entry points, but relatively large and coeval deltaic systems have been reported recently from subsurface data (Schwarz et al., 2016c), located to the south of the study area (Fig. 14). Thus, it is inferred that most of the siliciclastic sand that was deposited in the Pilmatué shoreface system was sourced by littoral drift from these deltas, associated with major fluvial systems. This hypothesis is also supported by the predominant north-east directed longshore palaeocurrents identified for several parasequences (Fig 13; Table 2). This reconstruction of the Pilmatué Member is analogous to several modern examples in which longshore sand drift provides siliciclastic sediment to form strandplains and barriers in a down-drift direction (Curray et al., 1969; Anthony & Blivi, 1999). It is also similar to that generated for an ancient pure siliciclastic example (Ksp40-Panther Tongue of Hampson et al., 2011). Thus, it is reasonable to suggest that long-term evolution and, ultimately, controls on stratigraphic architecture could be similar in both shoreface–shelf pure siliciclastic systems and the siliciclastic-dominated end of mixed systems. For example, the change in local palaeogeography and shoreline migration that is recorded in the uppermost parasequences (rotation of 90° from an east–west orientation to a more north–south orientation; see PS500 in
Fig. 13) could be described as a large-scale rotational event, as recently reported for some nearshore Cretaceous successions (Madof et al., 2015). This shoreline rotation event, as in pure siliciclastic systems, could have been triggered by different mechanisms such as tectonic forcing, changes in the overall sand volume supplied by deltaic systems to the basin and/or the transport efficiency of the existent littoral drift (Fig. 14).
One basin, one climate regime, different types of mixed systems

Examples of ancient mixed carbonate–siliciclastic systems include both icehouse and greenhouse climatic regimes (Table 3). Even within one climatic mode, mixed systems can be highly variable, especially if factors such as siliciclastic transport processes and carbonate factories vary in space and time (Table 3). The Neuquén Basin, which includes Upper Jurassic to Lower Cretaceous mixed carbonate–siliciclastic successions, provides an opportunity to explore the wide range of mixed systems that can be generated within a single basin and under relatively uniform climatic conditions.

Mixed carbonate–siliciclastic systems in the Neuquén Basin have been recognized for many years (Groeber, 1946; Legarreta & Uliana, 1991; Spalletti et al., 2000, 2001), but few studies have attempted to reconstruct them in detail across their depositional dip. Recently, Zeller et al. (2015) reviewed the depositional conditions and controls of the Tithonian–Berriasian mixed depositional system (Vaca Muerta–Pucn Leufú–Quintuco system). These authors concluded that during progradation (i.e. highstand), this gently inclined shelf was a mixed system, with a prevailing carbonate factory in the inner shelf providing ooids and skeletal fragments to form pure carbonate (Fig. 15A). High-energy, ooid-rich bodies were mostly detached from the shoreline and probably deposited under tide-related currents. In the outer shelf and gentle slope, along-shelf currents were responsible for bringing terrigenous silt and very fine sand from remote regions, producing mixed facies belts. However, because these currents were of low efficiency during highstand conditions due to the relative low depth for them to operate (Zeller et al., 2015), siliciclastic supply was comparatively low at that time and a mixed, but carbonate-dominated, system developed (Fig. 15A). Additionally, Zeller et al. (2015) suggested that terrigenous supply to the system was higher during lowstand and transgressive intervals due to more efficient distribution of along-shelf currents, which resulted in genetic units (high-frequency cycles and sequences) with siliciclastic-dominated, lowstand and transgressive sediments (Fig. 15A).

In marked contrast, the shallow-marine system of the Pilmatué Member was mixed, but siliciclastic-dominated during regressive conditions (Fig. 15B). High-energy, mixed deposits were attached to the shoreline and resulted from the mixing of siliciclastic sediment supplied mostly by littoral drift (from the south; Fig. 14), and biogenic and non-biogenic carbonate production. Furthermore, the inability of storm-surge flows to export relatively coarse carbonate offshore produced siliciclastic facies belts in the middle zone of the system (Fig. 15B). The upper intervals of parasequences reported in this study are enriched in high-energy mixed sediments, but only if upper shoreface deposits are present. Therefore, the presence of mixed facies is dependent on the facies-belt distribution and cannot be related to temporal changes in the efficiency of along-shelf currents to supply terrigenous sediment to the system, as proposed by Zeller et al. (2015) for the Tithonian–Berriasian system. Moreover, the basal intervals of parasequences in the Pilmatué Member are associated with maximum carbonate concentration and shell-bed generation, and these are interpreted to be related to sediment starvation during shoreline transgression (Fig. 15B). As a result, the sequential architecture of genetic units in each case is markedly different.

This comparison highlights the complexity that mixed systems, even within the same basin and with similar climate regime, can produce (Fig. 15). The general proportion of carbonate production with respect to siliciclastic supply, combined with dominant marine transport processes (for example, along-shelf currents, storm-related cross-shelf flows and longshore currents) can create a variety of mixed systems, ranging from carbonate-dominated to siliciclastic-dominated (Table 3).

