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Record of a nonbarred clastic shoreline

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ABSTRACT

The morphology of wave-dominated clastic shorelines (i.e., foreshore and upper-shoreface sediments) can vary from barred to nonbarred, though the ancient record of nonbarred, sand-dominated shorelines has yet to be recognized. Here, a facies and quantitative architectural analysis of a clastic succession characterized by sandy inclined beds is presented and interpreted as the record of a high-gradient, nonbarred shoreline. Inclined beds dip seaward, have a tangential geometry (<3 m height, <40 m length, <11° dip), and are composed of planar lamination along the foresets and subordinate small-scale trough cross-bedding in the bottomsets. This facies distribution reflects a steep beach profile with a narrow surf zone and the development of plane beds both in foreshore and proximal upper-shoreface settings. Successive packages of inclined beds (a few tens of meters wide) are interpreted as the seaward accretion of this shoreline morphology, producing distinctive architectural elements (foresets and bottomsets). For the first time, we propose diagnostic criteria for identification in the rock record of the widely used modern nonbarred clastic shoreline model, and we contrast them with classical facies models of barred systems. Moreover, we discuss similarities and differences with radar-based Holocene coastal architectural elements, highlighting the need to incorporate detailed two-dimensional quantitative studies for refining the reconstruction of deep-time and recent clastic shorelines.

INTRODUCTION

The morphology of prograding, wave-dominated shoreline systems (i.e., strand plains, barriers, and spits) is well known from modern and Holocene environments (Clifton, 2006; Davidson-Arnott, 2010). In sandy microtidal systems, its configuration can range from multiple bar-trough morphology (barred) under predominantly dissipative conditions to a nonbarred steep beach face under dominantly reflective conditions (Masselink and Short, 1993). It seems reasonable to assume that sand accretion and seaward migration under prevalent barred and nonbarred morphological configuration should leave behind different stratigraphic records. Although barred morphology has been widely interpreted from the Holocene and the ancient record, a nonbarred configuration (here considered for simplicity as the record of a long-lived steep beach face with or without swash bars developed in the intertidal zone) remains to be identified.

Barred morphologies have been inferred from lithofacies (tabular/trough cross-bedding in upper-shoreface and planar lamination in foreshore environments; Walker and Plint, 1992; Hampson and Storms, 2003), and from georadar facies, with reflections having a marked slope break between the interpreted high-angle foreshore and the low-angle upper-shoreface strata (Tamura et al., 2008; Clemmensen and Nielsen, 2010; Hede et al., 2013). A contrasting ground-penetrating radar (GPR)–based architectural style has also been identified in studies of Holocene wave-dominated coastal environments, with radar facies characterized by steep, closely spaced, tangential reflections interpreted as upper-shoreface to foreshore deposits (Bristow and Pucillo, 2006; Rodríguez and Meyer, 2006; Fruergaard et al., 2015).

The detailed characterization of inclined beds with abundant internal planar lamination overlying lower-shoreface deposits in the Lower Cretaceous Pilmatué Member of the Neuquén Basin (western Argentina) offers the opportunity to propose, for the first time, lithofacies and architectural criteria for identification of a dominant nonbarred morphology within sandy, clastic shorelines. The results have application to understanding the coastal evolution and to establishing the basis for high-resolution clinoform analysis—a key tool for refining the study of shoreline morphology in deep time.

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STUDY AREA

The Pilmatué Member of the Agrio Formation (Neuquén Basin) represents a large-scale transgressive-regressive cycle that accumulated between the late Valanginian and early Hauterivian, in a backarc setting (Howell et al., 2005). This unit mostly represents fluvial-dominated deltaic systems in the south, and equivalent storm-dominated shoreface–offshore ramp systems developed in shallow waters (<50 m depth) in the north. In the study area (Fig. 1A), the Pilmatué Member is dominated by offshore mudstones with subordinate shoreface siliciclastic and bioclastic sandstones, showing a number of parasequences (PS100 to PS520; Schwarz et al., 2018).

