Sedimentary Geology 367 (2018) 146–163

Contents lists available at ScienceDirect

Sedimentary Geology

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

Trace fossils, sedimentary facies and parasequence architecture from the Lower Cretaceous Mulichinco Formation of Argentina: The role of fair-weather waves in shoreface deposits

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ARTICLE INFO

Article history:
Received 4 November 2017
Received in revised form 16 February 2018
Accepted 18 February 2018
Available online xxxx

Editor: Dr. B. Jones

Keywords:
Parasequences
Shoreface variability
Fair-weather waves
Mulichinco Formation
Neuquén Basin

ABSTRACT

Shorefaces can display strong facies variability and integration of sedimentology and ichnology provides a high-resolution model to identify variations among strongly storm-dominated (high energy), moderately storm-affected (intermediate energy), and weakly storm-affected (low energy) shoreface deposits. In addition, ichnology has proved to be of help to delineate parasequences as trace-fossil associations are excellent indicators of environmental conditions which typically change along the depositional profile. Shallow-marine deposits and associated ichnofaunas from the Mulichinco Formation (Valanginian, Lower Cretaceous) in Puerta Curaco, Neuquén Basin, western Argentina, were analyzed to evaluate stress factors on shoreface benthos and parasequence architecture.

During storm-dominated conditions, the *Skolithos* Ichnofacies prevails within the offshore transition and lower shoreface represented by assemblages dominated by *Thalassinoides* isp. and *Ophiomorpha irregulaire*. Under weakly storm-affected conditions, the *Cruziana* Ichnofacies is recognized, characterized by assemblages dominated by *Thalassinoides* isp. and *Gyrochorte comosa* in the offshore transition, and by *Gyrochorte comosa* within the lower shoreface. Storm-influenced conditions yield wider ichnologic variability, showing elements of both ichnofacies.

Storm influence on sedimentation is affected by both allogenic (e.g. tectonic subsidence, sea-level, and sediment influx) and autogenic (e.g. hydrodynamic) controls at both parasequence and intra-parasequence scales. Four distinct types of parasequences were recognized, strongly storm-dominated, moderately storm-affected, moderately storm-affected – strongly fair-weather reworked, and weakly storm-affected, categorized based on parasequence architectural variability derived from varying degrees of storm and fair-weather wave influence. The new type of shoreface described here, the moderately storm-affected – strongly fair-weather reworked shoreface, features storm deposits reworked thoroughly by fair-weather waves. During fair-weather wave reworking, elements of the *Cruziana* Ichnofacies are overprinted upon relict elements of the *Skolithos* Ichnofacies from previous storm induced deposition. This type of shoreface, commonly overlooked in past literature, expands our understanding of the sedimentary dynamics and stratigraphic architecture in a shoreface susceptible to various parasequence and intra-parasequence scale degrees of storm and fair-weather wave influence.

1. Introduction

Shorefaces may display strong sedimentologic (Hart and Plint, 1995; Clifton, 2006; Plint, 2010) and ichnologic variability (MacEachern and Pemberton, 1992; Pemberton et al., 2012). This is the result of alternating and contrasting hydrodynamic energy levels due to overall storm intensity, storm frequency, and relative water depth, resulting in a multitude of stress factors on benthic communities (MacEachern and Pemberton, 1992; Buatois and Mángano, 2011; Pemberton et al., 2012). These varying stress factors at the sediment-water interface are detected by integration of sedimentology and ichnology which aids in detecting variations between strongly storm-dominated (high energy), moderately storm-affected (intermediate energy), and weakly storm-affected (low energy) shoreface facies (MacEachern and Pemberton, 1992; Pemberton et al., 2012). In addition, placement of these deposits within a sequence-stratigraphic framework has been instrumental for refining facies models (Pemberton et al., 2001; Buatois and Mángano, 2011). The use of ichnology to delineate parasequences is facilitated by the fact that trace-fossil associations are excellent indicators of environmental conditions that typically change along the depositional profile (Pemberton et al., 1992).

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https://doi.org/10.1016/j.sedgeo.2018.02.007
0037-0738/

Within the Neuquén Basin of western Argentina, the Mulichinco Formation (Valanginian, Lower Cretaceous) in the vicinity of Yesera del Tromen, consists exclusively of shallow-marine deposits within a large scale progradational succession, typically forming wave-dominated parasequences (Gulisano et al., 1984; Vergani et al., 1995; Schwarz, 1999; Schwarz et al., 2011, 2016) based on superbly exposed outcrops in the locality of Puerta Curaco. Exceptional outcrop quality and a relatively high abundance and diversity of trace fossils provide the opportunity to facilitate characterization of storm-dominated, weakly storm-affected, and two types of moderately storm-affected, shallowing upward parasequences in the upper member. The objective of this study, promoted by examination of distinct types of shallowing-upwards parasequences, is to expand our understanding of the sedimentary dynamics and parasequence architecture in shoreface complexes. Previous schemes have emphasized the importance of storm waves in shaping facies characteristics and sedimentary architecture of shoreface deposits. Our study highlights the importance of fair-weather waves through the recognition of a type of shoreface parasequence, commonly overlooked in past literature.

2. Stratigraphic setting

The Neuquén Basin (Fig. 1) is located east of the Andes in west-central Argentina and comprises approximately 6000 m of Upper Triassic to Paleogene strata formed in a back-arc basin covering over 120,000 km^2 (Leanza et al., 1977; Uliana et al., 1977; Legarreta and Uliana, 1991; Howell et al., 2005; Schwarz, 2012). During the Middle Jurassic to Early Cretaceous, as the Andes formed due to the eastward subduction of the proto-Pacific oceanic crust beneath the western margin of Gondwana (Schwarz et al., 2006), the Neuquén Basin experienced thermal subsidence, interrupted by several episodes of structural inversion (Vergani et al., 1995; Schwarz and Howell, 2005). The basin later evolved into a shallow water epeiric seaway during the Late Jurassic and Early Cretaceous, with ramp type margins in the east and south creating a funnel shaped morphology open to the north and west (Legarreta and Uliana, 1991; Schwarz and Howell, 2005). Within the basin, sedimentary infill alternated from transgressive and regressive successions of the Mendoza Group (Tithonian–Barremian) (Groeber, 1946; Legarreta and Gulisano, 1989; Legarreta and Uliana, 1991; Schwarz et al., 2006), promoted by regional subsidence, tectonic inversion and uplift, as well as fault-controlled subsidence (Vergani et al., 1995; Schwarz et al., 2006). More distal deposits accumulated more proximally during the shoreline transgression, forming retrogradational stacking patterns, and proximal sediments deposited more distally during shoreline regression forming progradational stacking patterns. This infill reflecting the interaction between eustacy and tectonics (Vergani et al., 1995; Howell et al., 2005; Schwarz et al., 2006; Schwarz, 2012), developed an extensive second-order highstand from Tithonian to early Valanginian (Schwarz and Howell, 2005). During the early Valanginian, a tectonic inversion pulse occurred, accounting for a relative drop in sea-level (Vergani et al., 1995; Schwarz and Howell, 2005), which led to deposition of the Mulichinco Formation lowstand wedge in the central part of the basin (Schwarz et al., 2006).

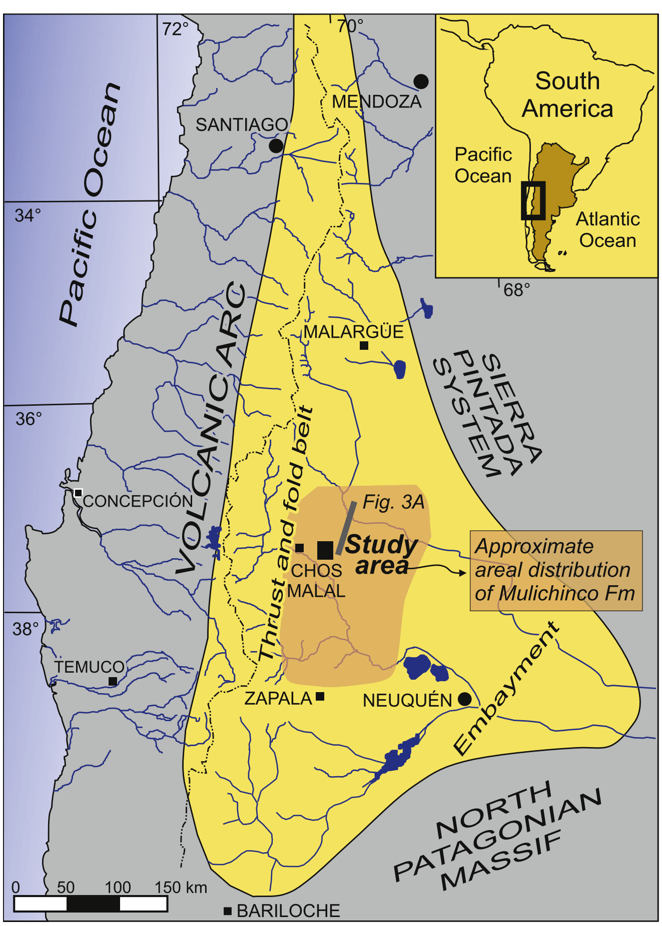

Fig. 1. Location map and approximate areal distribution of the Mulichinco Formation in the Neuquén Basin and study area (modified from Schwarz, 2012).

The study area is located within the central part of the Neuquén Basin (Fig. 1). The succession analyzed is within the second-order lowstand Mulichinco Formation wedge (Fig. 2), with the base of the unit overlying the Intra-Valanginian unconformity, separating the Mulichinco Formation above from the anoxic shales of the Vaca Muerta Formation below (Gulisano et al., 1984; Schwarz and Howell, 2005; Schwarz et al., 2011; Schwarz and Buatois, 2012). The Intra-Valanginian unconformity represents a sequence boundary demarcated by alluvial deposits overlying anoxic shale in proximal settings, and shallow-marine carbonates above anoxic shale and marl in distal settings (Gulisano et al., 1984; Schwarz and Buatois, 2012). Capping the Mulichinco Formation are the dark gray to black, parallel-laminated shales of the Agrio Formation exhibiting a sharp base, directly above tabular or massive carbonates and siliciclastic successions at the top of the measured sections. Subdivision of these formations has been facilitated by detailed biostratigraphic zonations of Lower Cretaceous (Berriasian–lower Barremian) strata through analysis of ammonite biozones and calcareous nanofossil bioevents within the Neuquén Basin (Aguirre-Urreta et al., 2005).

The Mulichinco Formation is composed of three members; lower, middle and upper (Fig. 3A), with as many as fourteen facies associations identified ranging from continental, marginal marine, and shallow to outer-shelf marine settings (Schwarz and Howell, 2005). The lowermost member of the formation is siliciclastic dominated, encompassing from lower shoreface sandstone to offshore mudstone. The middle carbonate member ranges from offshore marl and wackestone to oyster-rich floatstone and boundstone (Schwarz and Howell, 2005; Schwarz et al., 2016). The upper member, subject to the focus of this study, is a mixed siliciclastic-carbonate succession, comprising thin carbonates and thick, siliciclastic, open-marine deposits, stacked forming the parasequences discussed in this paper. In more proximal positions south of the study area, marginal-marine deltaic, as well as, fluvial systems (Schwarz and Howell, 2005), are interpreted to have acted as the sediment source for the uppermost part of the formation (Schwarz et al., 2008, 2016; Liberman et al., 2014).

3. Methodology

Methodology for this research consisted of systematic mapping and standard sedimentary facies analysis based on bed-by-bed measuring of three stratigraphic sections; PCS1 (S 37° 22.577' W 069° 56.846'), PCS2 (S 37° 23.764' W 069° 56.195'), and PCS3 (37° 24.388' W 069° 56.888')

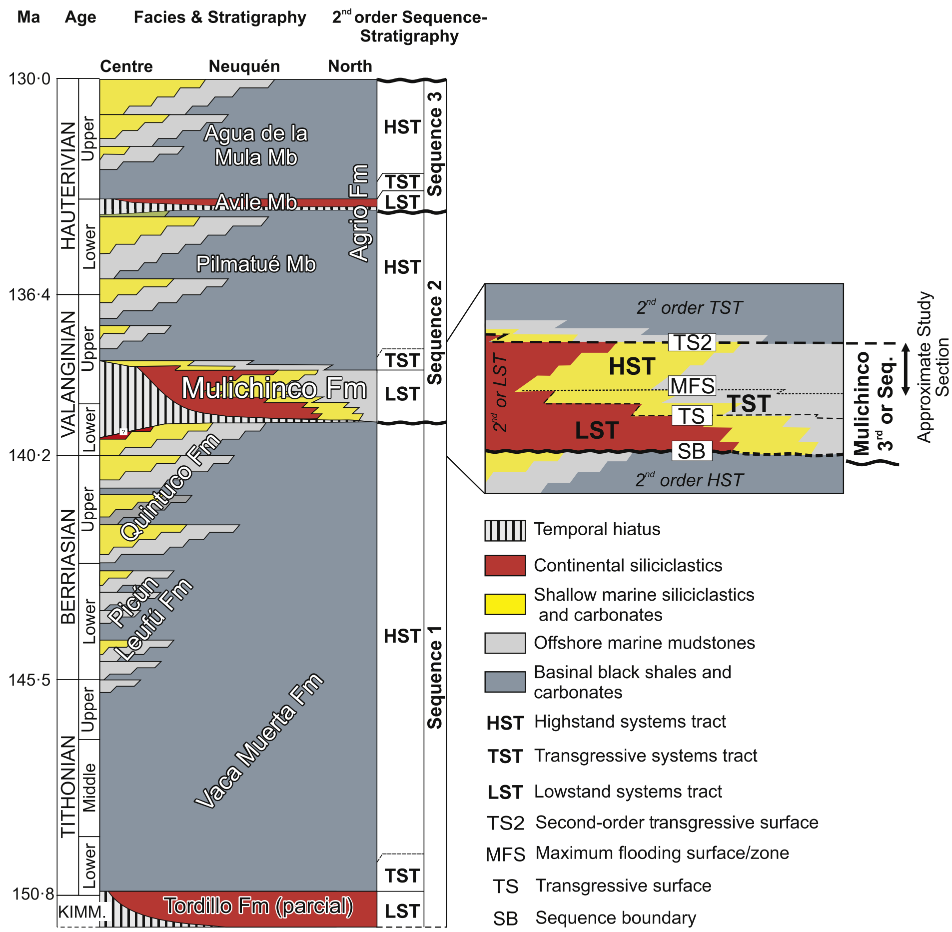

Fig. 2. Chronostratigraphic chart for the Tithonian-Huaterivian of the Neuquén Basin with age of units from Leanza (1993), Aguirre-Urreta et al. (2005) and Schwarz and Howell (2005). Time scale after Ogg et al. (2004). The second-order lowstand Mulichinco Formation wedge was formed during relative sea-level drop facilitated by tectonic activity in the region. Schwarz and Howell (2005) identified third-order systems tracts (LST, TST, and HST), further refined by Schwarz et al. (2006) including key stratigraphic surfaces recognized within the Mulichinco strata (Fig. 3A), allowing classification of a third-order Mulichinco Lowstand Sequence (Schwarz et al., 2006, 2016; Schwarz, 2012). Approximate vertical dimension of the study section is shown within the Mulichinco third order sequence (modified from Schwarz, 2012).

(Fig. 3C), with a Jacob's staff and an abney level recording the non-deltaic, open marine sediments found within the Puerta Curaco region (Fig. 3B) (Schwarz and Howell, 2005; Schwarz et al., 2006). Carbonate ramp oyster accumulations were used as the base of the study sections as they are easily recognizable across the study area. These three outcrops were selected based on exposure quality, accessibility, and distance from PCS1 and PCS3 from PCS2 being roughly equidistant (Fig. 3C), as well as covering the entire unit.

