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Facies characterization and sequential evolution of an ancient offshore dunefield in a semi-enclosed sea: Neuquén Basin, Argentina

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Abstract This study analyses a 30-m-thick, sand-dominated succession intercalated between offshore mudstones in the Lower Cretaceous record of the Neuquén Basin, Argentina, defining facies associated with unidirectional currents as sand dunes (simple and compound), rippled sand sheets and heterolithic sheets. These facies associations are related to the development of an offshore, forward-accreting dunefield developed as a response to the onset of a tidal-transport system. The reported stratigraphic record results from the combination of the gradual downcurrent decrease of the current speed together with the long-term climbing of the entire system. Maximum amplification of the tidal effect associated with incoming oceanic tides to this epicontinental sea would develop at the time of more efficient connection between the basin and the open ocean. Thus, the onset of the offshore tidal system approximately corresponds to the time of maximum flooding conditions (or immediately after). The short-term evolution of the tidal-transport system is more complex and characterized by the vertical stacking of small-scale cycles defined by the alternation of episodes of construction and destruction of the dunefield. The development of these cycles could be the response to changes in tidal current speed and transport capacity.

Introduction

Tidal offshore deposits have been widely described and debated in the literature both in modern (e.g. McCave and Langhorne 1982; Belderson et al. 1982; Berné et al. 1988; Harris et al. 1995; Bassetti et al. 2006) and ancient examples (e.g. Anderton 1976; Levell 1980; Anastas et al. 1997; Olariu et al. 2012; Reynaud et al. 2013). Most of the discussion has focused on the development of large-scale bar systems (tidal ridges or sandbanks) and their sequence stratigraphic significance (e.g. Snedden and Dalrymple 1999; Berné et al. 2002; Posamentier 2002; Schwarz 2012) and, therefore, depositional models for dune systems (dunefields) are much less common (e.g. Berné et al. 1988; Anastas et al. 1997; Olariu et al. 2012). Additionally, published depositional models for dunefield systems mostly concentrate on examples associated with narrow seaways or straits, some of them of tectonic origin (e.g. Anastas et al. 1997; Reynaud et al. 2013), and this configuration is commonly considered a pre-requisite for the development of tidal currents strong enough to establish a tidally dominated transport and depositional system. Therefore, a detailed facies study on late Valanginian deposits of the Pilmatué Member in the Neuquén Basin of Argentina, which characterizes facies arrangement and distribution of tidal dunefield systems within a semi-enclosed epeiric sea with minimum relief in the offshore, poses a challenge because the development of tidal currents must be related to oceanic circulation and its connection with the inland sea, rather than to local topographic factors.

Notwithstanding recent advances in facies models for dunefield systems and facies sequences associated with their long-term evolution (Anastas et al. 2006; Reynaud and Dalrymple 2012), little attention has been placed on the detailed stratigraphic evolution of these offshore systems. High-frequency changes in tidal current speed or sand supply may

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result in a complex stratigraphic architecture that departs from simplistic models associated with the long-term downcurrent migration of a tidal-transport pathway. This is particularly important when considering that thick successions of sandy accumulations in offshore settings are prone to constituting important hydrocarbon reservoirs. The characterization of these reservoirs depends not only on the complex internal architecture generated by dune migration (Berné et al. 1988; Anastas et al. 1997; Olariu et al. 2012) but also on the development of stratigraphic surfaces related to the aggradation and migration of the whole system. Therefore, understanding the high-frequency evolution of these dunefield systems requires information not only on the characteristics of depositional models but also on the dynamics of intermediate-scale factors that ultimately control facies distribution and the development of internal bounding surfaces.

Particularly for the understanding of the evolution of the Neuquén Basin, the development of strong tidal currents in the offshore is rather uncommon during most of the Lower Cretaceous epeiric sea stage. Therefore, the succession represents an opportunity to explore the potential triggering mechanisms for the development of a tidal dunefield system after a second-order major flooding event of the basin in the late Valanginian. Within this context, the aims of this study are (1) to describe the facies distribution and stratigraphic evolution of this offshore tidal succession, (2) to reconstruct a depositional model and its long- and short-term evolution in a sequence stratigraphic context and (3) to discuss the implications of the development of this type of tidal offshore system for the palaeogeography of the basin.

Geological setting

The Neuquén Basin is a large Mesozoic basin located in west-central Argentina (Fig. 1a). The basin has a complex history but, during most of its Late Jurassic and Early Cretaceous history, it was situated in a back-arc setting associated with the active south-western margin of Gondwana (Howell et al. 2005). The basin is limited by cratonic areas to the NE and SW, and was partially connected to the proto-Pacific ocean through a series of gaps in the active volcanic arc (Fig. 1b). The Neuquén Basin was an epicontinental sea during most of this time (Howell et al. 2005), although the nature of the connection with the open ocean was very dynamic, especially during some relative sea-level drops associated with active tectonics both in the arc and within the basin (Vergani et al. 1995). During transgressive and highstand stages, relatively high sea levels allowed a complete connection with the proto-Pacific (Legarreta and Uliana 1991) and the development of a ramp system strongly influenced by waves and storms in the more marginal settings (Spalletti et al. 2001; Schwarz et al. 2006).

The Lower Cretaceous Agrio Formation clearly exemplifies the depositional record of this complex scenario in the central part of the Neuquén Basin (Spalletti et al. 2011). The unit is composed of three members. The lower Pilmatué Member and the upper Agua de la Mula Member are marine units that record basinal, offshore and shoreface conditions, and are dominated by dark mudstones and shales (with variable carbonate participation) in which shallowing-upward sequences (parasequences) record the transition to wave- and storm-dominated shoreface environments (Fig. 1c). The middle Avilé Member is a non-marine unit that sharply overlies the Pilmatué Member and represents accumulation in fluvial, aeolian and lacustrine settings during a low-order lowstand stage (Veiga et al. 2011).

Study area

The Pilmatué Member of the Agrio Formation was investigated in the Cerro Mesa (or Table Hill) area located about 20 km to the northeast of the city of Zapala in the central Neuquén Province, western Argentina, easily accessible by provincial road 16 (Fig. 2a). Here, marine deposits of the basal Pilmatué Member are exposed across laterally continuous cliffs and ridges that allow the 3-D reconstruction of the sedimentary and stratigraphic architecture of the study interval (Fig. 2b).

The Pilmatué Member overlies continental and estuarine deposits of the Mulichinco Formation (Schwarz et al. 2006), representing a low-order basin-wide flooding of the depocentre (major transgressive surface, Schwarz et al. 2006; Figs. 1c, 2b, 3). The unit in this region is more than 400 m thick and largely dominated by offshore mudstones interbedded with thin shell concentrations (Fig. 3). Based on ammonite and bivalve biostratigraphy, the unit in this locality ranges from late Valanginian to early Hauterivian (Lazo et al. 2009; Fig. 3). Ammonites of the *Pseudofavrella angulatiformis* ammonoid zone and trigonioid bivalves belonging to the *Steinmanella pehuenmapuensis* zone occur in horizons near the basal transgressive surface (Lazo et al. 2009, 2012). In the middle of the section, shell accumulations comprise trigonids of the *Steimanella transitoria* zone together with ammonites belonging to the partially equivalent *Holcoptychites agrioensis* subzone, indicating the transition to the early Hauterivian (Lazo et al. 2009).

The study interval occurs about 40 m above the basal transgressive surface, and comprises an ~60-m-thick package composed of fine-grained sandstones and bioclastic medium- to coarse-grained sandstones. The best exposures of this package occur in the lower 30 m between two relatively thick fine-grained intervals, which is the focus of the present analysis (Fig. 3).

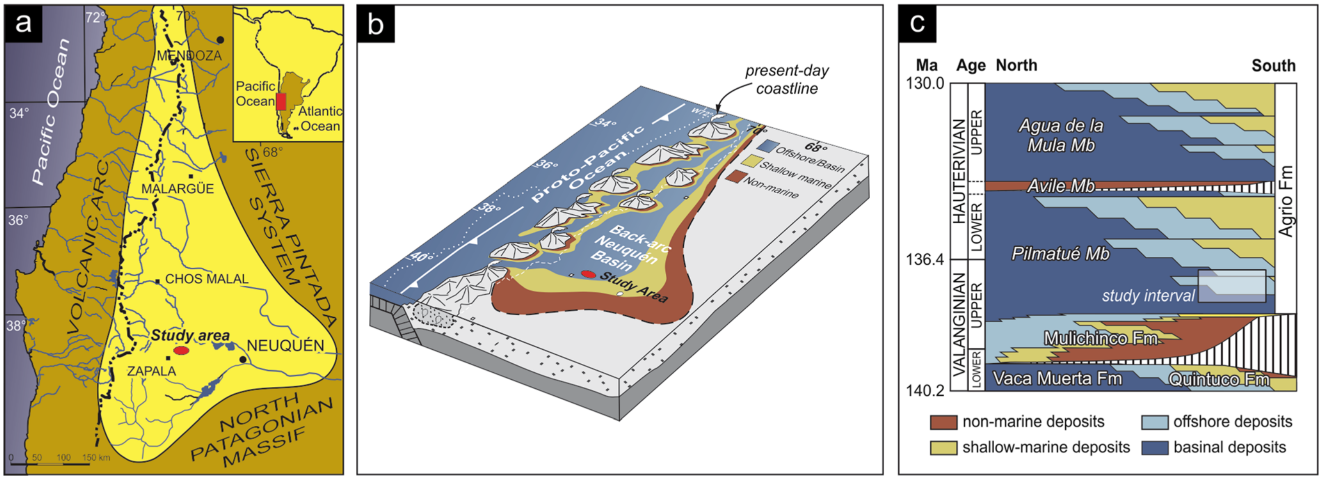

Fig. 1 **a** Location map of the Neuquén Basin, with study area (cf. Fig. 2). **b** Schematic geological setting of the Neuquén Basin during the Early Cretaceous (after Howell et al. 2005; Schwarz et al. 2006), when the basin was an epeiric sea partially connected to the proto-Pacific Ocean through gaps in the volcanic arc. **c** Chronostratigraphic chart for the late Tithonian–late Huaterivian of the Neuquén Basin (modified from Schwarz et al. 2006). The base of the Pilmatué Member of the Agrio Formation represents a major flooding of the basin