One of these parasequences, termed PS300, was mapped for 17 km across depositional dip (Schwarz et al., 2018). PS300 is internally composed of five bedsets (i.e., concordant successions of genetically related beds within parasequences; sensu Van Wagoner et al., 1990) that consist of smaller-scale, coarsening-upward successions (Schwarz et al., 2018). The youngest bedset (BS300.5) represents the stratigraphic interval where inclined strata were interpreted as the record of a high-gradient, nonbarred shoreline (Figs. 1B and 1C).

In its lower part, bedset BS300.5 shows a shallowing-upward trend from siltstones with interbedded storm-related sandstone beds to bioturbated very fine-grained sandstones (Fig. 1B). Such trends were extensively reported over several parasequences in the Pilmatué Member, and they were interpreted to represent deposition in offshore-transition and lower-shoreface settings, respectively (Schwarz et al., 2018). The lower-shoreface sandstones grade upward to siliciclastic and bioclastic, fine-grained sandstones arranged in large-scale inclined strata (Fig. 1C). These facies are uncommon in the shallow deposits of the Pilmatué Member, which are often

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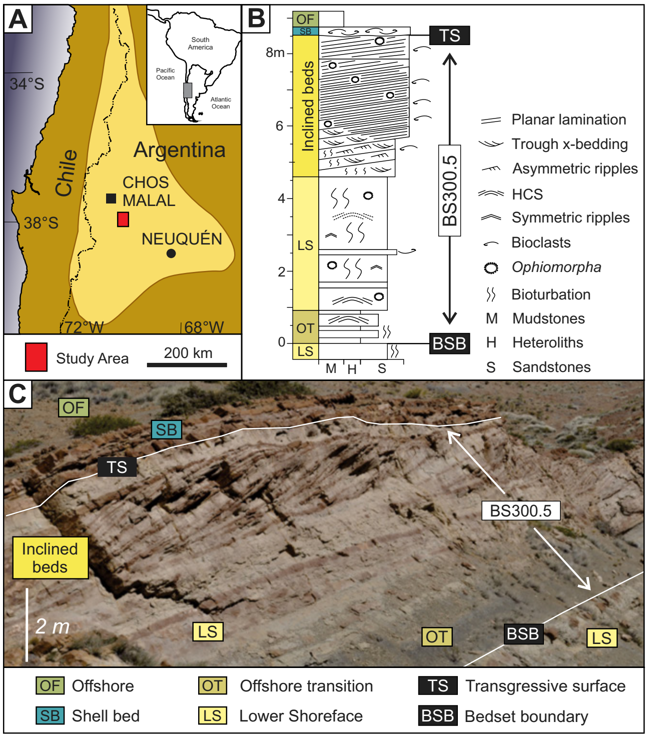

Figure 1. (A) Location of the study area in Neuquén Basin, western Argentina. (B) Simplified sedimentary log of the studied bedset (BS300.5) showing facies and vertical trends. HCS—hummocky cross-stratification. (C) Outcrop view and studied inclined beds.

dominated by trough cross-bedded sandstones (Isla et al., 2018) interpreted to reflect upper-shoreface conditions associated with a barred morphology (Sitkiewicz et al., 2019). The bedset is capped by a continuous transgressive shell bed marking the base of the overlying parasequence (Figs. 1B and 1C).

METHODS

A continuous 600-m-long outcrop face was selected for high-resolution architectural study of the uppermost section of bedset BS300.5. The two-dimensional (2-D) exposure runs north-south, parallel to the progradation direction of parasequence PS300. We logged 15 sedimentary sections at 40 m spacing (Fig. 2A), and drew 2-D sketches tracing the inclined strata, in the field. Dip and dip direction of inclined strata, bed boundaries, and paleocurrents from ripple crests and small-scale trough cross-bedding were measured. We combined field information with detailed mapping of dipping surfaces on high-resolution photomosaics, relative to the main datum located above the sandstone package (Figs. 2A and 2B). For every identified foreset bounded by a pair of dipping surfaces, width, thickness, geometry, dip angle, and orientation were recorded and treated statistically. The contribution of siliciclastic and carbonate grains was defined by standard petrography.