Sedimentologic analysis involved detailed facies characterization on the basis of lithology, sedimentary structures, mean grain size, bioturbation (Table 1), macrofossils, composition and sorting (Fig. 4). Outcrops were photographed at different scales to exhibit important sedimentary features and stratigraphic surfaces.

Ichnologic analysis involved trace-fossil sampling, preliminary recognition and identification of the ichnofossils present; study of density, abundance and distribution of individual ichnotaxa; measurement of degree of bioturbation, estimation of ichnodiversity; identification of trophic types and ethologic groups; and relationships among trace fossils, physical sedimentary structures, and bedding types in each sedimentary facies. Trace fossil abundances are categorized as dominant, subordinate, and accessory. Dominant entails the ichnotaxa most prevalent in an assemblage, whereas subordinate refers to ichnotaxa which are less abundant, followed by accessory, constituting rare occurrences of ichnotaxa with an assemblage. Bioturbation intensity was quantified on the basis of bioturbation index (Taylor and Goldring, 1993).

Detailed maps and photographic panels of the ichnofossil-bearing strata were prepared similarly to photographs of sedimentary features, stratigraphic surfaces and creation of stratigraphic column for PCS1 (Fig. 4) utilizing CorelDraw X8, depicting all-important sedimentologic and ichnologic features. Sedimentologic and ichnologic information was integrated in a sequence stratigraphic framework as outlined by Catuneanu (2006) and incorporated into a regional depositional model for the Mulichinco Formation within the Neuquén Basin (Schwarz and Howell, 2005; Schwarz et al., 2006, 2016; Schwarz, 2012; Veiga and Schwarz, 2017) in order to provide an accurate delineation of parasequences. Field work has allowed for in situ characterization of trace fossil content and sedimentary facies of the units studied. Integration of ichnologic data with sedimentologic and sequence stratigraphic data is essential to evaluate the paleoenvironmental distribution of trace fossils and their paleoecologic significance.

4. Sedimentary facies association and trace-fossil distribution

4.1. FA1: carbonate ramp oyster accumulations

4.1.1. Description

This facies association consists of massive, bioturbated nodular wackestone, bivalve shell bed floatstone (Fig. 5A) and packstone which are laterally extensive for hundreds of meters before pinching out. Contact between FA1 and underlying facies association is typically

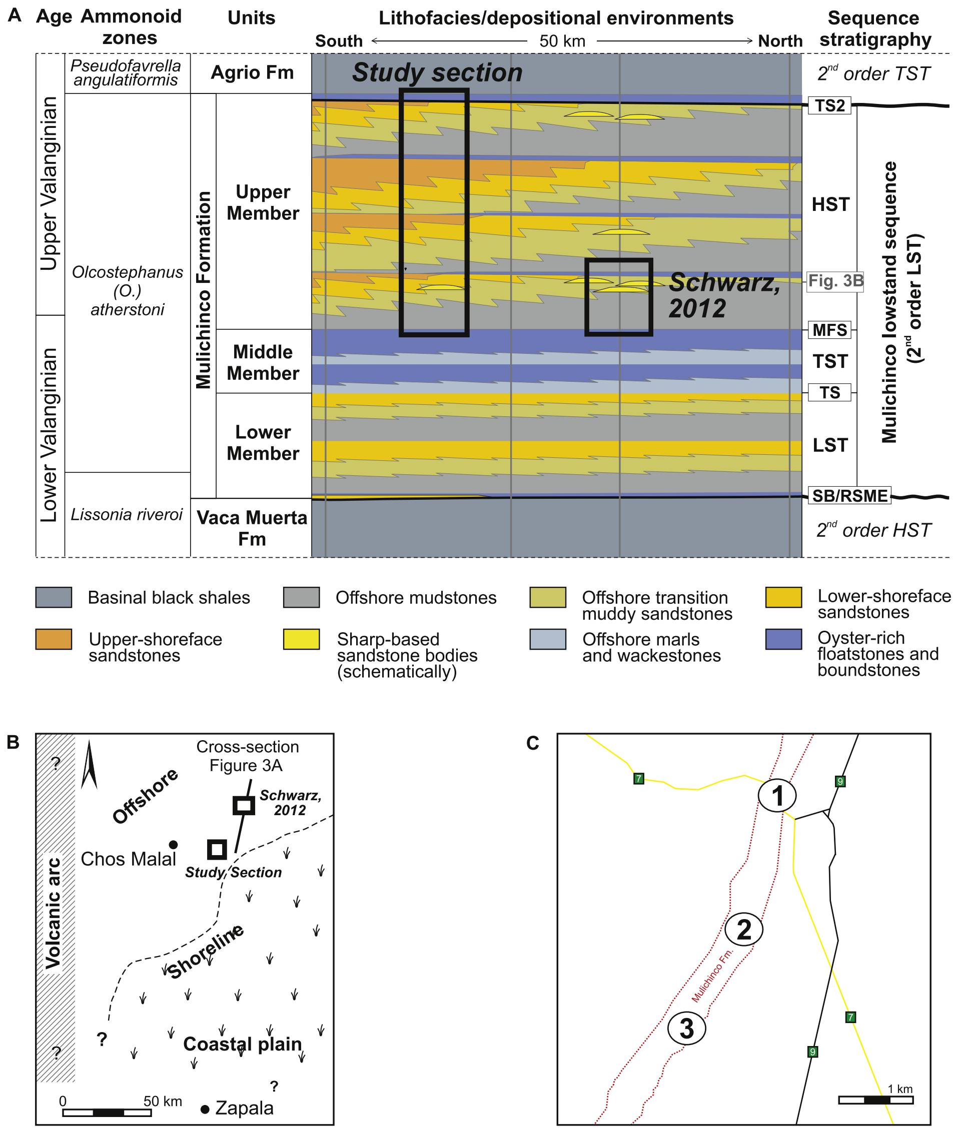

Fig. 3. (A). Cross-section showing age, facies, depositional systems and sequence stratigraphic framework of the Mulichinco Formation in the central region of the Neuquén Basin based on four sedimentological logs (grey vertical lines) (after Schwarz, 2012). See Fig. 1 for location of cross-section and extrapolated cross section perpendicular to it including the outcrops of this study. Note the north-east to south-west proximal to distal trend defined for the upper member of the Mulichinco Formation. The sharp-based sandstone bodies which are described in Schwarz (2012) and identified within the measured sections in this study are shown schematically, found within a succession dominated by offshore and offshore transition strata. (B). Highly schematic paleogeographical reconstruction of the Upper Member of the Mulichinco Formation from a time slice indicated in (A). Reconstruction is based on previously reported data (Schwarz and Howell, 2005; Schwarz et al., 2006, 2016; Schwarz, 2012; Schwarz and Buatois, 2012) and this paper. (C). Close-up of the location of the study section outcrops; PCS1 (1), PCS2 (2), and PCS3 (3) within the Neuquén Basin.

scoured into FA2 and FA3. Tangential cross stratification may be observed locally within the packstone with the top of the beds capped by wave ripples. Fossils include articulated and disarticulated shallow-infaunal bivalves (*Trigonia* sp.), deep-infaunal bivalves (*Panopea* sp.), cemented oysters (*Ceratostreon* sp.), few polychaetes (serpulids) and ammonoid shell fragments.

Monospecific suites of *Thalassinoides* isp. are present. The degree of bioturbation is high (BI = 5–6). FA1 is commonly associated within offshore (FA3 and FA4) deposits, occurring at the top of a coarsening upwards succession at the base of the study sections, constituting the middle member of the Mulichinco Formation, and capping the top of the formation, above more proximal facies associations.

4.1.2. Interpretation

This facies association is interpreted as transgressive deposits within high frequency mixed carbonate–siliciclastic successions produced by changes in sediment supply, facilitated by orbitally induced climate fluctuations (Schwarz, 2012). During intervals of extreme arid temperatures, low to minor amounts of siliciclastic influx were introduced to the system resulting in carbonate (FA1) deposition on the shelf and subsequent transgression of the carbonate ramp (James, 1997; Schwarz and Howell, 2005; Schwarz, 2012; Hönig and John, 2015; Navarro-Ramirez et al., 2015; Schwarz et al., 2016). Dominance of wackestone and packstone suggests siliciclastic starvation in a low energy system on a ramp-type open-marine setting. Low energy conditions are further supported by abundant articulated bivalves. The floatstone, though indicative of a low energy system, has coarser grains hosting an identical assemblage of fossils similar to the wackestone and is composed predominantly of siliciclastic and lime mud in an offshore (Burchette et al., 1990) or muddy middle ramp (Christ et al., 2012; Schwarz et al., 2016) setting. In the most proximal settings of the carbonate system within FA1, packstone having the same fossil composition as the floatstone with a greater fragmentation indicates further reworking of sediment by wave action found above fair-weather wave base in

Table 1
Facies association table.

Facies association	Lithology	Inorganic sedimentary structures	Thickness	Ichnology	Distribution and vertical facies transition	Interpretation
FA1: Carbonate ramp oyster accumulations	Bioturbated, nodular wackestones, tabular and massive densely packed bivalve shell bed (± serpulids) floatstone and packstones.	Massive with tangential cross stratification locally in packstones. Tabular geometry.	0.05–0.5 m thick beds; 0.5–5.5 m thick facies intervals.	BI = 5–6. *Thalassinoides* isp.	PCS1, PCS2, and PCS3. Associated within, above, or below lower offshore (FA3) sediments, or below euxinic basinal deposits (FA2).	Transgressive conditions within high-frequency cycles on a low energy, siliciclastic starved, ramp-type open-marine carbonate system.
FA2: Lower offshore	Mudstone locally interbedded with very thin, very fine-grained silty sandstone. Sandstone / mudstone ratios very low (typically >1: 20).	Parallel laminations.	<0.02 m thick silty sandstone beds; 0.3–0.5 m thick mudstone beds; 2–15 m thick facies intervals.	BI = 5–6 in background mudstones (mottled texture). Sandstone with *Thalassinoides* isp. *Teichichnus rectus*, and *Phycosiphon incertum*.	PCS1, PCS2, and PCS3. Deposited above and below tabular or massive carbonates (FA1), and grades up into upper offshore (FA4) sediments.	Low energy, suspension fallout punctuated infrequently by higher energy storm events, and lies directly above the storm wave base.
FA3: Upper offshore	Mudstone locally interbedded with very thin, very fine-grained sandstone. Sandstone / mudstone ratio vary from 1: 5 to 1: 2.	Parallel laminations and wave-ripple cross lamination.	0.02–0.1 m thick very fine-grained sandstone beds; 0.1–0.4 m thick mudstone beds; 1–5.5 m thick facies intervals.	BI = 5–6 in background mudstones (mottled texture). Sandstone with *Thalassinoides* isp., and *Teichichnus rectus*.	PCS1, PCS2, and PCS3. Situated above lower offshore (FA3), and underneath offshore transition deposits (FA5 and FA6).	Low energy, suspension fallout punctuated frequently by higher energy storm events.
FA4: Storm-dominated offshore transition	Interbedded silty mudstones and very fine-grained sandstone. Sandstone/mudstone ratio vary from 1:2 to 1:1.	HCS and parallel laminations.	0.1–2.5 m thick very fine-grained sandstone beds; 0.1–2.5 m thick mudstone beds; 2–5 m thick facies intervals.	BI = 3–4 in background mudstones, and BI = 0–2 in sandstones. *Thalassinoides* isp., *Ophiomorpha irregulaire*, escape traces, equilibrium structures, *Gyrochorte comosa*, *Lockeia siliquaria*, and *Hillichnus* isp.	PCS1, PCS2, and PCS3. Deposited between upper offshore (FA4) and storm-dominated lower shoreface (FA7) sediments.	Regular alteration of low energy, suspension fallout with higher energy storm events, lying directly underneath the fair-weather wave base.
FA5: Weakly storm-affected offshore transition	Muddy-silty sandstone	Parallel laminations, wave-, and current-ripple cross-lamination faint, to primary sedimentary fabric not preserved. Tabular geometry.	0.1–2.5 m thick beds; 1–9 m thick facies intervals.	BI = 3–6. *Thalassinoides* isp., *Gyrochorte comosa*, *Teichichnus rectus*, equilibrium structures, *Lockeia siliquaria*, and escape traces.	PCS1, PCS2, and PCS3. Located above upper offshore (FA4) sediments and below weakly storm-affected lower shoreface (FA8) deposits.	Low energy, suspension fallout with low intensity and low frequency of storms, directly beneath the fair-weather wave base.
FA6: Storm-dominated lower shoreface	Amalgamated, very fine-grained sandstone	HCS.	0.1–0.15 m thick beds; 0.6–6 m thick facies intervals.	BI = 0–2. *Ophiomorpha irregulaire*, *Skolithos* isp., *Sinusichnus* isp., and *Gyrochorte comosa*.	PCS1, PSC2, and PCS3. Grading up from storm-dominated offshore transition (FA5) deposits into weakly storm-affected lower shoreface (FA7), or upper shoreface (FA9) deposits.	High energy, oscillatory and combined flow above the fair-weather wave base.
FA7: Weakly storm-affected lower shoreface	Very fine-grained sandstone	Wave-, and current-ripple cross-lamination. Tabular geometry.	< 0.01 m thick individual ripple laminae amalgamated to produce <0.04 m thick ripple cross-laminated beds. 0.4–9 m thick facies intervals.	BI = 2. *Gyrochorte comosa*, *Thalassinoides* isp.,? *Scolicia* isp., *Lockeia siliquaria*, *Ophiomorpha irregulaire*, *Spongeliomorpha* isp., escape traces, *Hillichnus isp., Arenituba verso, Teichichnus rectus, and Protovirgularia* isp.	PCS1, PCS2, and PCS3. Situated above weakly storm-affected offshore transition (FA6), or storm-dominated lower shoreface (FA7), and below upper shoreface deposits (FA9).	Low energy environment with low intensity and low frequency of storms above the fair-weather wave base. May also include low energy reworking of storm-dominated lower shoreface (FA7) deposits, exhibiting relict *Skolithos* ichnofacies.
FA8: Upper shoreface	Amalgamated, very fine- to fine-grained sandstone	Trough cross-stratification.	0.25–0.5 m thick beds; 5.5–14 m thick facies intervals.	BI = 0–1. *Ophiomorpha irregulaire*, *Gyrolithes* isp. and *Gyrochorte comosa*.	PCS1, PCS2, and PCS3. Grading out of the underlying lower shoreface deposits (FA7 and FA8).	High energy, wave and current action, beneath the low tide.
FA9: Offshore sand ridge	Skeletal sandstones, fine-grained sandstones, and bioturbated sandstones.	Cross-stratified (planar-tangential or trough), current ripple cross-lamination, and massive.	0.2–0.5 m thick beds; 3.5–9 m thick facies intervals.	BI = 0–4. *Ophiomorpha irregulaire* (?).	PCS1, and PCS2. Associated within offshore (FA3 and FA4) sediments, having various degrees of proximity to storm-wave base (FA7 and FA8).	High energy, mostly 2-D dune migration in an open shallow marine environment with well oxygenated, clean waters, moving in an offshore direction.

inner-ramp settings (Burchette et al., 1990; Christ et al., 2012; Rankey, 2014; Schwarz et al., 2016). Benthic fauna largely consisting of bivalves (*Trigonia* sp., *Panopea* sp.) further supports a well oxygenated mobile substrate and under conditions of a high stressed, sediment starved environment, cemented oysters (*Ceratostreon* sp.) dominated the sediment-water interface (Schwarz and Howell, 2005). FA1 is described