Methods

Twenty-one detailed sedimentological sections covering the entire study interval were measured in an area of approximately 6 km^2 (Fig. 2a). Sections spaced between 100 and 400 m were logged with conventional sedimentological methods, describing bed thickness, texture, sedimentary structures, trace fossils and invertebrate fauna. Bioturbation intensity was characterized using the bioturbation index (BI) defined by Taylor and Goldring (1993).

Main depositional surfaces and sandstone bodies were walked along the outcrop and correlated in the field. Together with photographic documentation, these served for correlation purposes as well as architectural analyses. Palaeocurrent measurements were taken from both horizontal and steeply dipping strata, and restored where necessary. Petrographical analyses of 20 thin sections were used to characterize the composition and texture of sandstones.

Results

Facies associations

Based on facies distribution, geometry and internal architecture, four facies associations were defined in the study interval (Fig. 4). These associations record the transition between low-energy environments dominated by fine-grained sediment settling and the influence of unidirectional currents with different energy and transport capacity.

FA1: offshore mudstones

Description Mudstones dominate most of the Pilmatué Member in this area; within the study interval, these deposits are characterized by gray to green mudstones massive to horizontally laminated in tabular beds <1 m thick (Fig. 4). These deposits show moulds of articulated bivalves that can be concentrated in layers of a few centimetres. Bioturbation is difficult to identify in these deposits, although massive intervals may have a higher degree of biological postdepositional modification.

Interpretation These deposits represent low-energy conditions and stable substrates in an offshore setting, where sediment accumulates by settling from suspension and without the influence of high-energy flows. The concentration of bivalve remains, without major fragmentation, also indicates low-energy conditions and periods of reduced sediment supply.

FA2: heterolithic sheets

Description These units are dominated by heterolithic deposits characterized by mm- to cm-thick coarse-grained siltstone or fine-grained sandstone layers that intercalate between greenish mudstones (Figs. 4, 5a). The proportion of mudstones (claystones and fine-grained siltstones) vs. coarse-grained siltstones/sandstones is highly variable. The finer-grained intervals are characterized by mm-thick, discontinuous layers of coarse silt that intercalate with laminated to massive mudstones, defining a very fine lamination. On the other hand, coarser-grained heterolithics show very fine-grained

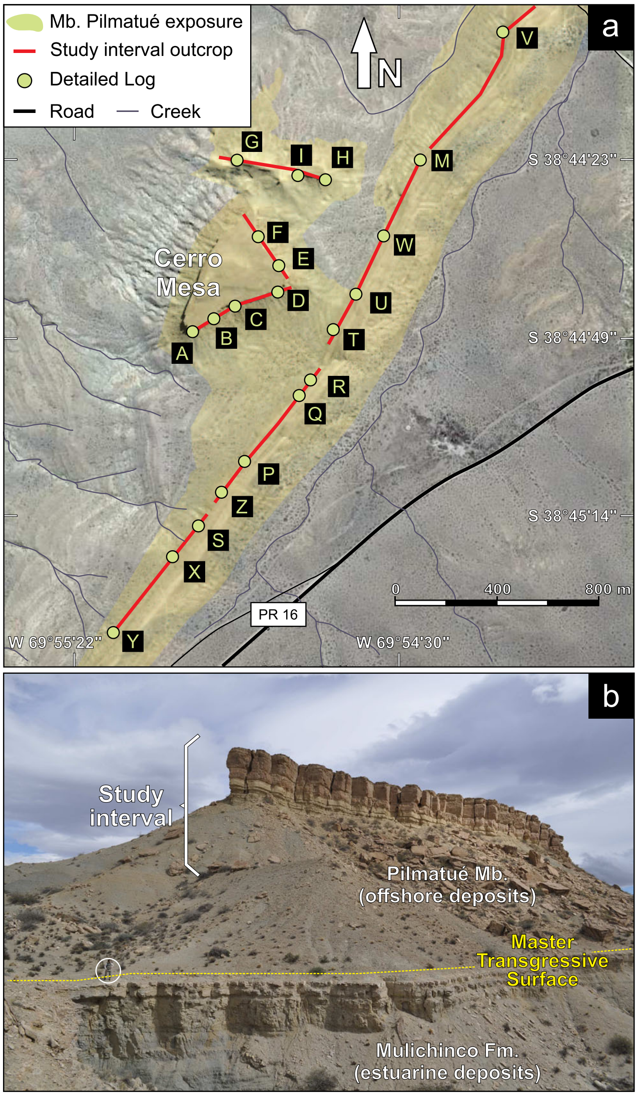

Fig. 2 **a** Satellite image of the study area showing the distribution of the Pilmatué Member exposures and the locations of the sedimentological sections in the study interval (Google Earth® image). **b** Field view of the study interval (*white circle* person for scale). The Pilmatué Member in this region begins with up to 30 m of offshore mudstones and thin shell beds that sharply overlie estuarine, sandstone-dominated deposits of the uppermost Mulichinco Formation

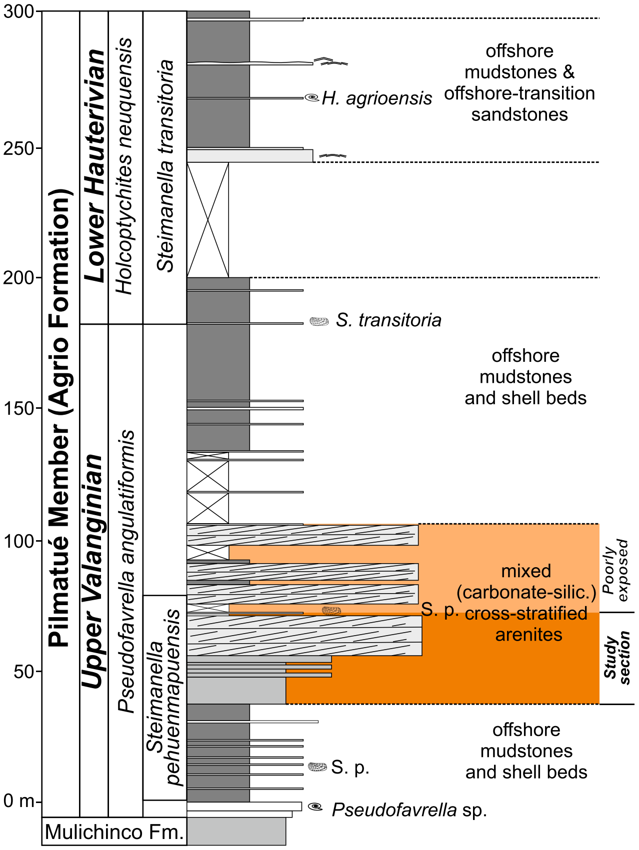

Fig. 3 Simplified stratigraphic section of the Pilmatué Member in the study area. Ammonite refined biostratigraphy is supplemented with bivalve biostratigraphy (Lazo et al. 2009). This paper focuses on a conspicuous sandy interval (60 m thick) characterized by oolitic-skeletal-siliciclastic sandstones occurring above a thick succession of offshore mudstones. The study section is represented by the lower 30 m of strata; the upper section is poorly exposed

sandstone beds in different proportions defining structures that range between lenticular and wavy/flaser bedding (Fig. 5a). Most of the sandstone beds are characterized by a single set of ripple cross-lamination and sometimes by preserved ripple tops. Bioturbation is important in these units and its intensity increases with sand proportion, grading from moderate to high (BI 3–6), sometimes completely obliterating the original structure to give rise to muddy sandstones (Fig. 5b). The trace fossil assemblage comprises *Chondrites*, *Gyrochorte*, *Palaeophycus*, *Planolites* and *Teichichnus*. These heterolithic deposits show thicknesses that vary between 0.4 and 1.3 m. However, they show important lateral continuity in the whole study area, reaching up to 2 km in a NE–SW direction. Thicker intervals may show a coarsening-upward succession, with lenticular/wavy heterolithics passing upwards into beds with flaser bedding and occasionally rippled sandstones. Thin beds (2–4 cm thick) of very fine-grained sandstones with horizontal and low-angle cross lamination occasionally occur intercalated between these heterolithic intervals. These beds are very discontinuous and usually show an erosional base with gutter casts.