Reservoir implications

The present study, by expanding the spectrum of mixed systems towards the siliciclastic-dominated end, provides new insights for conventional and unconventional hydrocarbon exploration in these highly complex systems. This can be especially significant for the prediction on composition, geometry and location of high-energy facies in conventional exploration, as well as the composition of the distal fine-grained rocks in an unconventional reservoir.

Oolitic–skeletal bodies in carbonate-dominated mixed systems, such as that reconstructed in
Table 3. Case studies of mixed carbonate–siliciclastic systems, ordered from the carbonate-dominated end (top) to the siliciclastic-dominated end (bottom) of the expected spectrum (this work). For those case studies where different mixed regressive and transgressive systems are reported (Coffey & Sunde, 2014), only the regressive system is considered for comparison. Location, age, climate regime, depositional setting, source of siliciclastic sediments, dominant carbonate factory and cross-shelf transport are provided in each case, together with a schematic reconstruction of the depositional system.

| CASE STUDY | LOCATION | AGE | CLIMATE/CLIMATE REGIME | DEPOSITIONAL SETTING | SOURCE OF SILICICLASTICS | CARBONATE FACTORY | CROSS-SHELF TRANSPORT | FACIES BELT COMPOSITION | SCHEMATIC RECONSTRUCTION OF MIXED SYSTEM |
|------------|----------|-----|------------------------|----------------------|-------------------------|-------------------|---------------------|------------------------|----------------------------------------|
| Gui scher & Lomando (2005) | NW Persian Gulf, Kuwait | Holocene | Tropical & Arid/Icehouse | Ramp, Interior Sea | Aeolian + Longshore currents | Heterozoan + Ooids | Wave energy, storm-related currents | Inner Ramp: M/C Middle and Outer Ramp: C Basin: M | ![Reconstruction](image1.png) |
| Zeller et al. (2015) | Neuquén Basin, Argentina | Late Jurassic–Early Cret. | Temperate & Arid/Greenhouse | Gentle shelf, Epeiric sea | Along-shelf currents | Heterozoan + Ooids | Tidal/Shelf-related currents | Nearshore and Inner Shelf: C Middle and Outer Shelf: S | ![Reconstruction](image2.png) |
| Sanders & Höfling (2000) | Northern Calcareous Alps, Austria | Late Cretaceous | Tropical & Temperate/Greenhouse | Shelf | Along-shelf currents | Heterozoan + Photozoan | Limited | Nearshore: C Middle Shelf: M Middle Shelf to Outer Shelf: S | ![Reconstruction](image3.png) |
| Purdy & Gischler (2003) | Barrier Reef, Belize | Holocene | Tropical & Semi-arid/Icehouse | Shelf | Local fluvial entry points | Photozoan | Limited | Nearshore: S/M Lagoon: M Lagoon to Reef Barrier: C | ![Reconstruction](image4.png) |
| Coffey & Read (2007) | Albermarle Basin, USA | Palaeogene | Tropical & Temperate/Icehouse | Distally steepened ramp | Local fluvial entry points | Heterozoan | Storm-related currents | Nearshore: S/M Inner Shelf: C Outer Shelf: C/M | ![Reconstruction](image5.png) |
| Labaj & Pratt (2016) | South-Central Arizona, USA | Middle-Late Cambrian | Equatorial & Humid/Icehouse | Ramp, Epeiric sea | N/A | Heterozoan + Ooids | Storm-related currents | Nearshore: S Offshore-Transition: C Offshore: M | ![Reconstruction](image6.png) |
| ‘Agostini et al. (2015) | Abrolhos Shelf, Brazil | Pleistocene-Holocene | Tropical/Icehouse | Shelf | Local fluvial entry points + Longshore currents | Photozoan + Heterozoan | N/A | Inner Shelf: S Middle Shelf: M Outer Shelf: C | ![Reconstruction](image7.png) |
| Coffey & Sunde (2014) | Albermarle Basin, USA | Early Cretaceous | Tropical & Humid/Icehouse | Shelf | Local fluvial entry points + Longshore currents | Heterozoan + Ooids | Storm-related currents | Nearshore: S Offshore-Transition: M Offshore: S Basin: M | ![Reconstruction](image8.png) |
| This work | Neuquén Basin, Argentina | Early Cretaceous | Temperate & Arid/Greenhouse | Ramp, Epeiric sea | Longshore currents | Ooids + Heterozoan | Storm-related currents | US: M LS+OT+OF: S Basin: M | ![Reconstruction](image9.png) |
Fig. 15A, would have an elongated geometry oriented parallel to prevailing tidal currents. These bodies would be developed in shelf regions detached from the coeval shoreline and surrounded by non-reservoir muddier facies. In marked contrast, similar facies in the Pilmatué Member would conform wedge-shape bodies located near the shoreline and oriented parallel to it (i.e. mixed upper shoreface deposits in Fig. 15B). Internal (depositional) heterogeneity would be comparatively low, and these bodies would pass laterally into pure siliciclastic lower shoreface sandstones.