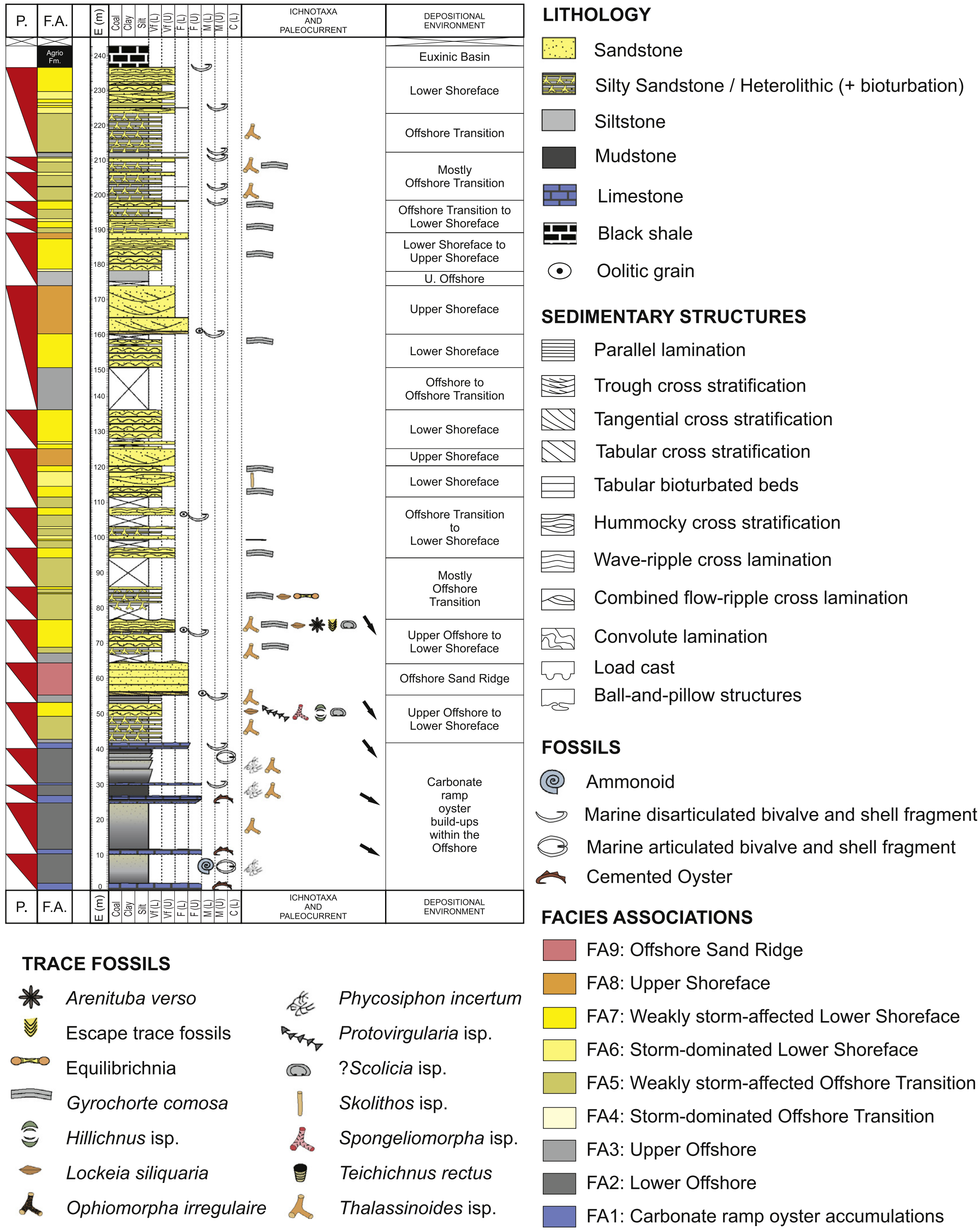

Fig. 4. Sedimentary Log for PCS1, representative of the study section. Measured interval corresponds to the upper member, with the exception of the lowermost carbonate interval, which belongs to the middle member. Legend depicting lithology, sedimentary features, fossils, trace fossils, and facies associations.

and interpreted here for the sake of completeness, but will not be discussed further.

4.2. FA2: lower offshore

4.2.1. Description

This facies association consists of dark gray, bioturbated mudstone locally interbedded with thin, very fine-grained silty sandstone exhibiting faint parallel lamination (Fig. 5B). Contact of FA2 with the underlying facies association is invariably sharp. Fossils include articulated bivalves (*Trigonia* sp., *Panopea* sp.) and ammonoids.

Intensity of bioturbation in background mudstone is high (BI = 5–6), commonly evidenced by a mottled texture, whereas intensity of bioturbation in silty sandstone beds is low (BI = 0–1) with discrete *Thalassinoides* isp., *Teichichnus rectus*, and *Phycosiphon incertum* occurring in sandstone beds. FA2 is deposited above and below tabular or massive carbonates (FA1), and grades up into upper offshore (FA3) deposits.

4.2.2. Interpretation

This facies association is interpreted as being deposited by low energy, suspension fallout mud, punctuated infrequently by storm events. FA2 was formed well beneath the fair-weather wave base and thus, these deposits have only been modified by the strongest storm

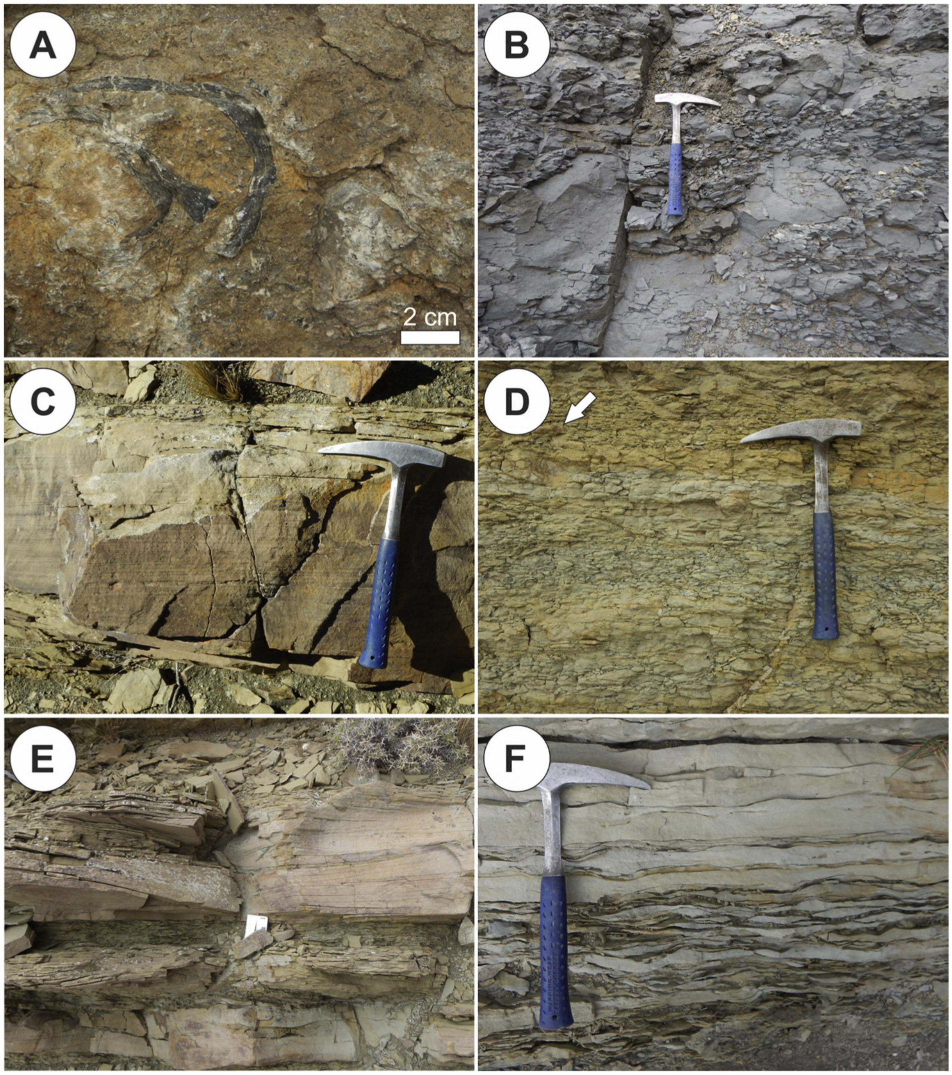

Fig. 5. Facies Associations 1–7. (A). Facies Association 1. Close-up of floatstone in outcrop with a large oyster belonging to *Ceratostreon* sp. (B). Facies Association 2. Thoroughly bioturbated mudstones. (C). Facies Association 4. Bedding plane view of a storm bed with HCS interbedded with offshore mudstones. (D). Facies Association 5. Detailed view of bioturbated muddy-silty sandstone with *Thalassinoides* isp. (white arrow). (E). Facies Association 6. Bedding plane view of HCS dominated outcrop. (F). Facies Association 7. Generalized bedding plane view showing thin mud drapes between wave rippled fine-grained sandstone.

events. At such depths, these thin, parallel laminated sandstones are not affected by fair-weather waves, providing a high preservation potential for primary fabric (Dott, 1983, 1988; Wheatcroft, 1990; Pemberton et al., 2012).

4.3. FA3: upper offshore

4.3.1. Description

This facies association consists of dark gray, bioturbated mudstone locally interbedded with very thin, very fine-grained sandstone with parallel and wave-ripple cross-lamination that are found throughout the study sections (Fig. 6D–E). The contact of FA3 is gradational from FA2 and is demarcated by an increase in thickness and abundance of sandstone beds. Similar, yet relatively fewer, body fossils are observed in this facies association (*Trigonia* sp., *Panopea* sp.), in comparison to FA2.

Thalassinoides isp. and *Teichichnus rectus* occur in the sandstone. Bioturbation intensity is low (BI = 0–1) in the sandstone, and high (BI = 5–6) in the mudstone, exhibiting a mottled texture, whereas sandstone beds exhibit sharp boundaries. FA3 is situated above lower offshore (FA2), and underneath offshore transition deposits (FA4 and FA5).

4.3.2. Interpretation

This facies association is interpreted as low energy, suspension fallout mud punctuated frequently by higher energy storm events. FA3, representing deposition in the upper offshore, exhibits increased and thicker storm beds as the storm induced oscillation maintains greater energy in these relatively shallower waters as wave-ripple cross-lamination occurring in addition to parallel lamination, representing the waning stage of storm activity at the sediment-water interface (Pemberton et al., 2012). Hydrodynamics of symmetrical ripples dictate conditions of low to moderate oscillatory flow speed with at most superimposed unidirectional flow, whereas weakly asymmetrical ripples suggest combined flow conditions with similar oscillatory flow conditions, but a moderate to strong unidirectional flow component (Dumas et al., 2005). The storm-induced tempestites contain no fossil, and display low bioturbation intensities (BI = 0–1) supporting high energy conditions that were suboptimal for colonization of organisms in stark contrast to the fair-weather mudstone that represents low energy suspension fallout characterized by high degree of bioturbation (BI = 5–6), similar to the more distal lower offshore deposits (FA2) (MacEachern and Pemberton, 1992).

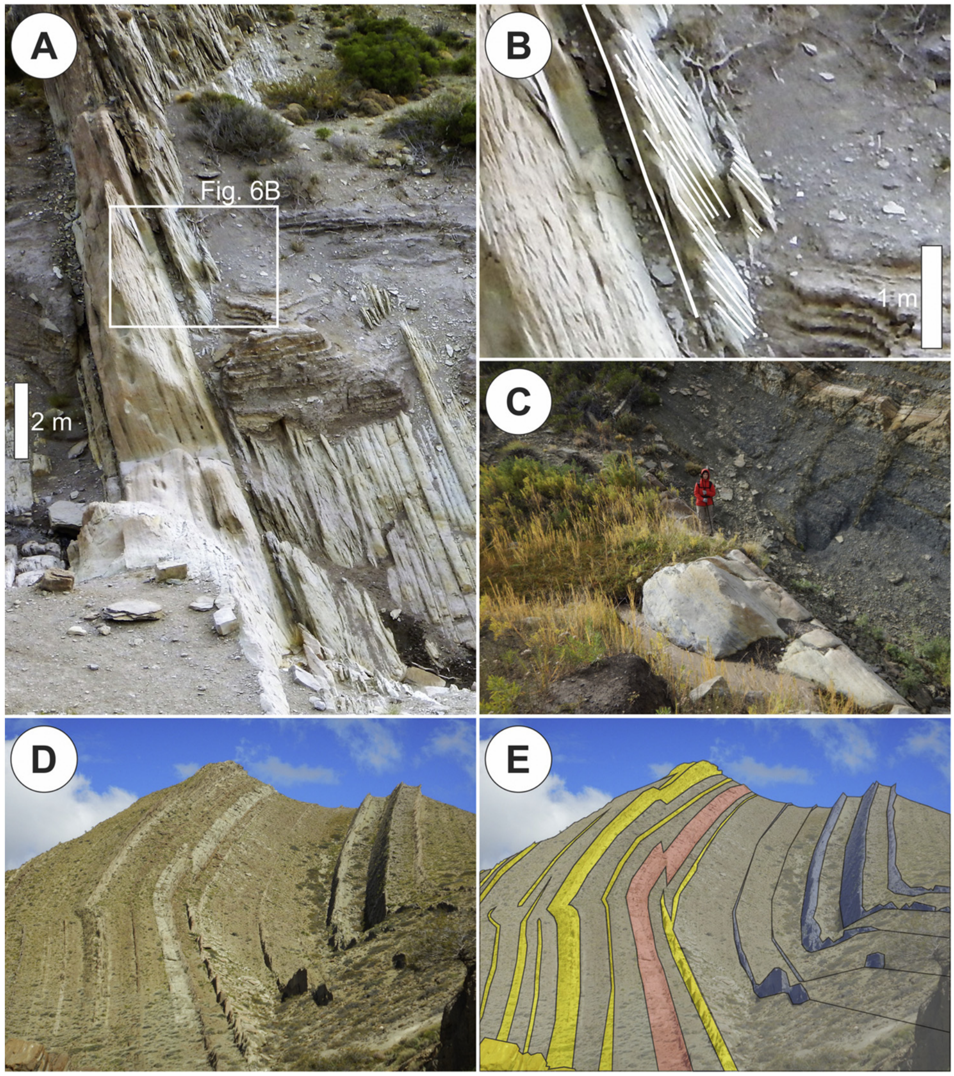

Fig. 6. Facies Associations 8–9. (A). Facies Association 8. Outcrop photograph of cross-stratified deposits. (B). Close-up of cross-bedded stratification depicting the low angle surface at the base with the foresets angled above. (C). Facies Association 9. Outcrop photograph of the top of an offshore sandstone ridge capped by offshore mudstones (FA 2 and FA 3). (D). Panoramic view of FA 9 physically separated from shoreface sandstones by offshore mudstones. (E). Panoramic view with shading representative of depositional environment. Offshore sand ridge (red). Shoreface sandstones (yellow). Carbonate ramp oyster accumulations (blue). Offshore muds and offshore transition heteroliths (gray). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.4. FA4: storm-dominated offshore transition

4.4.1. Description

This facies association consists of interbedded silty mudstones and very fine-grained sandstone with hummocky cross stratification and parallel lamination (Fig. 5C). A sharp base is present on the bottom of the sandstone beds; however, this facies association is overall gradational from the underlying upper offshore (FA3) deposits. If uninterrupted by a change in the degree of storm influence, FA4 will grade upwards into the storm-dominated lower shoreface (FA6) deposits.