Interpretation These deposits are interpreted to represent a relatively low-energy environment in which generation and migration of current ripples alternate with mud deposition from settling. Muddy seafloors were heavily bioturbated by a *Cruziana* ichnofacies suite, suggesting multiple colonization events by deposit feeders (Desjardins et al. 2012) associated with stable substrates. These observations suggest these conditions would represent the presence of discontinuous unidirectional currents below dune stability fields (Belderson et al. 1982; Dalrymple 2010). Coarsening-upward successions represent a gradual increase in the effect of unidirectional currents

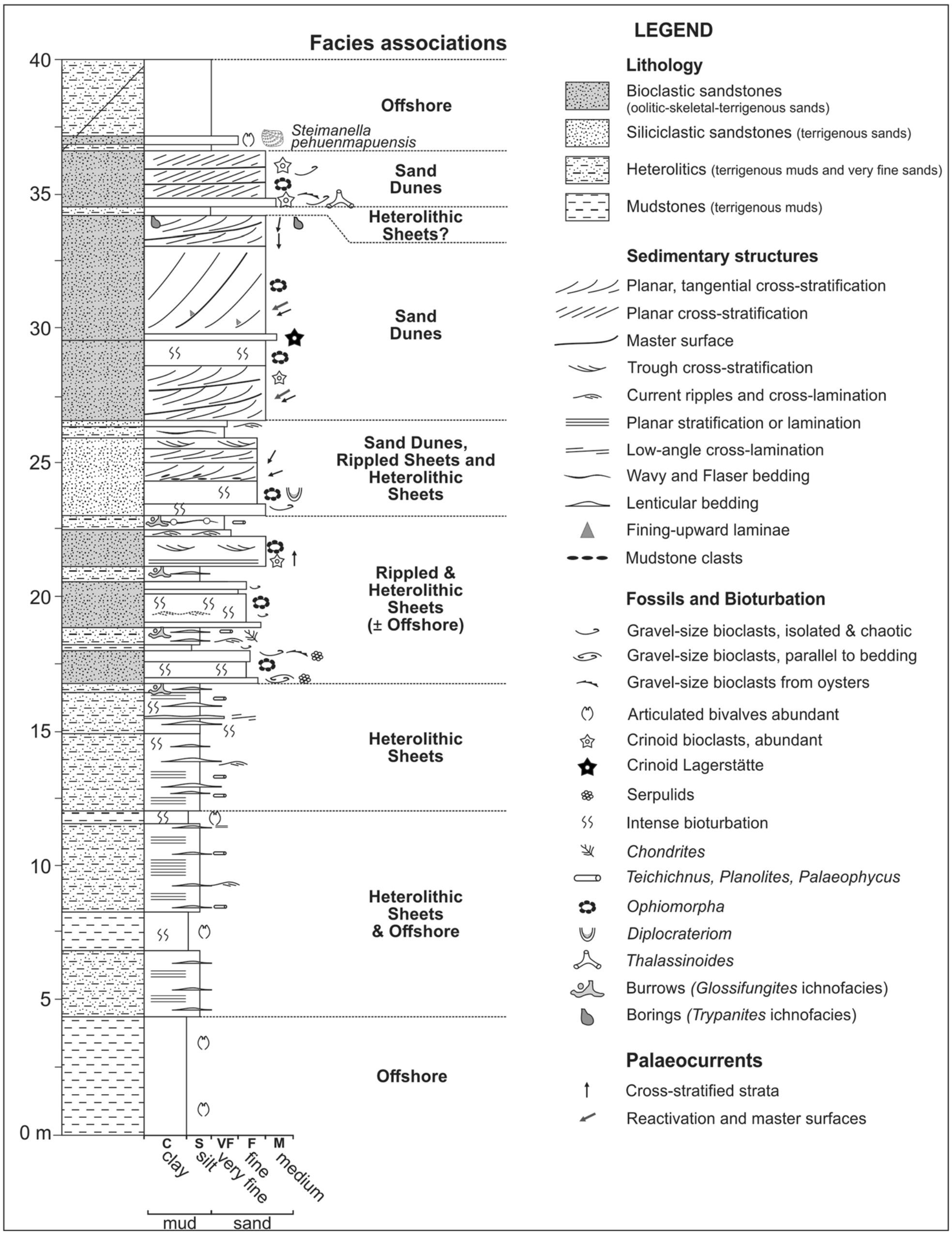

Fig. 4 Representative sedimentological section of the study interval with the facies associations described and interpreted in this study

in the substrate, and the transition to more sand-prone seafloors. Discrete episodes of erosion, immediately followed by deposition under upper-stage plane bed conditions, could be attributed to the infrequent passage of storm-related flows.

FA3: rippled sand sheets

Description These units are composed of beds up to 50 cm thick comprising fine- to medium-grained sandstones dominated by current-ripple cross-lamination (Figs. 4, 5c). In some cases, these units appear at the top of heterolithic, coarsening-upward successions showing strong lateral continuity without major changes in thickness. In other cases, they show evidence of erosion at their lower boundary, sometimes accompanied by the occurrence of gravel-size bioclasts (infaunal bivalves, oysters, crinoids, serpulids and echinoids); the basal contacts are also associated with *Glossifungites*-related burrows (mostly *Thalassinoides*), which penetrate down into the underlying heterolithics by as much as 0.10 m (Fig. 5d). These erosion-based units show more conspicuous changes in thickness across relatively short distances and, internally, they may have horizontal laminations or small-scale trough cross-bedded sets (up to 30 cm thick) at the base, grading laterally into rippled beds. Bioturbation in individual beds varies from high to moderate (BI 6–3) and is dominated by *Ophiomorpha* (Fig. 5e), with subordinated *Palaeophycus*.

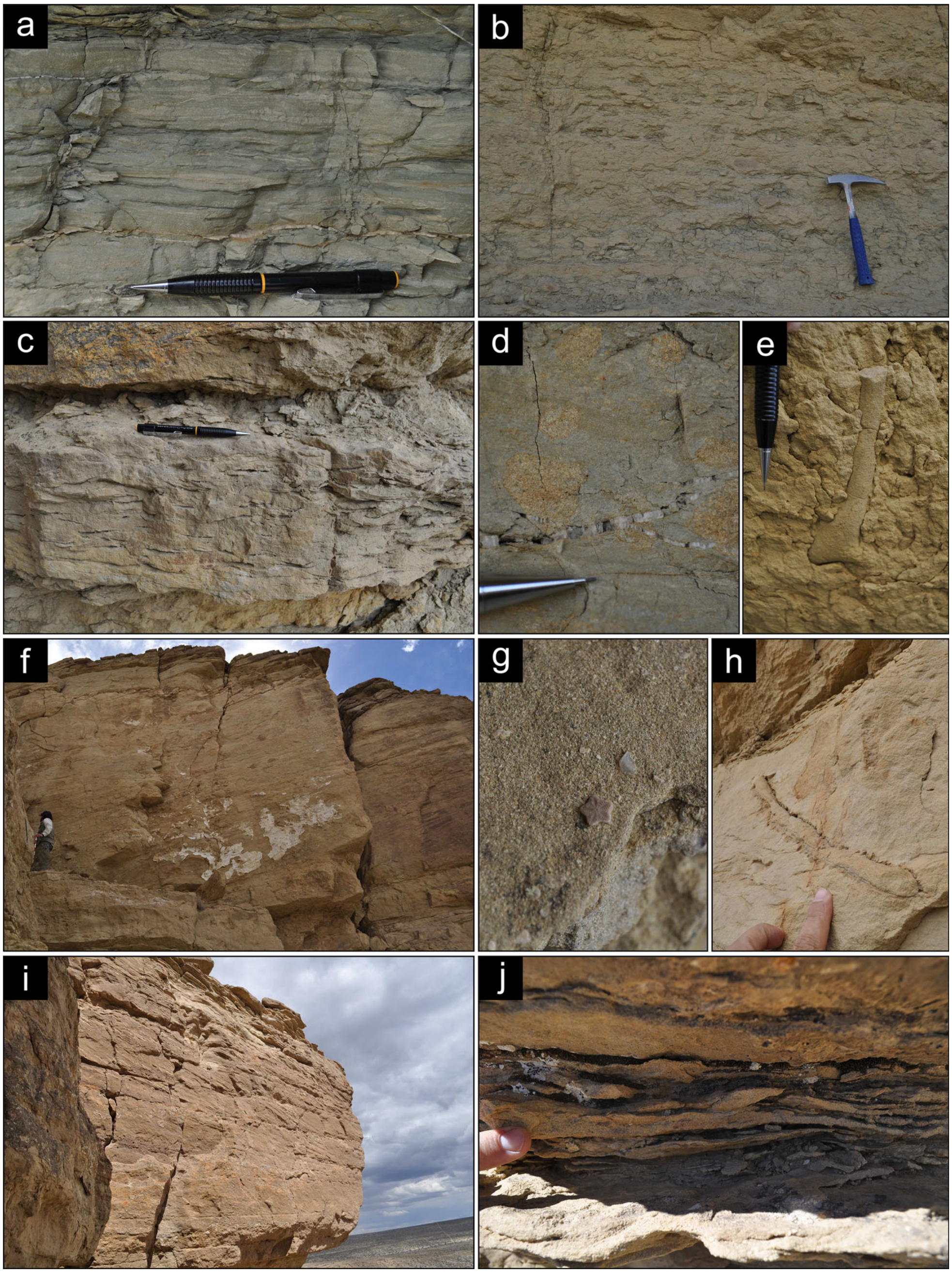

Fig. 5 Main facies associations of the Pilmatué Member in the study area. **a** Wavy heterolithic deposits of FA2. **b** Bioturbated muddy sandstones (FA2). **c** Fine-grained sandstones with current-ripple cross-lamination (FA3). **d** Detail of the *Glossifungites* suite (*Thalassinoides*) at the contact between fine-grained sandstones (FA3) and lenticular heterolithic deposits (FA2). **e** Detail of *Ophiomorpha* in bioturbated sandstones with ripple cross-lamination (FA3). **f** Very thickly bedded, cross-stratified arenites (FA4), sets are up to 4 m thick. **g** Detail of crinoid fragment in FA3. **h** *Ophiomorpha* vertical shaft in cross-stratified bed (FA4), commonly oriented perpendicular to foresets. **i** Medium- to thick-bedded cross-stratified arenites separated by low-angle surfaces. **j** Rippled forms at the bottom set of cross-stratified sets