INCLINED BEDS: GEOMETRY AND FACIES

The inclined strata at the top of bedset BS300.5 are characterized by seaward-dipping tangential beds within a geobody up to 4 m thick (Fig. 2B). In total, 133 beds were mapped within the studied outcrop. Facies showed a systematic distribution across individual inclined beds. Planar-parallel lamination was ubiquitous in the foreset segments, both in the fine-grained siliciclastic sandstones and in fine- to lower medium-grained bioclastic sandstones (Fig. 2C). Small-scale trough and planar cross-bedding were common in the bottomsets, together with onshore-directed asymmetric ripples (Fig. 2D). Bioturbation varied in intensity from very low in the foresets to low in the bottomsets, as represented by *Ophiomorpha* sp. The inclined beds pass laterally (seaward) to subhorizontal beds of bioturbated sandstones (Fig. 2E).

The tangential geometry of these beds allowed us to trace them downdip for a few meters to tens of meters (2–40 m; Figs. 2B and 2F). Their mean downdip extent was 11.2 m, whereas the average difference between the highest and lowest points of a stratum was 1.2 m. The maximum dip of bed boundaries varied between 2° and 11°, with a mean of 8°. Foresets mostly dipped to the northwest (Fig. 2G).

Inclined beds were regularly bounded by erosional surfaces (Fig. 2B). These showed a scarp-like geometry in dip section and truncated underlying foreset beds. Beds above these truncation surfaces were enriched in coarse bioclasts and carbonate cement. The steep segment of the erosional surfaces rapidly became subhorizontal; however, due to the distinct reddish color of the associated deposits, these erosional surfaces were traceable downdip into the bioturbated sandstones (Fig. 2B). We mapped 13 erosional surfaces over the 600-m-long section (Fig. DR1 in the GSA Data Repository[1]). Their downdip extent ranged from 27 to 112 m, but most were between 30 and 80 m long (mean 60 m). They were spaced between 20 and 40 m apart (Fig. 2F), and they dipped dominantly to the north and northwest (Fig. 2G). Inclined beds bounded between successive erosional surfaces are here termed "foreset packages" (Fig. 2F), with each package containing between 3 and 20 inclined beds.

DEPOSITIONAL MODEL

The geometry and facies of the inclined beds overlying lower-shoreface sandstones have not been registered by existing facies models for microtidal, wave-dominated, sandy nearshore settings. The lack of tabular and/or trough cross-stratification, which tends to be ubiquitous in upper-shoreface deposits (Fig. 3A; Clifton, 2006), suggests the absence of dunes related to wave-generated currents. In contrast, inclined beds are mostly composed throughout of planar-laminated facies, interpreted in classic models as foreshore deposits related to swash and back-swash processes (Clifton, 1969; Walker and Plint, 1992; Reading and Collinson, 1996; Plint, 2010).

However, extensive planar lamination can be developed in the breaker zone. This situation was reported for modern environments by Clifton et al. (1971) and Schwartz and Birkemeier (2004), who described "upper-ramp" facies dominated by planar-laminated, fine-grained sandstones, with subordinate small-scale cross-stratification. The widespread development of plane beds seems to be favored when the surf zone is narrow or even nonexistent, and therefore the swash zone extends beyond the surf zone, which is typical of reflective beaches (Aagaard et al., 2013). This situation is linked to the steepness of the marine profile, where steeper profiles have narrower surf zones. Also, under steep gradients, bars would be less likely to form and be preserved, prompting non-barred, wave-dominated coastal morphologies (Masselink and Short, 1993; Schwartz and Birkemeier, 2004).