The trace-fossil association includes *Thalassinoides* isp. and *Ophiomorpha irregulaire* being dominant (Fig. 7A), escape trace fossils and equilibrium structures subordinate, and *Gyrochorte comosa*, *Lockeia siliquaria*, and *Hillichnus* isp. as accessory components. Degree of bioturbation in background mudstone is high (BI = 5–6), but with lower intensities in the interbedded tempestite sandstones (BI = 2).

4.4.2. Interpretation

This facies association is interpreted as regular alternation of low energy, suspension fallout with higher energy storm events, lying directly underneath the fair-weather wave base (Pemberton et al., 2001). Experimental work showed that HCS is formed under high oscillation speeds with at most weak unidirectional flow speed (Dumas et al., 2005; Dumas and Arnott, 2006). During these high-energy storm events, eroded sand would be transported distally towards the offshore transition (FA4), deposited as tempestites within the offshore (FA2 and FA3) (Walker and Plint, 1992). At depths directly beneath the fair-weather wave base, there is an almost equal dominance between both fair-weather, intensely bioturbated (BI = 5–6) silty mudstone displaying high ichnodiversity, and storm-induced, sparsely bioturbated (BI = 0–1), hummocky cross stratified and parallel laminated sandstone deposits showing low ichnodiversity (MacEachern and Pemberton, 1992; Buatois and Mángano, 2011).

4.5. FA5: weakly storm-affected offshore transition

4.5.1. Description

This facies association consists of muddy and silty sandstone with faint parallel laminations, or faint wave- and current-ripple cross-laminations,

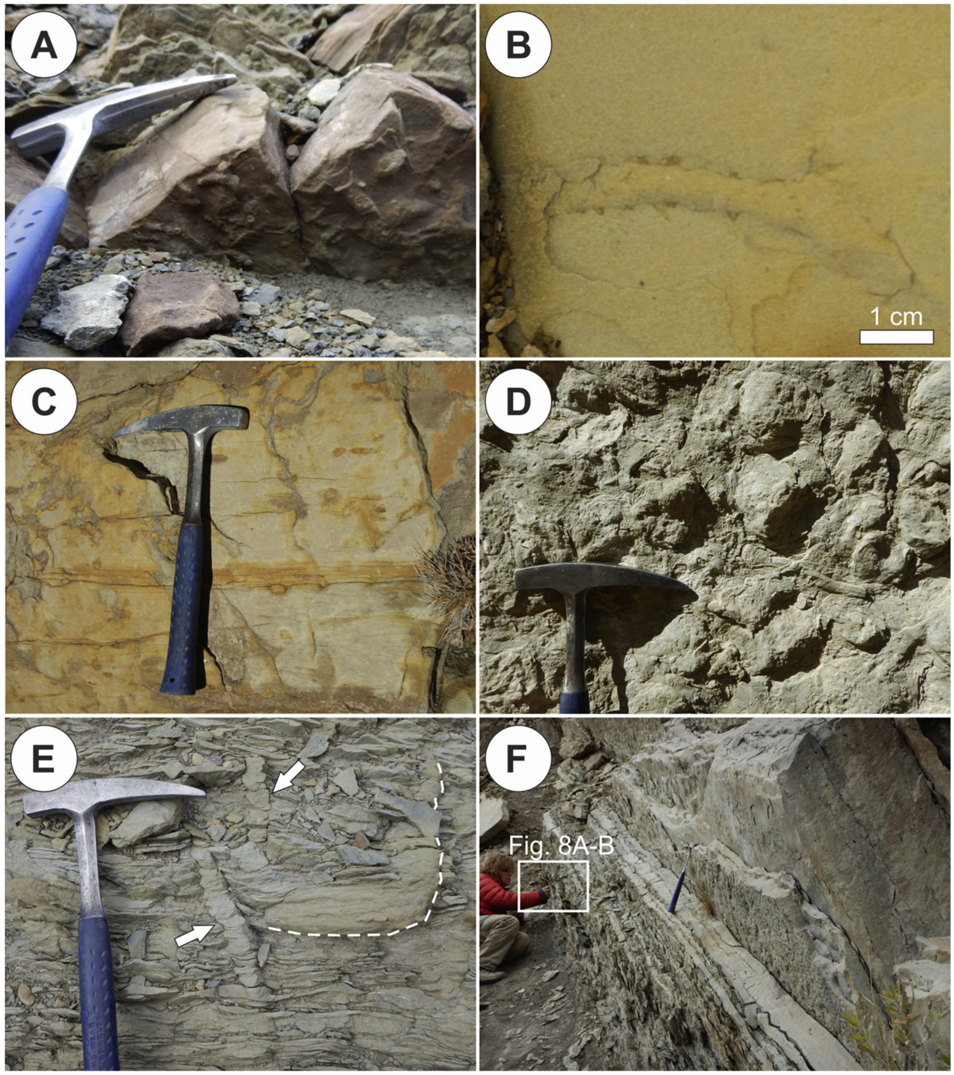

Fig. 7. Representative trace fossils. (A). Facies Association 4. Base of storm bed hosting three-dimensional burrow systems of *Ophiomorpha irregulaire* indicative of high energy conditions. (B). Facies Association 6. *Ophiomorpha irregulaire* at the top of a cross stratified bed. (C). Cross-sectional view of a HCS bed exhibiting horizontal and vertical shafts of *Ophiomorpha irregulaire*. (D). Facies Association 7. Base of ripple cross laminated bed with bivalve resting trace *Lockeia siliquaria* and *Thalassinoides* isp. (E). Wave rippled fine-grained sandstone with two different vertical expressions (white arrows and white hashed line) of the deposit feeding trace *Teichichnus rectus*. (F). Outcrop of FA 7 showing location of (Fig. 8A–B).

to primary sedimentary fabric not preserved, being completely obliterated by bioturbation (Fig. 5D).

Degree of bioturbation is high (BI = 3–6). *Thalassinoides* isp. and *Gyrochorte comosa* are dominant, *Teichichnus rectus* and equilibrium trace fossils are subordinated, and *Lockeia siliquaria* and escape trace fossils accessory. The base of FA5 is gradational with underlying upper offshore (FA3).

4.5.2. Interpretation

This facies association is interpreted as low energy, mud suspension fallout with low intensity and low frequency of storms, directly beneath the fair-weather wave base. In comparison to the storm-dominated offshore transition (FA4), the reduced intensity and frequency of storm events result in a long-term colonization window and pervasive bioturbation. Through bioturbation, the mudstone and silty sandstone were thoroughly mixed and original primary fabric is commonly completely obliterated (Kachel and Smith, 1986; Wheatcroft, 1990), reflecting fair-weather deposition (Pemberton et al., 1992) in a well-oxygenated, fully marine setting (MacEachern and Pemberton, 1992).

4.6. FA6: storm-dominated lower shoreface

4.6.1. Description

This facies association consists of amalgamated, hummocky cross-stratified, very fine-grained sandstone (Fig. 5E), with no mudstone intervals present throughout FA6 intervals.

Bioturbation intensity is low (BI = 0–2) with *Ophiomorpha irregulaire* dominant (Fig. 7B-C), *Skolithos* isp. subordinate, and *Sinusichnus* isp. and *Gyrochorte comosa* accessory. The base of FA6 is gradational with the storm-dominated offshore transition (FA4), and sharp when overlying the weakly storm-affected offshore transition (FA5).

4.6.2. Interpretation

This facies association is interpreted as high energy, oscillatory and combined flow above the fair-weather wave base (Walker and Plint, 1992; Schwarz and Howell, 2005). Water depths for the formation of HCS are estimated to range from 13 to 50 m (Dumas and Arnott, 2006). Long period waves can form with fine-grained sediments readily available in unrestricted open-water conditions (Dumas et al., 2005). As the high-energy conditions persisted, only organisms with primarily the most robust dwelling structures were able to colonize the substrate (MacEachern and Pemberton, 1992), representing opportunistic populations in a sandy storm-dominated environment (Echevarría et al., 2012).

4.7. FA7: weakly storm-affected lower shoreface

4.7.1. Description

This facies association consists of very fine-grained sandstone with wave- and current-ripple cross-lamination (Fig. 5F). A sharp base is present when overlying the storm-dominated lower shoreface (FA6); however, the base is gradational where overlying the weakly storm-affected offshore transition (FA5).

Degree of bioturbation is low (BI = 2) with *Gyrochorte comosa* (Fig. 8C–D) dominant, *Thalassinoides* isp. (Fig. 7D),? *Scolicia* isp. (Fig. 8E), *Lockeia siliquaria* (Figs. 7D, and 8D), *Ophiomorpha irregulaire*, *Spongeliomorpha* isp. (Figs. 7F, and 8A–B) subordinate, and *Hillichnus* isp., *Arenituba verso* (Fig. 8F), *Teichichnus rectus* (Fig. 7E), and *Protovirgularia* isp. accessory.

4.7.2. Interpretation

This facies association is interpreted as a low energy environment with low intensity and low frequency of storms above the fair-weather wave base (Schwarz and Howell, 2005). Under reduced intensity and frequency of storm events, wave and current-ripple cross lamination were pervasive, resulting from the migration symmetrical and weakly asymmetrical ripples produced by combined low oscillatory and weak unidirectional flows (Myrow and Southard, 1996; Schwarz and Howell, 2005; Zecchin, 2007; Schwarz et al., 2016). Within this facies association at more distal locations, symmetrical wave-ripples may be preferentially formed due to the small size of the wave orbitals. In contrast, the wave orbitals increase in size as wave orbital motion becomes more asymmetric in a proximal direction, generating asymmetric bedforms (Clifton, 1976) as the result of the frictional component of the sediment acting on the stronger wave orbital moving sediment locally shoreward (Swift et al., 1991; Dumas and Arnott, 2006). Under pervasive low oscillatory and weak unidirectional conditions, fair-weather waves reworked the underlying storm deposits of the storm-dominated lower shoreface (FA6). As the weakly storm-affected lower shoreface (FA7) is adjacent to the

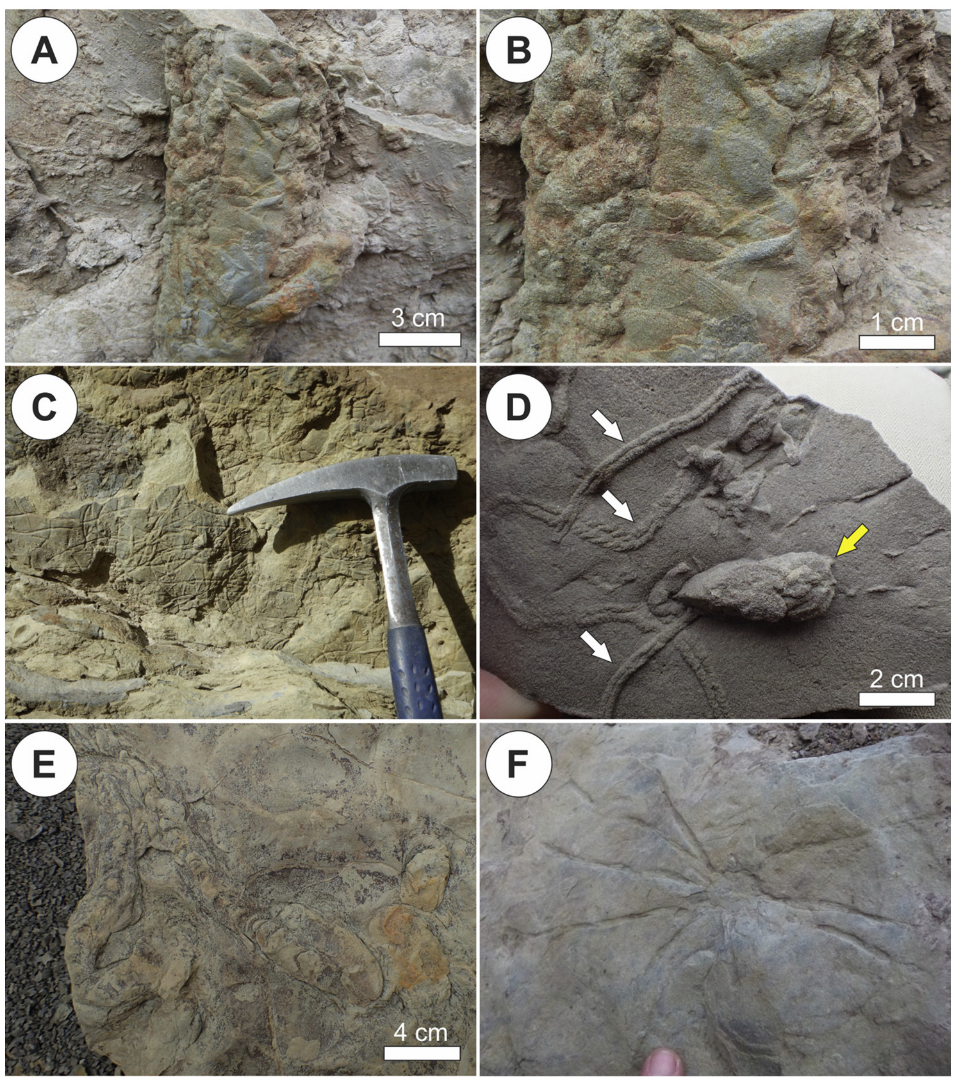

Fig. 8. Representative trace fossils. (A). Facies Association 7. Bedding plane view of a highly ornamented three-dimensional crustacean burrow system, *Spongeliomorpha* isp. Penetrating the wave rippled fine-grained sandstone with a smaller specimen cross cutting the original. (B). Close-up of *Spongeliomorpha* isp. With scratches observed on the ventral side, and bubbly like texture on the lateral sides. (C). Base of a ripple cross laminated bed with dense, horizontal detritus feeding trails belonging to *Gyrochorte comosa*. (D). Close-up of a bedding plane view displaying bilobate epichnial ridge and an underlying hypichnial groove of *Gyrochorte comosa* (white arrows) as well as a specimen of *Lockeia siliquaria* (yellow arrow). (E). Top of bedding plane view featuring echinoid deposit feeding trails of ?*Scolicia* isp. With menisci. (F). *Arenituba verso*, a system of radially branched tubes around a larger tube, at the base of a sandstone bed and probably produced by worm-like organisms. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

offshore transition (FA5) and deposited under the same marine regime, the ichnoassemblage of FA7 more closely resembles FA5 than FA4, with ichnodiversity remaining high.

4.8. FA8: upper shoreface

4.8.1. Description

This facies association consists of amalgamated, tabular and trough cross-stratified, very fine- to fine-grained sandstone (Fig. 6A–B).

Bioturbation intensity is low (BI = 0–1) with *Ophiomorpha irregulaire* dominant, *Gyrolithes* isp. and *Gyrochorte comosa* accessory. The base of FA8 is sharp when overlying both strongly storm-dominated (FA6) and weakly storm-affected (FA7) lower shoreface deposits.

4.8.2. Interpretation

This facies association is interpreted as the upper shoreface deposited under high energy, current conditions beneath the low tide line. Sediments representing the upper shoreface (FA8) are interpreted to be deposited laterally adjacent to the storm-dominated and weakly storm-affected lower shoreface facies associations, FA6 and FA7, respectively. High energy, fair-weather and longshore currents result in two- and three-dimensional dunes (Clifton et al., 1971; Greenwood and Mittler, 1985), formed under a unidirectional flow whose migration results in tabular and trough cross-bedding (Walker and Plint, 1992) (Dumas et al., 2005). Only the most robust organisms are able to colonize under these conditions (MacEachern and Pemberton, 1992; Buatois and Mángano, 2011).