Interpretation These deposits are associated with the development of relatively persistent unidirectional currents that most of the time evolved below the dune stability field. This FA may represent more proximal conditions than FA2, related to the development of rippled sand sheets (Anderton 1976; Belderson et al. 1982; Reynaud and Dalrymple 2012). When transitional from heterolithic deposits, these units may represent a gradual increase in the strength and recurrence of unidirectional currents. However, despite registering higher-energy conditions, they still represent relatively stable substrates prone to colonization by suspension-feeding organisms (*Skolithos* suite).

In contrast, some rippled units show a variety of features associated with a period of considerable erosion (although without major relief) prior to their accumulation. This suggests that some of these units may be the result of a sudden increase in current strength, promoting the suppression of part of the fine-grained record and the development of a *Glossifungites* suite at the contact with underlying fine-grained units, and the subsequent accumulation of large-scale wedge shapes with high concentrations of coarse-grained bioclastic material at the base. In these cases, associated with an increase in current transport capacity, and after the episode of erosion, currents could have had enough energy to promote the development of upper-flow regime conditions and locally the migration of small three-dimensional dunes.

FA4: dune deposits

Description Dune deposits dominate the upper portion of the study interval, mostly comprising cross-stratified, fine- to medium-grained siliciclastic and bioclastic sandstones with a variety of architectural styles. Some of these units show a relatively simple internal structure characterized by cross-bedded, tangential sets up to 3.5 m thick and continuous for over 10s of metres in a down-dip (down-current) direction (Figs. 5f, 6a). Sets are separated by steeply inclined surfaces (up to 30°), with younger cross-sets downlapping onto them (reactivation surfaces). Occasionally, ripple cross-lamination in sets migrating upwards is observed in the largest foresets. Siliciclastic sand dominates, but ooids and crinoid-derived bioclasts are common (Fig. 5g). Exceptional preservation of crinoids (crinoid Lagerstätte) is sporadically found associated with the base of large-scale cross-sets and reactivation surfaces (Fig. 6a). *Ophiomorpha* and *Diplocraterion* are distributed through most of the beds, typically oriented perpendicular to cross-bedding surfaces (Fig. 5h) but, overall, bioturbation intensity and diversity is low (BI 1–2). Locally, the base of these sets can be slightly erosional with a very gentle erosional relief (less than 0.5 m).

Alternatively, some dune elements show a more complex architecture characterized by smaller-scale, planar to trough cross-bedded sets between 0.5 and 1.5 m thick, which are recurrently bounded by surfaces that dip in the same direction as the main foresets but with a much lower angle (Figs. 5i, 6b). Palaeocurrents from bounding surfaces and cross beds are roughly parallel and oriented mainly towards the SW (Fig. 7). Bioturbation is generally low (BI 1), also composed of *Ophiomorpha* and *Diplocraterion*, but sometimes increases from the base to top of stacked cross-sets (up to BI 2). These cross-bedded sandstones can show a gradual transition, down the foresets, into fine-grained sandstones with current-ripple cross-lamination and discontinuous mudstone layers (flaser/wavy heterolithic deposits, Fig. 5j).

Interpretation The profusion of cross-bedded sandstones indicates the development of transverse large and very large dunes (cf. Ashley 1990) related to strong unidirectional currents. Foreset laminae (and lee-slope progradation) were mostly produced by pulses of grain-flow deposition. Current-ripple cross-lamination oriented in an opposite direction than the foresets, even when it could be due to flow reversion, was

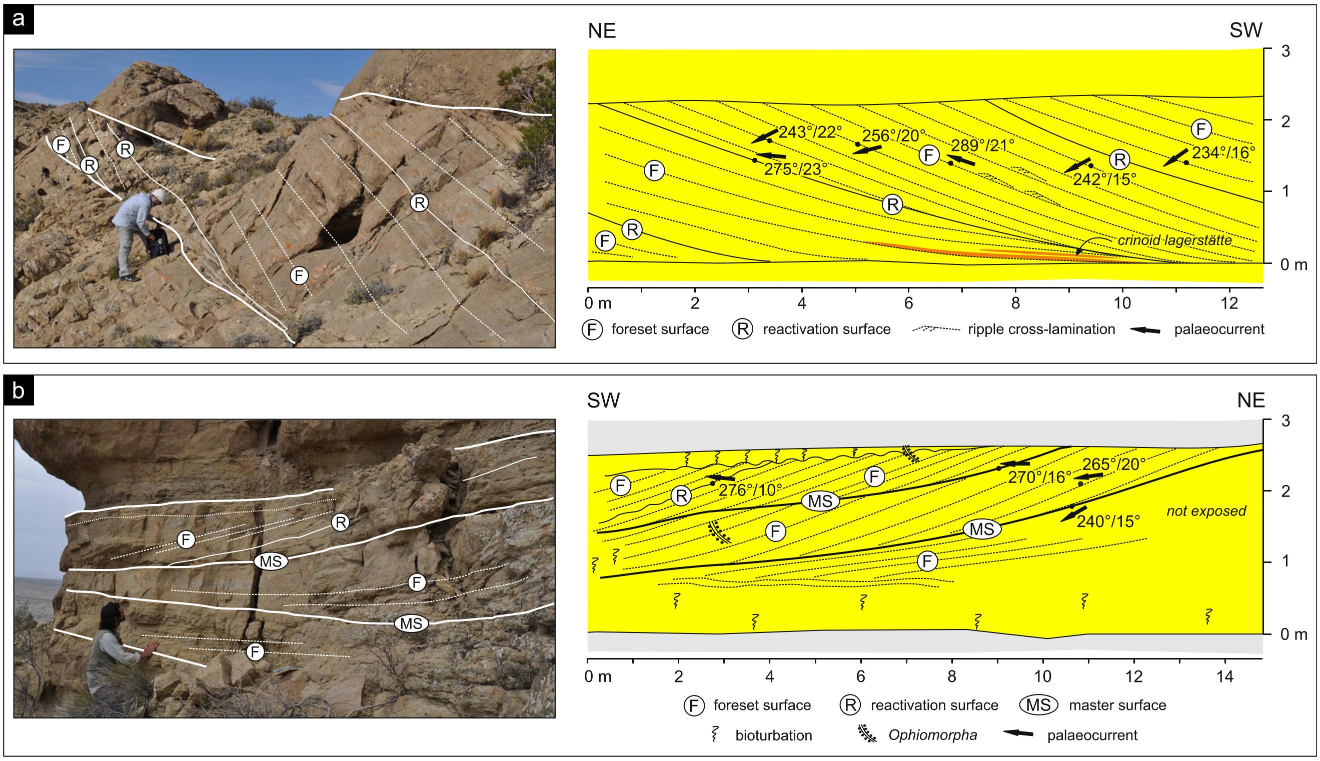

Fig. 6 Cross-bedded stratification and bounding surfaces in facies association FA4. **a** Relatively simple architecture characterized by thick foresets bounded by reactivation surfaces, interpreted as simple dunes. **b** More complex architecture in which the former elements are separated by additional low-angle surfaces (master surfaces), interpreted as the migration of compound dunes. Note that surfaces of different hierarchy in the same cross-bedded set show low palaeocurrent dispersion

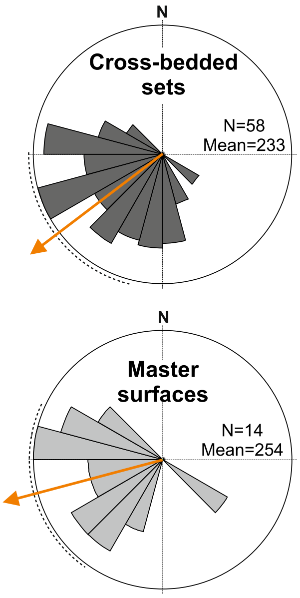

Fig. 7 Palaeocurrent directions from FA4. Cross-stratification suggests a south-western unidirectional migration both for simple and compound dunes. Master surfaces in the latter also depict a south-western migration, resulting in a forward-accretion architecture

more likely associated with the development of dunes large enough to promote flow separation over a significant segment of the leeward surfaces (Dalrymple 2010).