Fine-grained sediments in distal sectors of mixed systems can result from combination of carbonates (both biogenic and exported) and fine-grained siliciclastics brought by along-shelf currents (Fig. 15A). In that situation, a lateral trend characterized by an increment of carbonate contribution towards the proximal part of the system would be expected. Conversely, in mixed systems where fine-grained siliciclastics are transported distally by across shelf processes (Fig. 15B), the carbonate contribution would increase towards the distal most part of the system. Because the mineralogy of mudstone rocks exerts a strong control in several processes, such as organic matter conversion, expulsion of hydrocarbons, petrophysical properties and geomechanical attributes of unconventional reservoirs (Patterson & Henstridge, 1990; Patterson et al., 1990), understanding the composition of the fine-grained rocks in distal sectors of a mixed system and the expected lateral trends could be key results to predict lateral variability of reservoir properties in analogous unconventional reservoirs.
Conclusions

Based on the detailed sedimentological analysis of the early Hauterivian interval of the Pilmatué Member in a 25 km long and 300 m thick outcrop, the following conclusions are drawn:

1. A storm-dominated, shoreface–basinal depositional system comprising three parallel zones was developed during progradation: (i) a mixed distal zone (basin facies association); (ii) a middle siliciclastic zone (offshore to lower shoreface facies associations); and (iii) a mixed proximal siliciclastic–carbonate system.

Fig. 15. Contrasting regressive shallow-marine mixed systems. (A) Carbonate-dominated mixed system based on the Tithonian–Berriasian succession of the Neuquén Basin (after Zeller et al., 2015). (B) Siliciclastic-dominated mixed system reconstructed for the Pilmatué Member in this study. Distribution of pure siliciclastic, mixed and/or pure carbonate facies belts varies between systems, resulting in different sequence architecture of stratigraphic units. Note the different horizontal scale between systems. Coastal plain deposits are inferred in both examples. Colour of siliciclastic, mixed and carbonate sediments used in genetic units as in Table 3. Legend: WSSGF – wave-supported sediment gravity flows; TST – transgressive systems tract; LST – lowstand systems tract; SB – sequence boundary; TS – transgressive surface.
systems across the full carbonate epeiric sea, might help development of mixed and regional palaeogeographic scenarios.

2 In this siliciclastic-dominated mixed system, terrigenous sediment was mostly supplied via along-shore currents to the upper shoreface (probably from deltaic systems located to the south), where they mixed with ooids and bioclasts derived from a heterozoan factory. Storm-surge flows were the major mechanisms for across shelf transport, exporting fine sand and mud offshore. Terrigenous and carbonate medium-grained (and coarser) sediments were stored in the upper shoreface. The distal zone received low volumes of siliciclastics, which mixed with planktonic-derived carbonate material.

3 Seventeen parasequences (10 to 50 m thick) bounded by transgressive surfaces and composed of two to six beds (5 to 10 m thick) were identified in the study interval. Each parasequence represents up to 16 km of preferentially northward or north-eastward shoreline progradation, but with a significant change to westward progradation in the uppermost three parasequences. Landward migration of the shoreline during transgression favoured the formation of extensive shell beds associated with shoreface erosion and lag generation, as well as offshore condensation. Landward displacement of up to 20 km was estimated.

4 The inferred depositional model and resulting genetic units of the Pilmatué Member siliciclastic-dominated mixed system are markedly different from most carbonate-dominated mixed systems, even for examples developed in the same basin and under a similar climate regime.

5 Conversely, this siliciclastic-dominated mixed system resembles the storm-influenced and wave-influenced siliciclastic counterpart in several attributes, such as depositional processes, internal architecture of parasequences and regional palaeogeographic scenarios.

6 Basin-scale controls, such as arid climatic conditions and the development of a shallow epeiric sea, might help development of mixed systems across the full carbonate–siliciclastic spectrum. The interplay of processes that supply sand to the system, as well as processes transporting sediment offshore across the marine environment, are key controls in shaping the facies distribution and the genetic units of siliciclastic-dominated mixed systems.

7 Reservoir characteristics (geometry, distribution, heterogeneities, etc.) of conventional and unconventional facies would be strongly dependent on the type of mixed carbonate–siliciclastic system. In the regressive Pilmatué Member, proximal high-energy, mixed facies are subparallel and attached to the coeval shoreline, whereas distal fine-grained facies show a seaward increment in carbonate contribution.

ACKNOWLEDGEMENTS

The authors would like to thank CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas), Universidad Nacional de La Plata and YPF S.A. for financial support of this project. José Luis Burini and Agustín Argüello are thanked for field and laboratory assistance. The manuscript benefitted from constructive reviews by C. Di Celma, J. Kosse, P. Myrow and S. A. Abott, as well as additional comments by Associate Editor C. Fielding.

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