4.9. FA9: offshore sand ridge

4.9.1. Description

This facies association consists of skeletal, trough to planar cross-stratified, fine-grained sandstones (Fig. 6C-E). Current ripple cross-lamination is locally present and some beds appear massive.

Bioturbation ranges from absent to moderate (BI = 0–4) with *Ophiomorpha irregulaire* (?) being the only visible ichnotaxon. In cases of more intense bioturbation, bed boundaries are only visible providing insight on an overall tabular bed geometry. FA9 is associated within offshore (FA2 and FA3) sediments, having a scoured base beneath the skeletal sandstone, and demonstrates various degrees of proximity to storm-wave base (FA6 and FA7).

4.9.2. Interpretation

This facies association is interpreted as high energy, mostly two-dimensional dune migration in an open shallow marine environment with well oxygenated, clean waters, moving in an offshore direction. A skeletal sandstone demarcating a shell-rich transgressive lag, showing mixing of the benthic fauna, is diagnostic of this facies association. In places, this lag is mantling a transgressive ravinement surface and sequence boundary (TRS/SB). Directly above the skeletal sandstones, transgressive cross-bedded sandstones are deposited. Finally, highly bioturbated sandstones with only bed boundaries being visible cap the cross-bedded sandstones at the top of FA9, deposited under more fair-weather conditions where colonization and bioturbation can take place (Schwarz, 2012). Similar to FA1, FA9 will not undergo further analysis in the study presented here.

5. Variability and vertical distribution of facies associations

5.1. Offshore-transition variability

The offshore transition, also referred to as the distal lower shoreface by some authors (MacEachern and Bann, 2008; Pemberton et al., 2012), is located directly below the fair-weather wave base (Pemberton et al., 2001). Under storm-dominated conditions, the offshore transition (FA4) (Fig. 5C) reflects roughly equal alternation between high-energy storm event sandstones and fair-weather mud deposition (Buatois and Mángano, 2011), having *Skolithos* and *Cruziana* Ichnofacies, respectively (MacEachern and Pemberton, 1992). Within the storm-dominated offshore transition (FA4), *Thalassinoides* isp. and *Ophiomorpha irregulaire* are the most abundant ichnotaxa, with escape trace fossils and equilibrium structures subordinate, and *Gyrochorte comosa*, *Lockeia siliquaria*, and *Hillichnus* isp. as accessory elements (Figs. 9A–B, and 10A–B).

In contrast, the offshore transition in weakly storm-affected conditions (FA5) (Fig. 5D) consists of bioturbated muddy-silty sandstone (Morris et al., 2006; Schwarz, 2012; Schwarz et al., 2016) illustrating the *Cruziana* Ichnofacies (MacEachern and Pemberton, 1992), and hosting endo-byssate bivalves (Schwarz, 2012; Schwarz et al., 2016), where conditions reflect thorough fair-weather bioturbation of the sediment. The weakly storm-affected offshore transition (FA5) ichnoassemblage reflects the lower energy conditions and intense bioturbation of the substrate; with *Thalassinoides* isp., *Gyrochorte comosa*, and *Teichichnus rectus* (Figs. 9C–D, and 10C–D).

5.2. Lower-shoreface variability

The lower shoreface, located directly above the offshore transition and correspondingly above the fair-weather wave base (Reinson, 1984; Walker and Plint, 1992), also ranges from being strongly storm-dominated (FA6) to weakly storm-affected (FA7). In the strongly storm-dominated lower shoreface (FA6) (Fig. 5E) where wave action is the prevailing physical process, hummocky cross stratification is the dominant sedimentary structure. Continuous storm induced oscillations blocked fair-weather deposition and facilitated subsequent erosion and amalgamation throughout this setting. Within the strongly storm-dominated lower shoreface (FA6), only the deepest biogenic structures of the *Skolithos* Ichnofacies are present (MacEachern and Pemberton, 1992), with the ichnoassemblage dominated by *Ophiomorpha irregulaire* (Fig. 7A–C).

In the weakly storm-affected lower shoreface (FA7) (Fig. 5F), the frequency and magnitude of storms were not as dominant as compared to FA6, resulting in wave and current-ripple cross lamination preservation, representative of the migration of symmetrical and weakly asymmetrical ripples produced by combined low oscillatory and weak unidirectional flows (Myrow and Southard, 1996; Schwarz and Howell, 2005; Dumas and Arnott, 2006; Zecchin, 2007; Schwarz et al., 2016). In previous studies, similar deposits have also been referred to as "rippled sand sheets" (Anderton, 1976; Belderson et al., 1982; Reynaud and Dalrymple, 2012; Veiga and Schwarz, 2017), although in these cases, these are associated with primarily relatively persistent unidirectional currents and colonized by elements of the *Skolithos* Ichnofacies. However, similarities between the weakly storm-dominated lower shoreface and "rippled sand sheets" arise as both are transitional with heterolithic deposits (FA5) (Veiga and Schwarz, 2017). Intervals within a strongly storm-dominated lower shoreface (FA6) without significant erosion may experience low energy reworking preserving wave and combined ripples (Buatois and Mángano, 2011; Pemberton et al., 2012), suggesting a waning-flow stage where both purely oscillatory and combined (oscillatory and unidirectional) flows are recorded (Myrow and Southard, 1991, 1996; Schwarz, 2012) and categorized within FA7.

Within the weakly storm-dominated lower shoreface (FA7), *Gyrochorte comosa* is the most abundant ichnotaxon (Fig. 8C–D). These deposits exhibit the highest ichnodiversity in the study with several subordinate ichnotaxa, namely *Thalassinoides* isp.,? *Scolicia* isp. (Fig. 8E), *Lockeia siliquaria* (Figs. 7D, and 8D), *Ophiomorpha irregulaire*, and *Spongeliomorpha* isp. (Fig. 8A–B), as well as accessory ichnotaxa, such as *Hillichnus* isp., *Arenituba verso* (Fig. 8F), *Teichichnus rectus* (Fig. 7E), and *Protovirgularia* isp. Overall, the ichnofauna of the weakly storm-affected lower shoreface (FA7) illustrates the archetypal *Cruziana* Ichnofacies, in contrast to the *Skolithos* Ichnofacies of the strongly

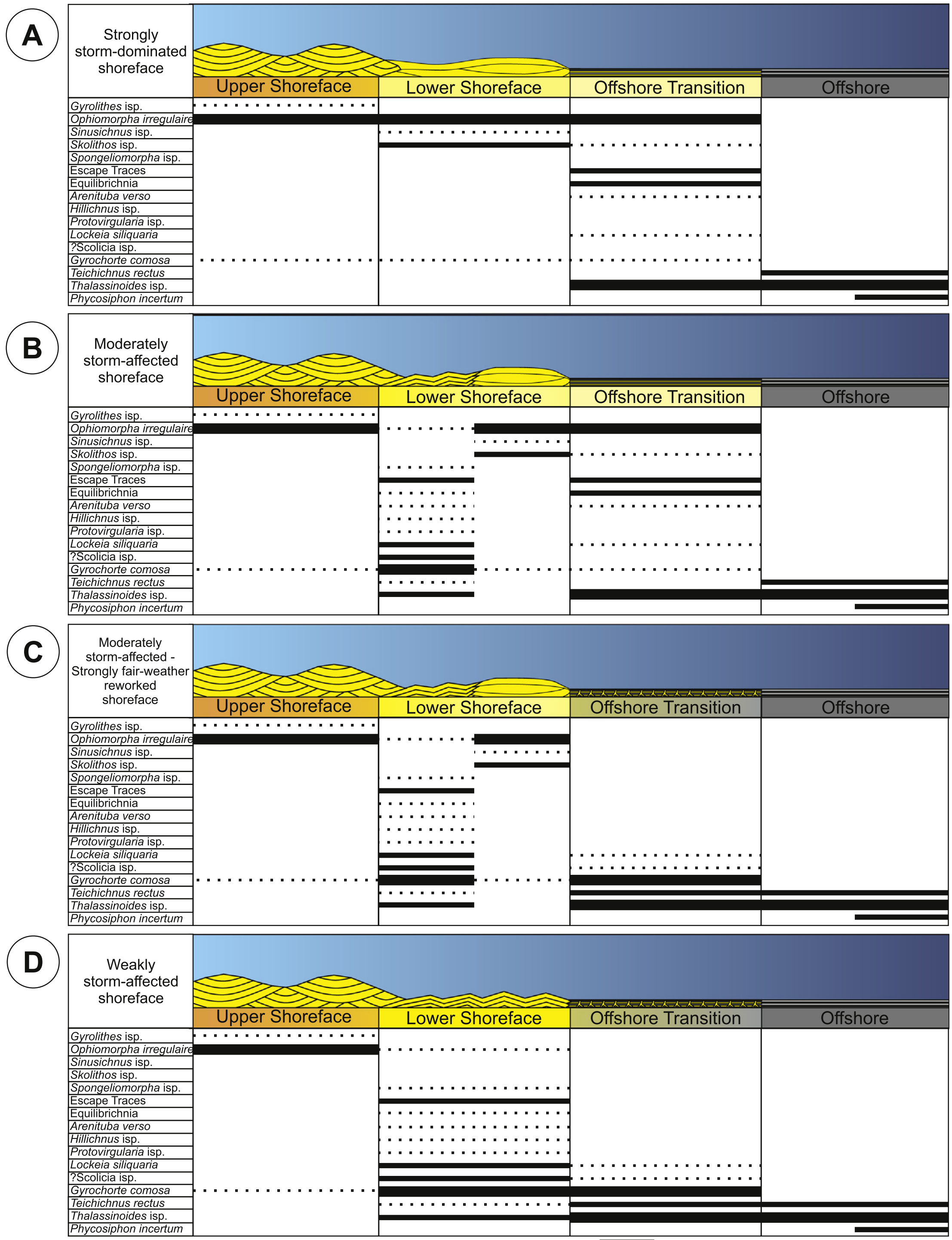

Fig. 9. Ichnoassemblages from shoreface complexes. (A). Strongly storm-dominated shoreface. (B) Moderately storm-affected shoreface. (C). Moderately storm-affected – strongly fair-weather reworked shoreface. (D) Weakly storm-affected shoreface, partitioned into the offshore, offshore transition, lower shoreface, and upper shoreface. Intensity of ichnofauna present from highest to lower; dominant, subordinate, and accessory (modified from Veiga and Schwarz, 2017).

storm-dominated lower shoreface (FA6) (MacEachern and Pemberton, 1992).

5.3. Intra-parasequence architecture

Intra-parasequence architecture has been studied in detail elsewhere over the years, evolving with the use of technology, as seen in numerical modeling utilizing the BARISM model, allowing evaluation of causational mechanisms of intra-parasequence variability; changes in sea level, sediment supply, and wave-height regime (O'Byrne and Flint, 1995; Pattison, 1995; Hampson, 2000, 2010, 2016; Hampson and Storms, 2003; Hampson and Howell, 2005; Storms and Hampson, 2005; Sømme et al., 2008; Charvin et al., 2010, 2011). Intra-parasequence architecture can be affected by both allogenic (i.e. tectonic subsidence, sea-level, and sediment influx) and autogenic (i.e. hydrodynamic) controls (Hampson, 2016) that commonly result

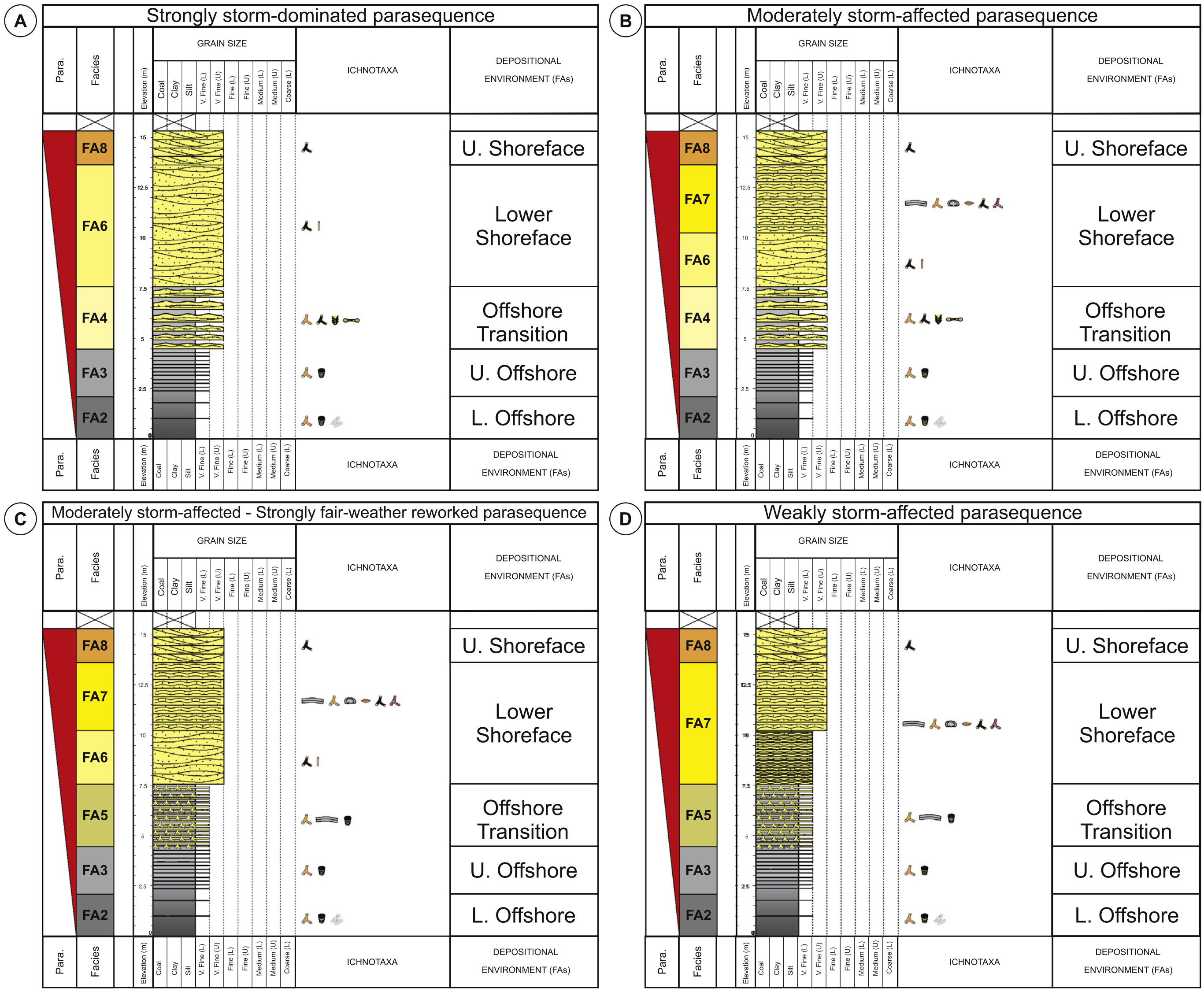

Fig. 10. Parasequence and intra-parasequence architectural variation. Four distinct types of parasequences were identified based on varying degrees of storm influence. (A). Strongly storm-dominated parasequence. (B). Moderately storm-affected parasequence. (C). Moderately storm-affected – strongly fair-weather reworked parasequence. (D). Weakly storm-affected parasequence. Accessory ichnotaxa not included. Within the lower offshore (FA2), *Thalassinoides* isp. Dominates, with *Teichichnus rectus* and *Phycosiphon incertum* subordinate. Upper offshore (FA3); *Thalassinoides* isp. Dominant, and *Teichichnus rectus* subordinate. Storm-dominated offshore transition (FA4); *Thalassinoides* isp. and *Ophiomorpha irregulaire* dominant, escape traces and equilibrium structures subordinate. Weakly storm-affected offshore transition (FA5); *Thalassinoides* isp. and *Gyrochorte comosa* dominant, *Teichichnus rectus* subordinate. Storm-dominated lower shoreface (FA6); *Ophiomorpha irregulaire* dominant, and *Skolithos* isp. Subordinate. Weakly storm-affected lower shoreface (FA7); *Gyrochorte comosa* dominant, *Thalassinoides* isp., ?*Scolicia* isp., *Lockeia siliquaria*, *Ophiomorpha irregulaire*, *Spongeliomorpha* isp. and escape trace fossils subordinate. Upper shoreface (FA8); *Ophiomorpha irregulaire* dominant.

in rearrangement of shoreline geometry that has a direct effect on local sediment supply and storm-wave influence (Charvin et al., 2010). Within the study section, four main types of parasequences have been identified on the basis of parasequence architecture; (1) Strongly storm-dominated parasequence, (2) Moderately storm-affected parasequence, (3) Moderately storm-affected – strongly fair-weather reworked parasequence, and (4) Weakly storm-affected parasequence (Fig. 10). Variability within parasequence architecture include changes in both the offshore transition (FA4 and FA5), and lower shoreface (FA6 and FA7) facies associations as previously discussed.