Large-scale sets represent the development of simple dunes or compound dunes with small superimposed bedforms (Fig. 8, top panel). In this context, reactivation surfaces are not considered to be the product of erosion of subordinate, reversing tidal currents, as suggested by Allen (1980), but rather caused by the migration of faster-moving superimposed dunes (Anastas et al. 1997), fluctuations in tidal current strength and/or direction, and/or catastrophic events (Dalrymple 2010; Reynaud and Dalrymple 2012). The exceptional preservation of crinoid Lagerstätten intimately associated with some of these reactivation surfaces would suggest the sudden burial of stalked crinoids that inhabited the dune toes and interdunes (Gonzalez, 1993 in Hess et al. 1999; Lazo et al. 2012). The rapid burial was likely produced by a short-term acceleration of the lee face migration due to a significant increase of current strength, which could have resulted from the mean tidal current being combined with an additional offshore-directed (storm-related?) current. On the other hand, stacked, smaller-scale cross-bedded sets are interpreted to represent compound transverse dunes, in which the largest dunes are covered by smaller dunes that are able to migrate and accumulate down the larger dune's lee side (Dalrymple 1984; Dalrymple and Rhodes 1995; Berné 2003; Olariu et al. 2012; Fig. 8, bottom panel). Each individual cross-bed represents the migration of a single dune, and the low-angle boundaries between sets represent master surfaces (Allen 1980). All dunes, irrespective of their sizes, migrated in approximately the same direction (SW), which is also parallel to the dip direction of the master surfaces, defining a characteristic forward-accretion architecture (Allen 1980; Dalrymple 1984; Dalrymple and Rhodes 1995; Olariu et al. 2012). Highly mobile substrates caused low colonization by filter feeders (low-ichnodiverse *Skolithos* ichnofacies suite), but dunes migrating more slowly and/or episodes of reduced sedimentation rate could have promoted intense, albeit local, bioturbation. Heterolithic deposits laterally associated with dune foresets may represent the bottomsets of these dunes, where flows could decelerate enough to promote the migration of current ripples and even the accumulation of thin muds due to settling from suspension.

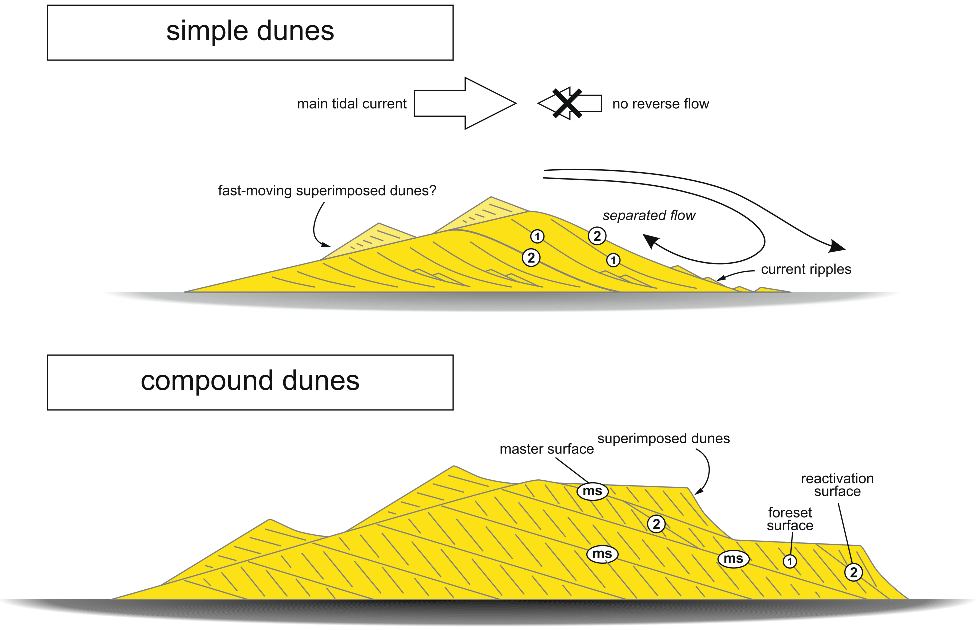

Fig. 8 Reconstruction of simple dunes (*top*) and compound dunes (*bottom*) represented by FA4, integrating cross-stratification, hierarchy of bounding surfaces and palaeocurrent analysis

Depositional model

The profusion of current-dominated structures both below and within the dune regime, the preservation of large submarine dunes (consistent with water depths well over 30 m; Harms et al. 1975; Flemming 1980; Ikehara 1993; Dalrymple and Rhodes 1995), and the intercalation of these deposits between offshore mudstones accumulated below both the fair-weather and storm wave bases suggest that the study interval records the setup and evolution of an offshore tidal-transport system on a low-energy seafloor that was previously characterized by mud deposition and episodic colonization by endo- and epi-benthic faunas. In this context, the four facies associations identified may record different relative positions within this system.

In a depositional environment in which the unidirectional current decelerates and loses transport capacity in a downcurrent direction (Fig. 9), dune deposits (FA4), rippled sand sheets (FA3) and heterolithic sheets (FA2) may represent this longitudinal transition from currents within the dune stability field, to currents below the dune field but with enough energy to consistently move sandy material, and intermittent currents that alternate with episodes of settling from suspension (Anderton 1976; Levell 1980; Belderson et al. 1982; Stride et al. 1982; Reynaud and Dalrymple 2012). The depositional model could be completed with a downcurrent sector not influenced by unidirectional currents (FA1), and an upcurrent area in which transport capacity is strong enough to promote erosion of older sediments and sand entrainment ("bedload parting" of Johnson et al. 1982; Harris et al. 1995). The system was likely sourced from both siliciclastic and oolitic sands, suggesting the development of a contemporaneous shallower depositional environment in which the tidal currents were capturing sands and supplying them to the tidal-transport system (Fig. 9). However, the system was also supplied by a significant proportion of autochthonous material. This was mainly in the form of bioclastic fragments, largely derived from the disintegration of defunct epibenthic crinoids living near or at the toe of the dunes (Fig. 9). Similar biota–bedform interactions have been proposed for modern analogue systems (e.g. Testa and Bosence 1999).

No clear evidence of flow reversion is recorded in this succession, suggesting that this tidal-transport system might have showed a high degree of asymmetry, recording only one direction of tidal transport in the study area. The absence of mud drapes in the foresets indicates that tides most likely did not experience slack water periods (Suter 2006), and that the currents were not affected by changes in speed or direction associated with individual tidal cycles (Reynaud and Dalrymple 2012). The dominant SW orientation of both simple and compound dune foresets and the fact that this direction is essentially parallel to the orientation of the master surfaces in the compound dunes indicate that this system was dominated by forward accretion, and most likely related to the development of an offshore dunefield rather than large-scale tidal ridges or bars (Longhitano et al. 2012; Olariu et al. 2012).

In terms of the stratigraphic evolution of this offshore tidal-transport system, there is a clear vertical trend that shows the transition from low-energy, fine-grained facies at the base (characterized by heterolithic sheets and rippled sand sheets), into more energetic conditions and the development of mainly simple and compound dunes towards the top (Fig. 4). This could represent the downcurrent migration of this transport system, defining an overall coarsening-upward trend that, as suggested, would be expected when dune complexes migrate over relatively distal deposits over time (Bridges 1982; Reynaud and Dalrymple 2012).

Stratigraphic architecture

Despite the fact that the studied succession can be interpreted as the result of the establishment and downcurrent migration of a tidal-transport pathway in an offshore setting, its vertical

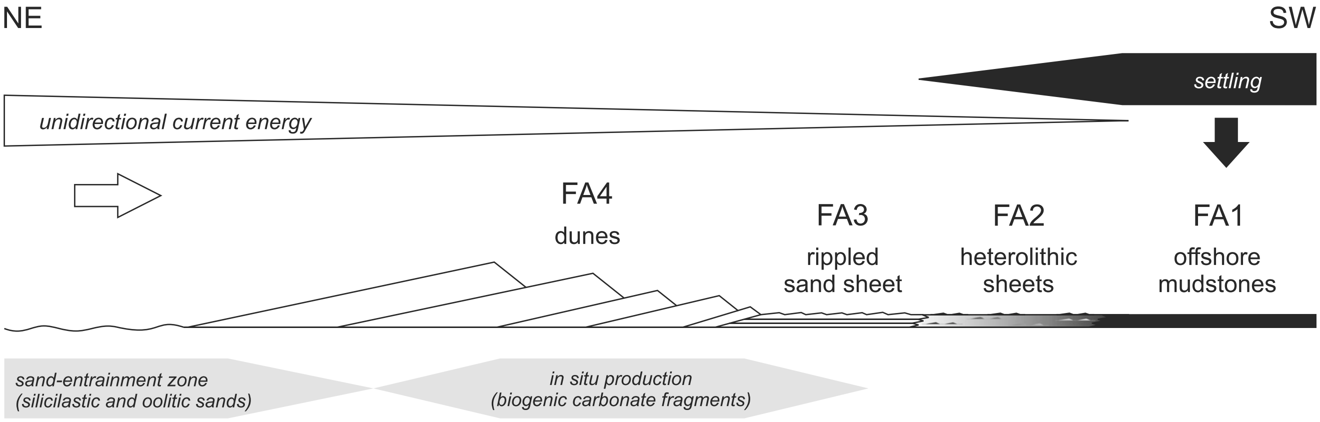

Fig. 9 Interpreted depositional model for the study interval. A tidal-transport pathway dominated by unidirectional, SW-oriented currents is inferred. Currents bring external terrigenous and ooids sands from shallow-marine coeval settings, which combines with in situ biogenic carbonate production (crinoid fragments)

evolution is far from recording the simple and gradual migration of a dunefield. This is evident in two specific aspects of this succession: (1) the presence of laterally continuous, fine-grained intercalations between sandy units, even in the upper part of the succession, and (2) the nature of both the lower and upper contacts of some of the coarse-grained units.