5.4. Strongly storm-dominated parasequence

In a strongly storm-dominated parasequence (Figs. 10A, and 11A), deposition occurs under pervasive high energy conditions where storm waves are the dominant physical process, resulting in a parasequence including lower offshore (FA2), upper offshore (FA3) storm-dominated offshore transition (FA4), storm-dominated lower shoreface (FA6), and upper shoreface (FA8) deposits. Within the strongly storm-dominated parasequence, paleoenvironmental controls dictate the presence of the *Skolithos* Ichnofacies (MacEachern and Pemberton, 1992) with the observed ichnoassemblage dominated by *Thalassinoides* isp. and *Ophiomorpha irregulaire* (Fig. 7A) within the tempestites of the storm-dominated offshore transition (FA4), and overwhelmingly by *Ophiomorpha irregulaire* (Fig. 7B–C) in the storm-dominated lower shoreface (FA6). Under pervasive fully marine conditions, oxygen remains high throughout progradation with high degrees of turbulence at the sediment water interface, increasing with reduced proximity to the shoreline. As a result of these conditions, a high abundance of *Ophiomorpha irregulaire* throughout the storm-dominated offshore transition (FA4) to upper shoreface (FA8) is observed in these shallow marine, high energy environments (Frey et al., 1978; Curran, 2007; Buatois et al., 2016).

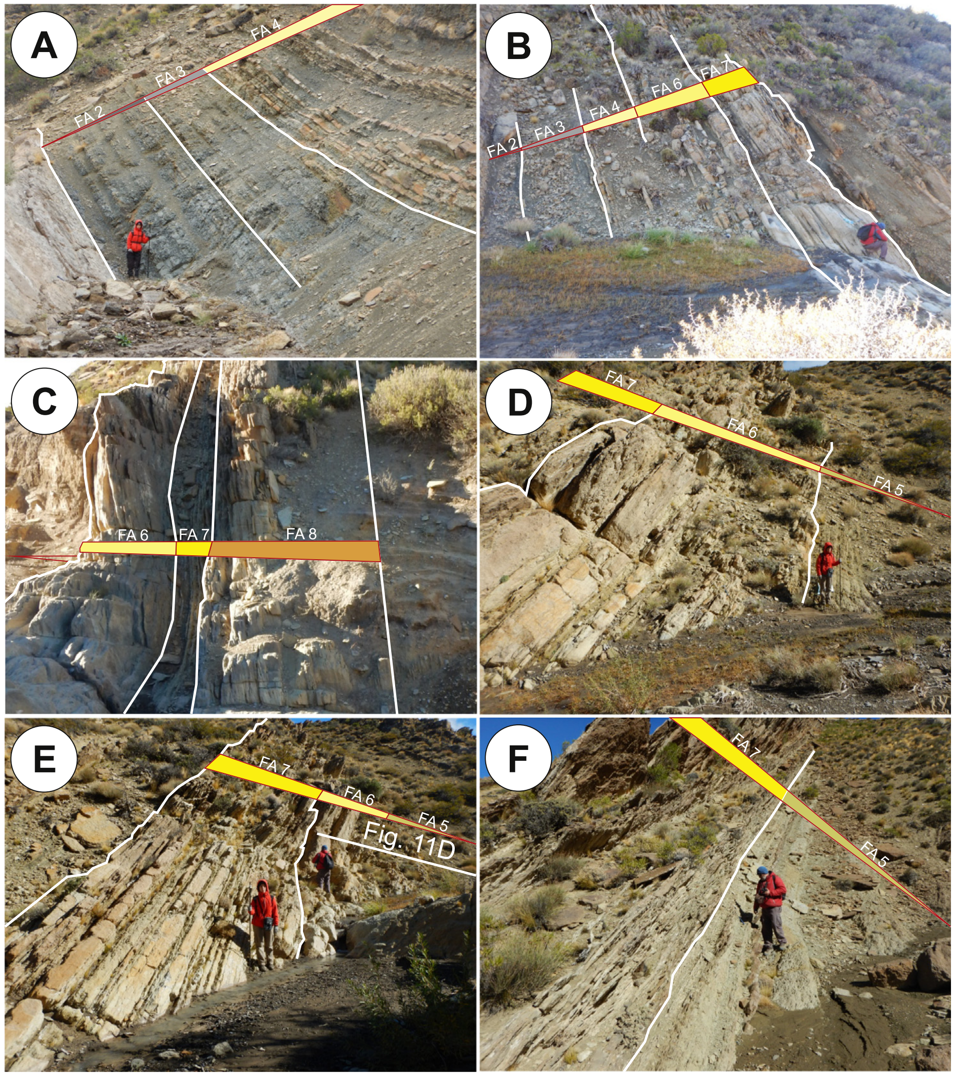

Fig. 11. Outcrop view of parasequences architecture. (A). Strongly storm-dominated parasequence. Lower offshore to offshore transition (FA 2, FA 3, and FA 4). FA 9 located beneath the parasequence. (B). Moderately storm-affected parasequence. Offshore (FA 2, FA 3), offshore transition (FA 4), and lower shoreface (FA 6, FA 7). (C). Lower shoreface (FA 6, FA 7) to upper shoreface (FA 8). (D). Moderately storm-affected – strongly fair-weather reworked parasequence. Offshore transition (FA 4), to lower shoreface (FA 6) in foreground. (E). Lower shoreface (FA 7) in foreground. (F). Weakly storm-affected parasequence. Offshore transition (FA 5) to lower shoreface (FA 7).

5.5. Moderately storm-affected parasequence

The moderately storm-affected parasequence (Figs. 10B, and 11B) comprises the lower offshore (FA2), upper offshore (FA3), storm-dominated offshore transition (FA4), storm-dominated lower shoreface (FA6), weakly storm-affected lower shoreface (FA7), and upper shoreface (FA8) deposits. Within this parasequence, storm wave action is pervasive until undergoing a waning-flow stage, represented by the weakly storm-affected lower shoreface (FA7), where both purely oscillatory and combined (oscillatory and unidirectional) flows developed (Fig. 9C). From an ichnologic perspective, this parasequence is characterized by alteration of the *Skolithos* and *Cruziana* ichnofacies within the lower shoreface represented by the storm-dominated lower shoreface (FA6) and the weakly storm-affected lower shoreface (FA7), respectively.

5.6. Moderately storm-affected – strongly fair-weather reworked parasequence

The moderately storm-affected – strongly fair-weather reworked parasequence (Figs. 10C, and 11D–E), features storm deposits reworked thoroughly by fair-weather waves and comprises the lower offshore (FA2), upper offshore (FA3), weakly storm-affected offshore transition (FA5), storm-dominated lower shoreface (FA6), weakly storm-affected lower shoreface (FA7), and upper shoreface (FA8) deposits. Fair-weather oscillatory and combined flows dominated in the weakly storm-affected offshore transition (FA5), followed by an increase in storm activity depicted by deposition of storm-dominated lower shoreface (FA6), before being reclaimed by fair-weather oscillatory and combined flows of the waning-flow stage of the weakly storm-affected lower shoreface (FA7). During this process, the fair-weather waves thoroughly reworked the underlying storm-dominated lower shoreface deposits and are diagnostic in the classification as fair-weather waves are dominant to storm-waves in this type of parasequence. During fair-weather wave reworking, elements of the *Cruziana* Ichnofacies are overprinted upon relict elements of the *Skolithos* Ichnofacies from previous storm induced deposition.

5.7. Weakly storm-affected parasequence

The weakly storm-affected parasequence (Figs. 10D, and 11F) is associated with lower energy conditions where storm influence is subordinate to combined low oscillatory and weak to absent unidirectional flows (Dumas and Arnott, 2006). Complete parasequence architecture consists of lower offshore (FA2), upper offshore (FA3), weakly storm-affected offshore transition (FA5), weakly storm-affected lower shoreface (FA7), and upper shoreface (FA8). Within the weakly storm-affected parasequence, paleoenvironmental controls in this scenario favor the establishment of the *Cruziana* Ichnofacies (MacEachern and Pemberton, 1992). The ichnoassemblage observed here is dominated primarily by *Thalassinoides* isp. and *Gyrochorte comosa* in the offshore transition, and by *Gyrochorte comosa* within the lower shoreface, and similar to the storm-dominated offshore transition and lower shoreface, waters were fully marine with relatively high degrees of oxygen, only differing in reduced turbulence within the weakly storm-affected parasequence.

6. Discussion

Shorefaces are open-marine, low gradient (1:200), seaward-sloping sediment ramps situated between the basal fair-weather wave base and the upper low-tide line, partitioned into three regions; the lower, middle and upper (Walker and Plint, 1992). In each region of the typical shoreface-shelf profile, different processes affect the sediment water interface. In the lower shoreface, located above the fair-weather wave base (Reinson, 1984; Walker and Plint, 1992), wave action is the dominant process (Walker and Plint, 1992). In the middle shoreface, shoaling and initial breaking of waves occur (Reinson, 1984; Clifton, 2006) under high energy conditions, sustaining migration of longshore bars (Walker and Plint, 1992). In the upper shoreface, beneath the low-tide line, multidirectional current flows in the build-up and surf zone are the dominant process, reflecting the highest energy conditions (Clifton et al., 1971; Komar, 1976; Walker and Plint, 1992).

During storm activity, storm-driven shelf current systems occur as the storm-induced onshore winds causing nearshore waters at the sediment-water interface to move seawards and deflected due to the Coriolis effect migrating along and offshore via combined flow (Swift et al., 1986; Duke, 1990; Walker and Plint, 1992; Plint, 2010). These types of storm-driven shelf currents include (1) relatively slow-moving unidirectional, coast-parallel to coast-oblique geostrophic flows culminating from wind stress on the water surface, and (2) fast-moving oscillatory flows resulting from wave motion propagation reaching depths of the sediment-water interface (Swift et al., 1986; Plint, 2010). Interaction between the resulting storm waves in the shallow waters and the sediment results in symmetrical elliptical patterns that preferentially moves the finer sand seaward towards the storm-wave base; however, during fair-weather, normal conditions, strongly asymmetrical elliptical conditions dominate, moving coarser sands preferentially landwards (Clifton, 2006; Plint, 2010).

6.1. Shoreface variability

Shoreface variability, assessed by both sedimentologic and ichnologic variation, is the greatest within the lower-middle shoreface (MacEachern and Pemberton, 1992). This variation results in different taphonomic pathways for emplacement and preservation of biogenic structures (Buatois and Mángano, 2011), facilitating categorization of three major types of shorefaces for storm-induced variability; (1) strongly storm-dominated (high energy), (2) moderately storm-dominated (intermediate energy), and (3) weakly storm-affected (low energy) (MacEachern and Pemberton, 1992).

Strongly storm-dominated shorefaces (Fig. 9A) lead to erosionally amalgamated tempestites with hummocky cross-stratification (HCS) and swaley cross-stratification (SCS) with few preserved biogenic structures (MacEachern and Pemberton, 1992; Pemberton et al., 2012), occurring when there is a short-term colonization window as erosion is facilitated by repeated storm events resulting in preservation of only the deepest tiered structure of vertical domiciles of the *Skolithos* Ichnofacies (MacEachern et al., 2010; Plint, 2010; Buatois and Mángano, 2011). Moderately storm-dominated shorefaces lead to alternating stacked tempestites and fair-weather beds displaying a lam-scram appearance (MacEachern and Pemberton, 1992; Pemberton et al., 2012). This type of shoreface occurs when moderate to little erosion occurs on a climax community, followed by renewed storm deposition, resulting in alternating intervals of the storm primary fabric overprinted by elements of the *Skolithos* Ichnofacies and bioturbated intervals containing representatives of the fair-weather suite *Cruziana* Ichnofacies (MacEachern and Pemberton, 1992; Buatois and Mángano, 2011). Weakly storm-affected shorefaces (Fig. 9D) lead too little to no preservation of tempestites and a succession dominated by fair-weather deposits that are heavily bioturbated (MacEachern and Pemberton, 1992; Pemberton et al., 2012), displaying high ichnodiversity and dominated by infaunal feeding structures of a climax community illustrating the *Cruziana* Ichnofacies. In addition to the already bioturbated fair-weather deposits, storm beds in weakly storm-affected shorefaces may be completely biogenically reworked (Buatois et al., 2002, 2003; Carmona et al., 2008; Buatois and Mángano, 2011). This type of shoreface occurs when there is a very long-term colonization window with little to no erosion (Buatois and Mángano, 2011). Conversely, in some cases where only the highest energy conditions prevail in the lower and middle shorefaces, this results in these facies being classified together as the lower-middle shoreface (MacEachern and Pemberton, 1992; Mángano et al., 2005; Plint, 2010). Energy variations vertically throughout the parasequence also affect other factors, including the degree of oxygenation, sand content, amount of organic particles in suspension, and mobility of the substrate (Pemberton et al., 1992; Buatois and Mángano, 2011).

At present, the shoreface ternary diagram has been developed to distinguish fair-weather waves, storm waves, and tides (Dashtgard et al., 2012; Pemberton et al., 2012); however, storm-affected, storm-influenced, and storm-dominated shorefaces represent the spectrum of wave-dominated shoreface settings, facilitating a classification scheme based on storm wave action alone (cf. MacEachern and Pemberton, 1992; Dashtgard et al., 2012). The tripartite spectrum of wave-dominated shorefaces in correspondence with the relatively newly designated tide-influenced and tidally modulated shorefaces (Fig. 12) (Dashtgard et al., 2009) provide increased resolution in shorefaces exposed to a range of storm-waves and tides. Tidally influenced shorefaces (TIS) have been identified only recently and are formed on coastal environments with strong tidal currents, such as strait margins and embayments, which produce grain sizes that are

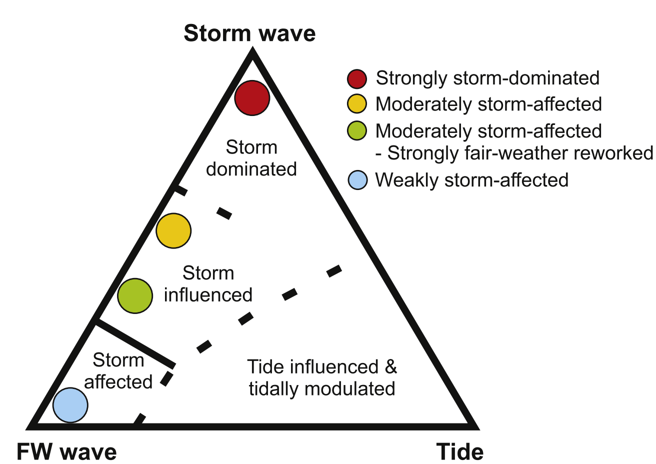

Fig. 12. Conceptual shoreface model ternary diagram designed to illustrate the three main influences on deposition at the sediment substrate interface: storm waves, fair-weather (FW) waves, and tides, with locations of all shorefaces described here spatially represented on the diagram. The newly observed moderately storm-affected – strongly fair-weather reworked shoreface, displays a dominance of fair-weather waves that thoroughly reworks preceding storm-wave beds (modified from Dashtgard et al., 2012).

relatively similar or increase distally from the shoreface to offshore, corresponding with a decreased percentage of mud content in the sediment (Frey and Dashtgard, 2011; Pemberton et al., 2012). Tidally modulated shorefaces (TMS), like tidally influenced shorefaces (TIS), are also relatively newly described (Dashtgard et al., 2009, 2012). These type of shorefaces occurs on the end member for the wave-tidal spectrum settings (Fig. 12) indicating tidal settings prone to strong wave energy resulting in lateral movement of wave zones across the shoreface-shelf profile in response to tidal action (Pemberton et al., 2012). However, even with this relatively new increased in resolution, this scheme cannot fully accommodate the broad range of shoreface variability (Dashtgard et al., 2012).

Shorefaces shaped by fair-weather waves have remained understudied because standard classification schemes for wave-dominated shorefaces have been formulated based on storm wave action alone (cf. MacEachern and Pemberton, 1992; Dashtgard et al., 2012). A newly identified shoreface, previously overlooked by past literature, consists of a shoreface comprising storm deposits reworked thoroughly by fair-weather waves, here referred to as the moderately storm-affected – strongly fair-weather reworked shoreface (Fig. 9C), represented in the study area as the moderately storm-affected – strongly fair-weather reworked parasequence (Figs. 10C, and 12). In contrast to the strongly storm-dominated (Fig. 10A) and weakly storm-affected parasequences (Fig. 10D), which both have been shaped by distinct depositional processes, the moderately storm-affected (Fig. 10B) and moderately storm-affected – strongly fair-weather reworked parasequences (Fig. 10C) have architectural elements of both the storm-dominated and weakly storm-affected parasequences.

The moderately storm-affected parasequence bears resemblance to several intervals of alternating weakly storm-affected and strongly storm-dominated shorefaces in the Spring Canyon and Sunnyside members of the Blackhawk Formation in the shallow-marine, epeiric Western Interior Seaway deposits of Utah (MacEachern and Pemberton, 1992; O'Byrne and Flint, 1995; Pattison, 1995). Intra-parasequence scale autogenic variation (hydrodynamic energy) of the Aberdeen and Sunnyside members indicates that more proximally, localized fluvial deposits underwent variation in sediment input and current velocity, facilitating deltaic lobe switching during progradation, modifying the local wave climate by redistributing sand via waves and longshore currents (Hampson and Howell, 2005; Storms and Hampson, 2005; Sømme et al., 2008; Charvin et al., 2010; Hampson, 2016). Sands that were redistributed alongshore formed spits and barriers, protecting certain locations of the shoreface where weakly storm-affected lower shorefaces (FA7) could be deposited in an otherwise storm-dominated environment in lieu of the storm-dominated lower shoreface (FA6). Longshore drift currents supplied the sediment from the gradual erosion of the abandoned fluvially fed promontory and as sands filled the protected, topographic low behind the spits and barriers, they were once again subject to wave and current processes switching back to a strongly storm-dominated shoreface (Charvin et al., 2011), as seen in the moderately storm-affected parasequence (Fig. 10B). Like the Blackhawk Formation with deltaic sands coming from the west, in the Mulichinco Formation, high volumes of sands were transported distally down the relatively steep fluvial and shelf gradient producing river-dominated deltaic deposits, associated with broad coeval fluvial deposit to the south and eastern portion of the Neuquén Basin (Schwarz et al., 2006).

6.2. Moderately storm-affected – strongly fair-weather reworked shoreface

In the newly described shoreface presented here, the moderately storm-affected – strongly fair-weather reworked shoreface (Fig. 9C), this shoreface features storm deposits reworked thoroughly by fair-weather waves. Within this shoreface, the moderately storm-affected – strongly fair-weather reworked parasequence (Fig. 10C), records a period where fair-weather oscillatory and combined flows dominated in the weakly storm-affected offshore transition (FA5), followed by an increase in storm activity depicted by deposition of storm-dominated lower shoreface (FA6), before being reclaimed by fair-weather oscillatory and combined flows of the waning-flow stage of the weakly storm-affected lower shoreface (FA7). Fair-weather waves thoroughly reworked the underlying storm-dominated lower shoreface deposits and are diagnostic in the classification as fair-weather waves are dominant to storm-waves in this type of shoreface (Figs. 9C, and 12). Vertical facies patterns suggest that this type of shoreface records high intensity but low frequency of storms in an environment regularly affected by vigorous fair-weather waves. For storm deposits to be thoroughly reworked by fair-weather waves as seen here in the moderately storm-affected – strongly fair-weather dominated shoreface, large fair-weather waves characterized by oscillatory flow would have occurred pervasively, facilitated by multiple factors including distantly generated storm swells (Peters and Loss, 2012). The shallow water epeiric seaway, filing the Neuquén Basin at the time of deposition, would have provided ideal circumstances for increased wind speed and duration, as well as an expansive fetch to generate large fair-weather waves. The ramp type morphology of the basin extending from the west would have provided expansive regions of deposition above the fair-weather wave base, where these large fair-weather waves would have had the opportunity to interact with the sediment water interface, reworking previous storm deposits.

7. Conclusions

1. Shorefaces can display strong sedimentologic and ichnologic variability which can be assessed in order to provide a high-resolution model to identify variations between storm-dominated and weakly storm-affected facies. In addition, to help determine shoreface variability, ichnology can be used to help delineate parasequences by the fact that trace-fossil associations are excellent indicators of environmental conditions that typically change along the depositional profile. Shallow-marine parasequences of the Mulichinco Formation within the Neuquén Basin of western Argentina, were mapped to evaluate stress factors exhibited by parasequence architecture.
2. Four distinct types of parasequence architecture were described within the study sections. All four variants of parasequences are capped by an upper shoreface (FA8), and are underlain by lower and upper offshore deposits; FA2 and FA3, respectively.

   1) Strongly storm-dominated parasequence: storm wave action is pervasive throughout the parasequence represented by storm-dominated offshore transition (FA4), and storm-dominated lower shoreface (FA6) deposits.
   2) Moderately storm-affected parasequence: wave action is the dominant physical process followed by a waning-flow stage where both purely oscillatory and combined (oscillatory and unidirectional) flows occur. This is represented in the studied parasequences by a storm-dominated offshore transition (FA4), storm-dominated lower shoreface (FA6) succession diverging from the storm-dominated parasequence, as weakly storm-affected lower shoreface (FA7) strata is located directly above the storm-dominated lower shoreface (FA6).
   3) Moderately storm-affected – strongly fair-weather reworked parasequence: storm-wave action is subordinate to fair-weather waves. Wave action initially holds a decreased influence on the sediment substrate, represented by a weakly storm-affected offshore transition (FA5), eventually increasing with an increased storm presence and frequency in the lower shoreface characterized by storm-dominated lower shoreface (FA6), before moving back to a fair-weather dominated scheme undergoing pervasive fair-weather wave action which reworked the previously deposited storm-dominated lower shoreface into the weakly storm-affected lower shoreface (FA7).

4) Weakly storm-affected parasequence: storm wave action operates at both a lower magnitude and duration, where deposits are indicative of fair-weather combined oscillatory and unidirectional flows represented by weakly storm-affected offshore transition (FA5), and weakly storm-affected lower shoreface (FA7) strata.

3. For each idealized parasequence, parasequence and intra-parasequence architecture dictates varying degrees of storm and fair-weather wave influence on the sediment substrate interface, affected by both allogenic (i.e. tectonic subsidence, sea-level, and sediment influx) and autogenic (i.e. hydrodynamic) controls. The new type of shoreface described here, the moderately storm-affected – strongly fair-weather reworked shoreface, observes fair-weather wave dominance to storm waves, as the fair-weather deposits thoroughly rework the higher energy, storm-dominated lower shoreface sandstones. The previous classification scheme, which was focused on the role of storm-waves, has been altered to encompass this newly defined shoreface.

Acknowledgments

This work was supported by NSERC discovery grants 311726-13 and 311727-15 to L.A.B., and M.G.M., respectively. We thank Debora Campetella for her aid in the fieldwork. Comments by Bill Arnott, Sedimentary Geology reviewers Ernesto Schwartz and Francisco Rodriguez-Tovar and editor Brian Jones helped to improve this manuscript.

References

Aguirre-Urreta, M.B., Rawson, P.F., Concheyro, G.A., Bown, P.R., Ottone, E.G., 2005. Lower Cretaceous biostratigraphy of the Neuquén Basin. In: Veiga, G.D., Spalletti, L.A., Howell, J.A., Schwarz, E. (Eds.), The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics. Geological Society of London, Special Publication vol. 252, pp. 57–81.
Anderton, R., 1976. Tidal-shelf sedimentation: an example from the Scottish Dalradian. Sedimentology 23, 429–458.
Belderson, R.H., Johnson, M.A., Kenyon, N.H., 1982. Bedforms. In: Stride, A.H. (Ed.), Offshore Tidal Sands: Processes and Deposits. Chapman & Hall, London, pp. 27–57.
Buatois, L.A., Mángano, M.G., 2011. Ichnology: Organism-Substrate Interactions in Space and Time. Cambridge University Press, Cambridge, UK.
Buatois, L.A., Mángano, M.G., Alissa, A., Carr, T.R., 2002. Sequence stratigraphic and sedimentologic significance of biogenic structures from a late Paleozoic marginal to open-marine reservoir, Morrow Sandstone, subsurface of southwest Kansas, USA. Sedimentary Geology 152, 99–132.
Buatois, L.A., Bromley, R.G., Mángano, M.G., Bellosi, E., Carmona, N.B., 2003. Ichnology of shallow marine deposits in the Miocene Chenque Formation of Patagonia: complex ecologic structure and niche partitioning in Neogene ecosystems. In: Buatois, L.A., Mángano, M.G. (Eds.), Icnología: Hacia una convergencia entre geología y biología. Publicación Especial de la Asociación Paleontológica Argentina vol. 9, pp. 85–95.
Buatois, L.A., Carmona, N.B., Curran, H.A., Netto, R.G., Mángano, M.G., Wetzel, A., 2016. The Mesozoic marine revolution. In: Mángano, M.G., Buatois, L.A. (Eds.), The Trace-Fossil Record of Major Evolutionary Events. Springer, Netherlands, pp. 24–27.
Burchette, T.P., Wright, V.P., Faulkner, T.J., 1990. Oolitic sandbody depositional models and geometries, Mississippian of southwest Britain: implications for petroleum exploration in carbonate ramp settings. Sedimentary Geology 68, 87–115.
Carmona, N.B., Buatois, L.A., Mángano, M.G., Bromley, R.G., 2008. Ichnology of the Lower Miocene Chenque Formation, Patagonia, Argentina: animal–substrate interactions and the Modern Evolutionary Fauna. Ameghiniana 45, 93–122.
Catuneanu, O., 2006. Principles of sequence stratigraphy. Elsevier Publications, Oxford, UK.
Charvin, K., Hampson, G.J., Gallagher, K.L., Labourdette, R., 2010. Intraparasequence architecture of an interpreted asymmetrical wave-dominated delta. Sedimentology 57, 760–785.
Charvin, K., Hampson, G.J., Gallagher, K.L., Storms, J.E.A., Labourdette, R., 2011. Characterization of controls on high-resolution stratigraphic architecture in wave-dominated shoreface–shelf parasequences using inverse numerical modelling. Journal of Sedimentary Research 81, 562–578.
Christ, N., Immenhauser, A., Amour, F., Mutti, M., Tomas, S., Agar, S.M., Alway, R., Kabiri, L., 2012. Characterization and interpretation of discontinuity surfaces in a Jurassic ramp setting (High Atlas, Morocco). Sedimentology 59, 249–290.
Clifton, H.E., 1976. Wave-formed sedimentary structures - a conceptual model. In: Davis Jr., R.A., Ethington, R.L. (Eds.), Beach and Nearshore Sedimentation. Society for Sedimentary Geology (SEPM), Special Publication 24, pp. 126–148.
Clifton, H.E., 2006. A re-examination of facies models for clastic shorefaces. In: Posamentier, H.W., Walker, R.G. (Eds.), Facies Models Revisited. Society for Sedimentary Geology (SEPM), Special Publication 84, pp. 293–337.
Clifton, H.E., Hunter, R.E., Phillips, R.L., 1971. Depositional structures and processes in the non-bar high energy nearshore. Journal of Sedimentary Petrology 41, 651–670.
Curran, H.A., 2007. Ichnofacies, ichnocoenoses and ichnofabrics of Quaternary shallow-marine to dunal tropical carbonates: a model and implications. In: Miller III, W. (Ed.), Trace Fossils: Concepts, Problems, Prospects, Amsterdam, pp. 232–247.
Dashtgard, S.E., Gingras, M.K., MacEachern, J.A., 2009. Tidally modulated shorefaces. Journal of Sedimentary Research 79, 793–807.
Dashtgard, S.E., MacEachern, J.A., Frey, S.E., Gingras, M.K., 2012. Tidal effects on shorefaces: towards a conceptual framework. Sedimentary Geology 279, 42–61.
Dott Jr., H.R., 1983. Episodic sedimentation - how normal is average? How rare is rare? Does it matter? Journal of Sedimentary Petrology 53, 5–23.
Dott Jr., H.R., 1988. An episodic view of shallow marine classic sedimentation. In: Debor, P.L., Van Gelder, A., Nio, S.D. (Eds.), Tide-Influenced Sedimentary Environments and Facies. D. Reidel Publishing, Dordrecht, pp. 3–12.
Duke, W.L., 1990. Geostrophic circulation or shallow marine turbidity currents? The dilemma of paleoflow patterns in storm-influenced prograding shoreline systems. Journal of Sedimentary Petrology 60, 870–883.
Dumas, S., Arnott, R.W.C., 2006. Origin of hummocky and swaley cross-stratification - the controlling influence of unidirectional current strength and aggradation rate. Geology 34, 1073–1076.
Dumas, S., Arnott, R.W.C., Southard, J.B., 2005. Experiments on oscillatory-flow and combined-flow bedforms: implications for interpreting parts of the shallow-marine sedimentary record. Journal of Sedimentary Research 75, 501–513.
Echevarría, J., Damborenea, S.E., Manceñido, M.O., 2012. Palaeodemecological analysis of infaunal bivalves "Lebensspuren" from the Mulichinco Formation, Lower Cretaceous, Neuquén Basin, Argentina. Ameghiniana 49, 47–59.
Frey, S.E., Dashtgard, S.E., 2011. Sedimentology, ichnology and hydrodynamics of strait-margin, sand and gravel beaches and shorefaces: Juan de Fuca Strait, British Columbia, Canada. Sedimentology 58, 1326–1346.
Frey, R.W., Howard, J.D., Pryor, W.A., 1978. *Ophiomorpha*: its morphologic, taxonomic and environmental significance. Palaeogeography, Palaeoclimatology, Palaeoecology 23, 199–229.
Greenwood, B., Mittler, P.R., 1985. Vertical sequence and lateral transitions in the facies of a barred nearshore environment. Journal of Sedimentary Petrology 55, 366–375.
Groeber, P., 1946. Observaciones geológicas a lo largo del meridiano 70. 1. Hoja Chos Malal. Asociación Argentina de Sedimentología Revista 20, 177–208.
Gulisano, C.A., Gutiérrez Pleimling, A.R., Digregorio, R.E., 1984. Análisis estratigráfico del intervalo Tithoniano–Valanginiano (Formaciones Vaca Muerta, Quintuco y Mulichinco) en el suroeste de la Provincia de Neuquén. IX Congreso Geológico Argentino 1, pp. 221–235.
Hampson, G.J., 2000. Discontinuity surfaces, clinoforms, and facies architecture in a wave-dominated, shoreface-shelf parasequence. Journal of Sedimentary Research 70, 325–340.
Hampson, G.J., 2010. Sediment dispersal and quantitative stratigraphic architecture across an ancient shelf. Sedimentology 57, 96–141.
Hampson, G.J., 2016. Towards a sequence stratigraphic solution set for autogenic processes and allogenic controls: Upper Cretaceous strata, Book Cliffs, Utah, USA. Journal of the Geological Society 173, 817–836.
Hampson, G.J., Howell, J.A., 2005. Sedimentologic and geomorphic characterization of ancient wave-dominated shorelines: examples from the Late Cretaceous Blackhawk Formation, Book Cliffs, Utah. In: Bhattacharya, J.P., Giosan, L. (Eds.), Deltas Old and New. Society for Sedimentary Geology (SEPM), Special Publication 83, pp. 133–154.
Hampson, G.J., Storms, J.E.A., 2003. Geomorphological and sequence stratigraphic variability in wave-dominated, shoreface–shelf parasequences. Sedimentology 50, 667–701.
Hart, B.S., Plint, A.G., 1995. Gravelly shoreface and beachface deposits. In: Plint, A.G. (Ed.), Sedimentary Facies Analysis: A Tribute to the Research and Teaching of Harold G. Reading. Blackwell Publishing Ltd, Oxford, UK, pp. 75–99.
Hönig, M.R., John, C.M., 2015. Sedimentological and isotopic heterogeneities within a Jurassic carbonate ramp (UAE) and implications for reservoirs in the Middle East. Marine and Petroleum Geology 68, 240–257.
Howell, J.A., Schwarz, E., Spalletti, L.A., Veiga, G.D., 2005. The Neuquén Basin: an overview. In: Veiga, G.D., Spalletti, L.A., Howell, J.A., Schwarz, E. (Eds.), The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics. Geological Society of London, Special Publication vol. 252, pp. 1–14.
James, N.P., 1997. The cool-water carbonate depositional realm. In: James, N.P., Clarke, J.A.D. (Eds.), Cool-Water Carbonates. Society for Sedimentary Geology (SEPM), Special Publication 56, pp. 1–20.
Kachel, N.B., Smith, J.D., 1986. Geological impact of sediment transporting events on the Washington continental shelf. In: Knight, R.J., McLean, J.R. (Eds.), Shelf Sands and Sandstones. Canadian Society of Petroleum Geologists Memoir vol. 11, pp. 145–162.
Komar, P.D., 1976. Beach Processes and Sedimentation: Englewood Cliffs. Prentice Hall, Upper Saddle River, NJ, p. 429.
Leanza, H.A., 1993. Estratigrafía del Mesozoico posterior a los Movimientos Intermálmicos en la comarca del Cerro Chachil, provincia del Neuquén. Revista de la Asociación Geológica Argentina 48, 71–84.
Leanza, H.A., Marchese, H.G., Riggi, J.C., 1977. Estratigrafía del Grupo Mendoza con especial referencia a la Formación Vaca Muerta entre los Paralelos 35° y 40° l.s. Cuenca Neuquina-Mendocina. Revista de la Asociación Geológica Argentina 32, 190–208.
Legarreta, L., Gulisano, C.A., 1989. Análisis estratigráfico secuencial de la Cuenca Neuquina (Triásico Superior-Terciario inferior). In: Chebli, G., Spalletti, L.A. (Eds.), Cuencas Sedimentarias Argentinas. Serie Correlación Geológica vol. 6, pp. 221–243.
Legarreta, L., Uliana, M.A., 1991. Jurassic-Cretaceous marine oscillations and geometry of a back-arc basin fill, central Argentine Andes. In: MacDonald, D.I.M. (Ed.), Sedimentation, Tectonics and Eustasy. Sea level Changes at Active Margins. International Association of Sedimentologists, Special Publication 12, pp. 429–450.