Muddy and heterolithic deposits (FA1 and FA2) can be laterally associated with dune deposits especially in the bottomsets of dunes where locally currents are less energetic, which can lead to the accumulation of fine-grained sands with current (upward-migrating) ripples and mudstones (Reynaud and Dalrymple 2012). Although some of the fine-grained deposits identified in the study interval can be associated with these local conditions related to the bottomsets of compound dunes, the most striking feature of the vertical facies stacking in the study area is the presence of laterally extensive muddy/heterolithic units that intercalate both between sandy sheets (FA3) and dune deposits (FA4; Fig. 10). This stratigraphic architecture contrasts markedly with previous models that attempted to explain the evolution of downcurrent-migrating dunefields (Harris et al. 1995; Reynaud and Dalrymple 2012), and suggests that episodes of low-energy conditions punctuated the overall migration of the system. In other words, the vertical stacking of this succession is not characterized by a gradual coarsening-upward succession (Harris et al. 1995) but by successive coarsening-upward small-scale cycles (Fig. 10). Each cycle is characterized by fine-grained, more distal deposits at the base (FA2), occasionally grading upwards into rippled sands (FA3) and eventually into dune deposits (FA4). The lower contact of dune units can be locally erosional (Fig. 10), but this could be the result of local erosion associated with scour pits at the bottom of three-dimensional lee faces of dunes, rather than of the interruption of the gradual progradation of the system.

The complex stratigraphic evolution of the system becomes clearer when the nature and significance of some of the boundaries between the facies associations are considered within a high-resolution evolutionary context. For instance, when rippled sand sheets of FA3 are analysed, some of the units, especially in the lower section of the study interval, show a highly erosional lower boundary (Fig. 10). Associated with this erosional surface, there is evidence of *Thalassinoides* showing a passive sandy infill belonging to a *Glossifungites* suite (Fig. 11a). This implies the suppression of part of the older sedimentary record and the exposure of partially consolidated substrates (MacEachern et al. 2007) prior to the accumulation of the rippled sands. Therefore, the vertical transition from heterolithic intervals of FA2 into the rippled sandstones of FA3 cannot be regarded as the gradual transition into more proximal accumulation conditions due to the progradation of the system, because an episode of high-energy conditions is necessary to develop these erosional surfaces.

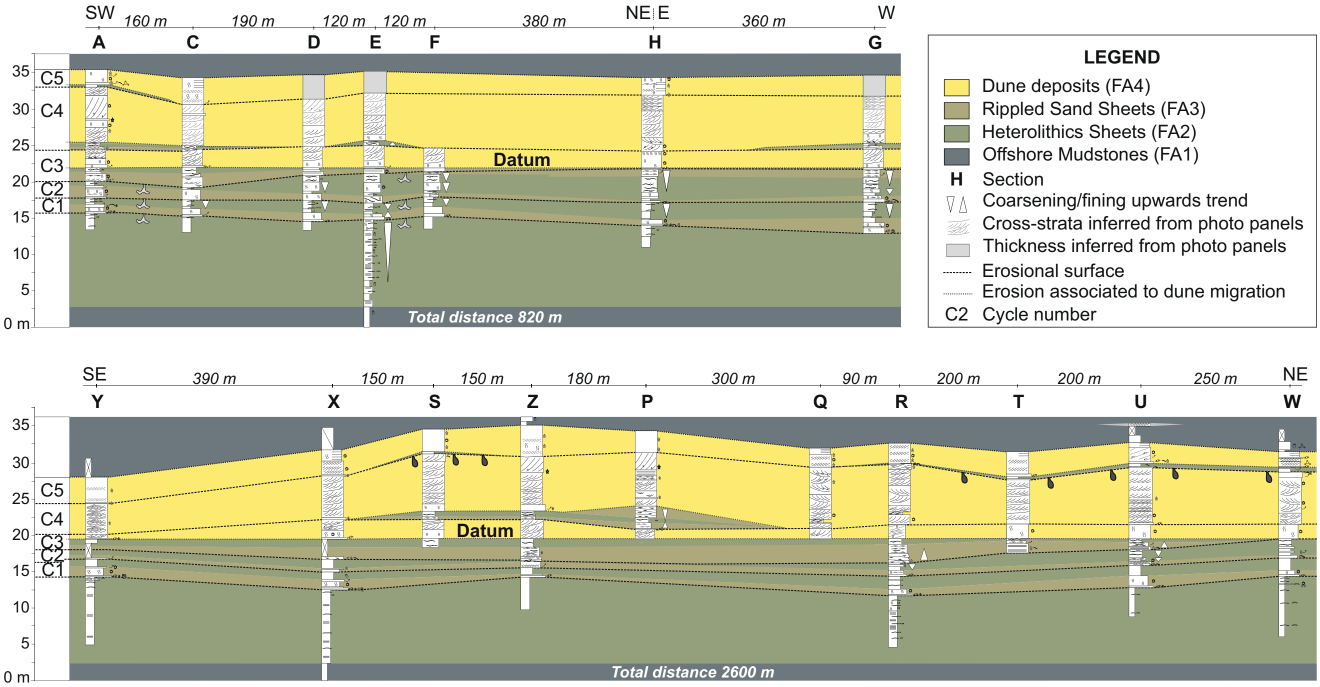

Fig. 10 Correlation panels showing facies association distribution, sandstone body architecture and key stratigraphic surfaces within the study interval of the Pilmatué Member. Erosional surfaces allow to identify up to five discrete cycles. For log locations, refer to Fig. 2. For legend on sedimentological sections, see Fig. 4

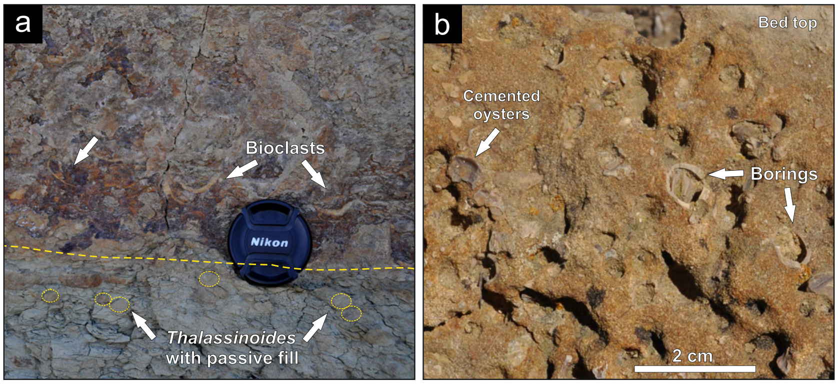

Fig. 11 Different expressions of erosional surfaces bounding small-scale cycles. **a** Cross-sectional view of a bed showing passively filled burrows (*Thalassinoides*) within FA2, suggesting a phase of significant erosion and mudstone exhumation prior to accumulation of sandstones belonging to FA3. Note concentration of large bioclasts at the base of the sandstone bed. **b** Top of sandstone package belonging to FA4 showing vertical clavate borings attributed to the bivalve ichnogenous *Gastrochaenolites*, associated with cemented oysters (*Ceratostreon* sp.)

Additionally, the upper boundaries of dune units in the transition to fine-grained deposits also show evidence of large-scale erosion, suggesting periods of destruction of dune relief. On the one hand, the geometry of the upper boundary of dune intervals is relatively horizontal. This suggests that, although covered by low-energy deposits, the older topography of the dunefield is not preserved (Fig. 10). Evidently, an episode of erosion, or at least of sediment bypassing without active dune climbing, destroyed the dune topography before settling and migration of current ripples occurred under subsequent low-energy conditions. Moreover, the upper boundary of dune deposits is sometimes characterized by the presence of *Gastrochaenolites* associated to cemented oysters (Fig. 11b). Collectively, this evidence suggests the formation of a subaqueous hardground due to early carbonate cementation and the subsequent colonization by a trace fossil suite that represents a *Trypanites* ichnofacies (MacEachern et al. 2007; Schwarz and Buatois 2012).

Discussion

Tidal-transport pathway in the Neuquén Basin

The development of the offshore dunefield recorded in the Lower Cretaceous deposits of the Neuquén Basin requires the inception and evolution of a tidal-transport pathway in the epicontinental sea developed eastwards of the active margin along the SW margin of Gondwana. These conditions are rather special for the Neuquén Basin, as most of the shallow- and deep-marine deposits accumulated during the Early Cretaceous show little evidence of strong tidal influence (Schwarz et al. 2006, 2011; Spalletti et al. 2011), compared to the latest Jurassic when, immediately after a major transgression of the basin during the early Tithonian, tidal action was common in nearshore settings (Spalletti et al. 2000; Zeller et al. 2015).

If the size and bathymetry of the Neuquén Basin are considered, it is highly unlikely that this epeiric sea might have developed its own tidal system (Pugh 1987; Reynaud and Dalrymple 2012). Therefore, the strong tidal influence may have derived from oceanic tides entering the basin through the arc in the west. According to the strong unidirectional component of the currents recorded in the studied section and the lack of univocal evidence of current reversal, it is probable that the tidal system developed in the Neuquén Basin during the early Valanginian was strongly asymmetric. This implies the development of a rotary tide system. Large-scale palaeogeographic reconstructions for the Lower Cretaceous of the Neuquén Basin (Fig. 1b) indicate shallower conditions to the east and northeast, suggesting that these currents were related to ebb conditions. This is also coherent with a clockwise rotation effect expected for tidal-wave propagation in the southern hemisphere (Pugh and Woodworth 2014).

Considering that the effects of tides within the basin were due to incoming oceanic tides, and that these conditions are exceptional in the Lower Cretaceous record of the Neuquén Basin, it is necessary to assume that they developed during a stage associated with a more effective connection with the open ocean. Within a large-scale sequence stratigraphic evolutionary scheme, it is highly unlikely that these conditions were attained at the beginning of the transgression recorded by the accumulation of the deep marine deposits of the Pilmatué Member. The western connection of the basin with the proto-Pacific ocean was supposedly becoming more effective as transgression proceeded and, therefore, the Pilmatué tidal-transport system could be related to final transgressive conditions and/or early highstand times (Fig. 12b). This contrasts significantly with previously studied offshore sandy successions, most of which are related to initial transgressive conditions (Fig. 12a) and to the reworking of highstand/lowstand sandstones as a result of the effect of shelfal currents, which

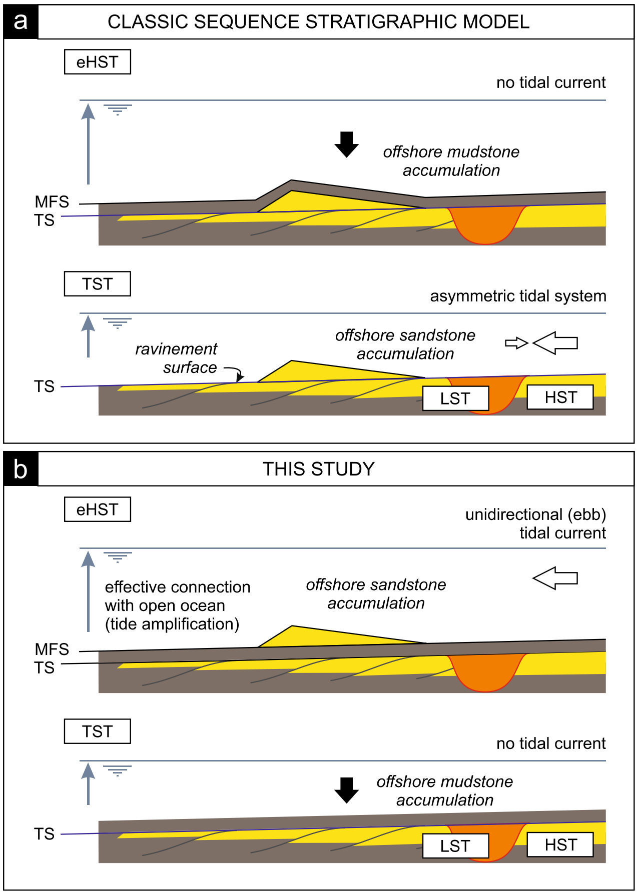

Fig. 12 Comparison between stratigraphic contexts for the generation of offshore sands. **a** Development during transgression of tidal sand ridges, with sands mostly sourced from previous lowstand and earliest transgressive estuarine deposits (after Dalrymple 1992; Snedden and Dalrymple 1999; Berné et al. 2002, among others). Tidal ridges are eventually capped by offshore mudstones during final transgression (maximum flooding surface) and subsequent highstand conditions. **b** Conditions inferred from the Neuquén epeiric sea in this study, in which the maximum tide effect would occur associated with the greatest connection with the open ocean. After a blanket of offshore mudstones is deposited during transgression, the tidal-transport pathway would start to develop. The sand source in this case would be provided by coeval mixed (carbonate-siliciclastic) shallow-marine systems

are subsequently abandoned and preserved once the transgression proceeds (Stride 1988; Dalrymple 1992; Snedden and Dalrymple 1999; Berné et al. 2002).

The source question

If it is assumed that these offshore sandy deposits are not the product of tidal ravinement onto older deposits during initial transgressive conditions, then what is the origin of the sandy material necessary to build this climbing dunefield? In the study area and in neighbouring areas where this unit is at the subsurface, little or no sandy accumulations are recorded below the study interval (Fig. 3), arguing against these deposits originating from the reworking of older accumulations due to the direct action of tidal currents on a sandy substrate. This also reinforces the idea that this dunefield is the result of tidal currents as opposed to other types of unidirectional currents that can be generated in shelf environments (e.g. wind-induced currents), which commonly rework relict sand inherited from older lowstand conditions (Bassetti et al. 2006). Most of the sediment constituting this dunefield record is composed of siliciclastic and oolitic, fine- to medium-grained sand material that had to be supplied from upcurrent areas, possibly associated with sand accumulation in shallower environments. However, also bioclastic material is sourced from within the system, mainly in the form of fragments of stacked crinoids. As clearly recorded due to the exceptional preservation of some of these specimens, these crinoids were living in the toe of the sandy dunes, associated with less energetic conditions. Nevertheless, continuous disarticulation and reworking of these organisms supplied important amounts of carbonate sand-size material.

Thick sandy accumulations of possible shoreface origin and contemporaneous with these offshore deposits are recorded about 25 km upcurrent to the NE (Fig. 13). This suggests the simultaneous accumulation in shallower settings and the entrainment of sandy material and subsequent transport to the offshore due to strong rotary tides. The lack of detailed studies of these shallower environments and their stratigraphic evolution makes it impossible to propose a larger-scale depositional model for this interval. More data are needed to adjust the morphodynamics of this shoreface–offshore system as a whole.

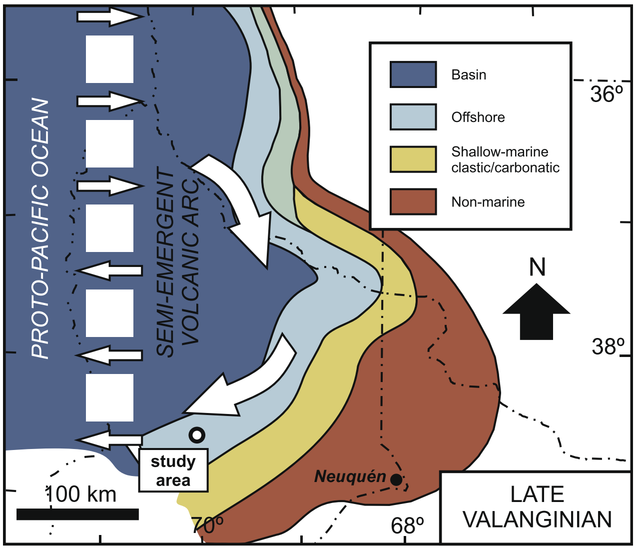

Fig. 13 Late Valanginian palaeogeographic reconstruction for the Neuquén Basin during the generation of the ebb-dominated tidal-transport system reported in this study (modified after Legarreta and Uliana 1991; Spalletti et al. 2011). Immediately after maximum transgression, the Neuquén sea would have had the possibility to combine a maximum tide effect within the basin with progradation of shallow-marine systems, providing both energetic tidal currents and sands to build the offshore tidal-transport pathway

Stratigraphic evolution of tidal-transport system

Although offshore dunefield accumulations have been the focus of numerous studies during the past 30 years both in modern environments (e.g. McCave and Langhorne 1982; Berné et al. 1988; Harris et al. 1995; Bassetti et al. 2006) and in the rock record (e.g. Anderton 1976; Levell 1980; Anastas et al. 1997; Olariu et al. 2012; Reynaud et al. 2013), little attention has been placed on the long- and short-term evolution of these systems and the resulting sedimentary record. This deficiency is more evident when compared to the studies of transgressive tidal ridges, for which several authors have proposed evolutionary models within a low-order sequence stratigraphic scheme (e.g. Snedden and Dalrymple 1999; Posamentier 2002; Berné et al. 2002; Schwarz 2012).