Liberman, A., Schwarz, E., Veiga, G.D., 2014. Caracterización Paleoambiental y secuencial de reservorios de la Formación Mulichinco en el yacimiento Aguada del Chivato (sector nororiental de Cuenca Neuquina, Argentina): su contribución para el desarrollo de un campo aún inmaduro. IX Congreso de Exploración y Desarrollo de Hidrocarburos, Trabajos Técnicos, pp. 351–373.

MacEachern, J.A., Bann, K.L., 2008. The role of ichnology in refining shallow marine facies models. In: Hampson, G., Steel, R., Burgess, P., Dalrymple, R. (Eds.), Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy. Society for Sedimentary Geology (SEPM), Special Publications 90, pp. 73–116.

MacEachern, J.A., Pemberton, S.G., 1992. Ichnological aspects of Cretaceous shoreface successions and shoreface variability in the Western Interior Seaway of North America. In: Pemberton, S.G. (Ed.), Applications of Ichnology to Petroleum Exploration: A Core Workshop. Society for Sedimentary Geology Core Workshop vol. 17, pp. 57–84.

MacEachern, J.A., Pemberton, S.G., Gingras, M.K., Bann, K.L., 2010. Ichnology and facies models. In: Dalrymple, R.W., James, N.P. (Eds.), Facies Models, fourth edition Geological Association of Canada, St. John's, Newfoundland, pp. 19–58.

Mángano, M.G., Buatois, L.A., Muniz-Guinea, F., 2005. Ichnology of the Alfarcito Member (Santa Rosita Formation) of northwestern Argentina: animal-substrate interactions in a lower Paleozoic wave-dominated shallow sea. Ameghiniana 42, 641–668.

Morris, J.E., Hampson, G.J., Johnson, H.D., 2006. A sequence stratigraphic model for an intensely bioturbated shallow-marine sandstone: the Bridport Sand Formation, Wessex Basin, UK. Sedimentology 53, 1229–1263.

Myrow, P.M., Southard, J.B., 1991. Combined flow model for vertical stratification sequences in shallow marine storm-deposited beds. Journal of Sedimentary Petrology 61, 202–210.

Myrow, P.M., Southard, J.B., 1996. Tempestite deposition. Journal of Sedimentary Petrology 66, 875–887.

Navarro-Ramirez, J.P., Bodin, S., Heimhofer, U., Immenhauser, A., 2015. Record of Albian to early Cenomanian environmental perturbation in the eastern sub-equatorial Pacific. Palaeogeography, Palaeoclimatology, Palaeoecology 423, 122–137.

O'Byrne, C.J., Flint, S.S., 1995. Sequence, parasequence and intra-parasequence architecture of the Grassy Member, Blackhawk Formation, Book Cliffs, Utah, USA. In: Van Wagoner, J.C., Bertram, G.T. (Eds.), Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America. American Association of Petroleum Geologists Memoir vol. 64, pp. 225–255.

Ogg, J.G., Agterberg, F.P., Gradstein, F.M., 2004. The Cretaceous period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), A Geologic Time Scale. Cambridge University Press, Cambridge, pp. 344–383.

Pattison, S.A.J., 1995. Sequence stratigraphic significance of sharp-based lowstand shoreface deposits, Kenilworth Member, Book Cliffs, Utah. American Association of Petroleum Geologists Bulletin 79, 444–462.

Pemberton, S.G., MacEachern, J.A., Frey, R.W., 1992. Trace fossil facies models: environmental and allostratigraphic significance. In: Walker, R.G., James, N.P. (Eds.), Facies Models and Sea Level Changes. Geological Association of Canada, St. John's, Newfoundland, pp. 47–72.

Pemberton, S.G., Spila, M., Pulham, A.J., Saunders, T., MacEachern, J.A., Robbins, D., Sinclair, I.K., 2001. Ichnology & sedimentology of shallow to marginal marine systems. Ben Nevis and Avalon Reservoirs, Jeanne d' Arc Basin. Geological Association of Canada Short Course Notes 15, p. 343.

Pemberton, S.G., MacEachern, J.A., Dashtgard, S.E., Bann, K.L., Gingras, M.K., Zonneveld, J.P., 2012. Shorefaces. In: Knaust, D., Bromley, R.G. (Eds.), Trace Fossils as Indicators of Sedimentary Environments. Elsevier, pp. 563–603.

Peters, S.A., Loss, D.P., 2012. Storm and fair-weather wave base: a relevant distinction? Geology 40, 511–514.

Plint, A.G., 2010. Wave- and storm-dominated shoreline and shallow-marine systems. In: Dalrymple, R.W., James, N.P. (Eds.), Facies Models, fourth edition Geological Association of Canada, St. John's, Newfoundland, pp. 167–199.

Rankey, E.C., 2014. Contrasts between wave-and tide-dominated oolitic systems: Holocene of Crooked–Acklins Platform, southern Bahamas. Facies 60, 405–428.

Reinson, G.E., 1984. Barrier island and associated strand-plain systems. In: Walker, R.G. (Ed.), Facies Models, second editionGeological Association of Canada, Geoscience Canada Reprint Series vol. 1, pp. 119–140.

Reynaud, J.-Y., Dalrymple, R.W., 2012. Shallow-marine tidal deposits. In: Davis, R.A., Dalrymple, R.W. (Eds.), Principles of Tidal Sedimentology. Springer, Dordrecht, pp. 335–369.

Schwarz, E., 1999. Facies sedimentarias y modelo deposicional de la Formación Mulichinco (Valanginiano), Cuenca Neuquina Septentrional. Asociación Argentina de Sedimentología Revista 6, 37–59.

Schwarz, E., 2012. Sharp-based marine sandstone bodies in the Mulichinco Formation (Lower Cretaceous), Neuquén Basin, Argentina: remnants of transgressive offshore sand ridges. Sedimentology 59, 1478–1508.

Schwarz, E., Buatois, L.A., 2012. Substrate-controlled ichnofacies along a marine sequence boundary: the Intra-Valanginian Discontinuity in central Neuquén Basin (Argentina). Sedimentary Geology 277, 72–87.

Schwarz, E., Howell, J.A., 2005. Sedimentary evolution and depositional architecture of a Lowstand Sequence Set: Lower Cretaceous Mulichinco Formation, Neuquén Basin, Argentina. In: Veiga, G.D., Spalletti, L.A., Howell, J.A., Schwarz, E. (Eds.), The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics. Geological Society of London, Special Publication vol. 252, pp. 109–138.

Schwarz, E., Spalletti, L.A., Howell, J.A., 2006. Sedimentary response to a tectonically-induced sea-level fall in a shallow back-arc basin: the Mulichinco Formation (Lower Cretaceous), Neuquén Basin, Argentina. Sedimentology 53, 55–81.

Schwarz, E., Veiga, G.D., Vela, R., Canalis, R., 2008. Paleoambientes y estratigrafía de la Formación Mulichinco en el yacimiento Volcán Auca Mahuida (Cuenca Neuquina, Argentina). Implicancias para la caracterización de sellos locales: VII Congreso de Exploración y Desarrollo de Hidrocarburos, Trabajos Técnicos, pp. 1–17.

Schwarz, E., Spalletti, L.A., Veiga, G.D., 2011. La Formación Mulichinco (Valanginiano). In: Leanza, H., Vallés, J., Arregui, C., Danieli, J.C. (Eds.), Relatorio del XVIII Congreso Geológico Argentino: Geología y Recursos Naturales de la provincia del Neuquén, pp. 131–144.

Schwarz, E., Veiga, G.D., Trentini, G.A., Spalletti, L.A., 2016. Climatically versus eustatically controlled, sediment-supply-driven cycles: carbonate-siliciclastic, high-frequency sequences in the Valanginian of the Neuquén Basin (Argentina). Journal of Sedimentary Research 86, 312–335.

Sømme, T.O., Howell, J.A., Hampson, G.J., Storms, J.E.A., 2008. Architecture and genesis of intra-parasequence discontinuity surfaces in wave-dominated deltaic deposits: Upper Cretaceous Sunnyside Member, Blackhawk Formation, Book Cliffs, Utah, USA. In: Hampson, G.J., Steel, R.J., Burgess, P.M., Dalrymple, R.W. (Eds.), Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy. Society for Sedimentary Geology (SEPM), Special Publications 90, pp. 421–441.

Storms, J.E.A., Hampson, G.J., 2005. Mechanisms for forming discontinuity surfaces within shoreface–shelf parasequences: sea level, sediment supply, or wave regime? Journal of Sedimentary Research 75, 67–81.

Swift, D.J., Han, G., Vincent, C.E., 1986. Fluid processes and sea-floor response on a modern storm-dominated shelf: Middle Atlantic shelf of North America. Part I: the storm-current regime. In: Knight, R.J., McLean, J.R. (Eds.), Shelf Sands and Sandstones. Canadian Society of Petroleum Geologists, Memoir II, pp. 99–119.

Swift, D.J.P., Oertel, G., Tillman, R., Thorne, J., 1991. Shelf sand and sandstone bodies; geometry, facies and sequence stratigraphy. International Association of Sedimentologists. Special Publication 14, 532.

Taylor, A.M., Goldring, R., 1993. Description and analysis of bioturbation and ichnofabric. Journal of the Geological Society 150, 141–148.

Uliana, M.A., Dellape, D.A., Pando, G.A., 1977. Análisis estratigráfico y evaluación del potencial petrolífero de las Formaciones Mulichinco, Chachao y Agrio, Cretácico Inferior de las Provincias de Neuquén y Mendoza. Petrotecnia 1-2, 41–46.

Veiga, G.D., Schwarz, E., 2017. Facies characterization and sequential evolution of an ancient offshore dunefield in a semi-enclosed sea: Neuquén Basin, Argentina. Geo-Marine Letters 37, 411–426.

Vergani, G.D., Tankard, A.J., Belotti, H.J., Welsink, H.J., 1995. Tectonic evolution and paleogeography of the Neuquén Basin, Argentina. In: Tankard, A.J., Suarez Soruco, R., Welsink, H.J. (Eds.), Petroleum Basins of South America. American Association of Petroleum Geologists Memoir vol. 62, pp. 383–402.

Walker, R.G., Plint, A.G., 1992. Wave- and storm-dominated shallow marine systems. In: Walker, R.G., James, N.P. (Eds.), Facies Models, Response to Sea Level Change. Geological Association of Canada, St. John's, Newfoundland, pp. 219–238.

Wheatcroft, R.A., 1990. Preservation potential of sedimentary event layers. Geology 18, 843–845.

Zecchin, M., 2007. The architectural variability of small-scale cycles in shelf and ramp clastic systems: the controlling factors. Earth-Science Reviews 84, 21–55.