It has been suggested that, for active climbing dunefields, the downflow deceleration of the tidal current (Belderson et al. 1982; Harris et al. 1995) and the simultaneous downcurrent migration of the tidal-transport system lead to the development of a coarsening-upward succession (Bridges 1982; Reynaud and Dalrymple 2012). This succession is the result of dunes migrating on top of rippled sandy successions and rippled patches developed farther downcurrent. For siliciclastic systems with limited sand supply, the migration of the system eventually leads to a deficit in sandy material and, therefore, the coarsening-upward succession is truncated at the top by an erosion surface that represents the concomitant migration of the bedload parting (Reynaud and Dalrymple 2012). On the contrary, for carbonate systems in which sediment is produced within the system (carbonate factory), the overall record is defined by a coarsening-/fining-upward succession (Anastas et al. 2006).

In the case of the offshore dunefield of the Pilmatué Member in the Neuquén Basin, the long-term evolution of the system shows some similarities with the proposed siliciclastic model, especially in the long-term evolution. The profusion of dune deposits towards the top of the succession and the larger proportion of muddy and heretolithic deposits towards the base suggest the long-term progradation of the system (Fig. 10), consistent with a downcurrent migration of a tidal-transport pathway. The studied interval is separated form overlying hybrid sandstones (not well exposed) by a relatively thick mudstone interval with a sharp and flat lower boundary, indicating also that the upper limit of the coarsening-upward succession corresponds to a relatively sharp surface, possibly representing a period of erosion due to high-energy currents.

More complex, however, is the shorter-term evolution of the system because it has been described that the vertical evolution of the system does not record the gradual transition from distal to proximal settings in the transport system (Fig. 10). Also the accumulation is repeatedly marked by episodes of erosion, suggesting high-frequency changes in the unidirectional current speed.

Periods of downcurrent climbing and gradual migration of the system (Fig. 14a) are truncated by episodes of erosion, suggesting a relatively abrupt increase in the transport capacity of the current. This erosion is recorded not only in the proximal parts of the system (where dune deposits are truncated) but also in distal areas where heterolithic deposits are eroded, producing exhumation of semi-consolidated muddy substrates and carving gutter casts in the process (Fig. 14b). The subsequent depositional record in different parts of the system suggests a gradual decrease of the current speed, leading to the accumulation of sharp-based rippled sandstones in the distal area, while erosion and bypass dominated the upcurrent areas, the latter evident by the development of a hardground-related ichnological suite in the upper boundary of dune deposits (Fig. 14c). Thin fining-upward packages overlying rippled sandstones suggest a persistent deceleration of tidal currents but a relatively high sedimentation rate, and this phenomena eventually led to a significant retreat of facies belts. Subsequently, the accumulation of relatively fine-grained, distal facies associations both in proximal and distal sectors of the study area resumed (Fig. 14d). The gradual downcurrent migration of the system therefore started again, leading to the normal climbing of the system and producing a new overall coarsening-upward trend (Fig. 14e).

The reported cyclic accumulation for the Pilmatué tidal-transport system, characterized by periods of normal downcurrent migration and episodes of generalized erosion, is relatively common in other depositional systems (aeolian, fluvial, shallow marine) but, with few exceptions (e.g. Anderton 1976), it has been rarely described in previous studies on offshore sandstone accumulations. Available facies and sequence stratigraphic models commonly predict relatively simple, coarsening-upward successions (Reynaud and Dalrymple 2012). These recurring episodes of erosion and accumulation cannot be explained by changes in sediment supply and/or availability (especially the low-energy accumulation after the erosional phase) and necessarily reflect high-frequency changes in the speed and transport capacity of the unidirectional tidal current of this offshore system.

The cyclic alternation of low- and high-energy facies, the development of system-scale erosional surfaces, and the presence of preferentially cemented contacts between sandstone units are all products related to the high-frequency evolution. These features, individually or collectively, could have significant impact for the meaningful characterization of hydrocarbon reservoirs developed in this type of systems.

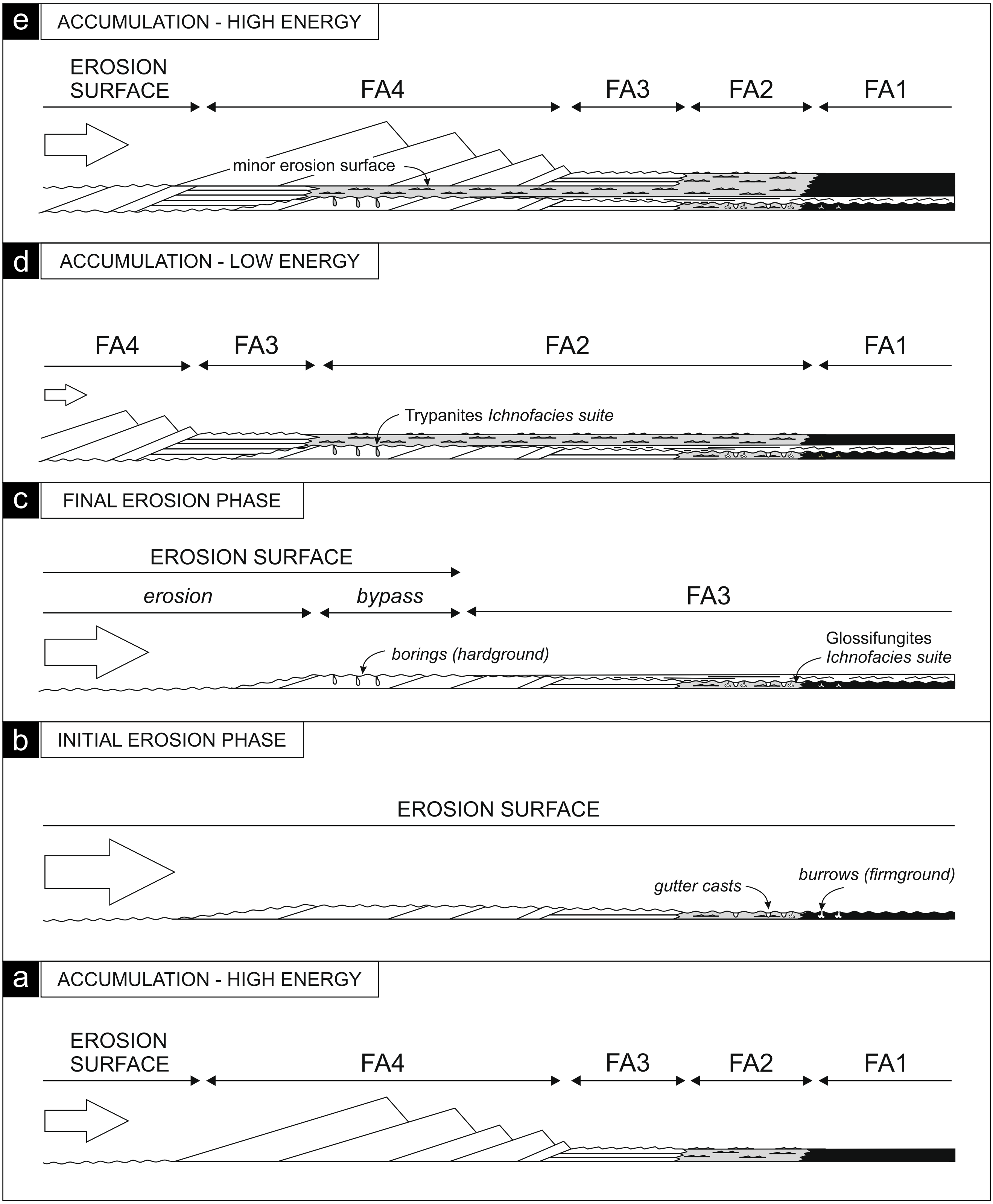

Fig. 14 Conceptual model explaining the internal sequence architecture of small-scale cycles recognized in the study interval. Each cycle records a principal phase of erosion followed by a phase of deposition. Downcurrent migration of the system during the depositional phase results in coarsening-upward concordant packages, with minor erosion related to the migration of the dune field. See text for discussion

Conclusions

Detailed analyses of the basal interval of the Pilmatué Member in the central Neuquén Basin enabled the definition of four facies associations related to the development of an offshore tidal system in response to the onset of a tidal-transport pathway in this epeiric sea. The tidal current responsible for the development of this system was probably the response to the effect of ocean tides within the epicontinental sea and had a high degree of asymmetry, only recording ebb flows in the study area.

The identified tidal system is characterized by a relatively simple forward-accretion dynamics suggesting the development of an offshore dunefield, rather than the onset of a complex, oblique, tidal sand ridge system. Unlike most published examples, the development of this tidal offshore system is not related to initial transgressive conditions but rather to the establishment of a full connection between the Neuquén Basin and the open ocean, most likely representing the final stages of a transgression and the beginning of normal regressive conditions. The latter is more likely, because the source of siliciclastic and oolitic material for the construction of the dunefield is not reworked from older accumulations but most probably supplied from prograding shorefaces developed to the northeast.

The vertical evolution of the tidal system reflects the superimposition of a long-term downcurrent migration of the transport system, together with high-frequency alternations of construction (progradation) and destruction (erosion) of the system likely to be the result of cyclic changes in the tidal current transport capacity. Understanding the high-frequency dynamics and depositional record of these offshore tidal systems may provide important information regarding facies distribution and internal bounding surfaces that can be essential for reservoir characterization of this type of deposits.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest with third parties.

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