In this context, the inclined sandstone beds described here are interpreted to represent high-gradient, marine depositional profiles (up to ~7°), stretching from foreshore to upper-shoreface settings (Fig. 3B). Most of this narrow marine profile was covered by planar-laminated facies produced under oscillatory or combined flows (Schwartz and Birkemeier, 2004), and without a distinct facies break between the foreshore and the proximal upper

[1]GSA Data Repository item 2020092, tables with measurements of inclined beds, and complete outcrop view with correlations, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.

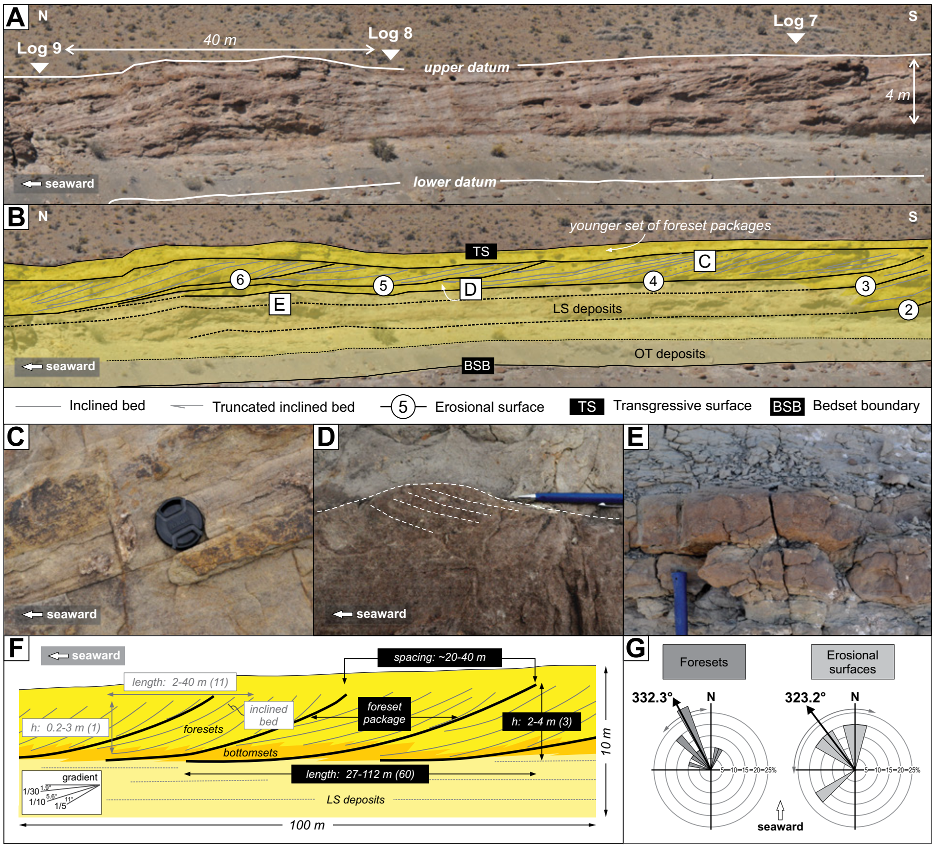

Figure 2. (A) Uninterpreted photomosaic showing 90-m-wide outcrop and location of detailed logs, from Neuquén Basin, western Argentina. (B) Interpreted photomosaic showing facies associations and detailed mapping of inclined beds. Most beds have tangential geometry (i.e., with foreset and bottomset segments) and can be traced for a few meters, but a few are bounded by more extensive surfaces that truncate underlying beds (numbered from oldest [2] to youngest [6]). LS—lower shoreface; OT—offshore transition. (C) Foreset segment of inclined sandstone bed with planar lamination. (D) Ripple cross-lamination in bottomset segment, dipping in the onshore direction. (E) Highly bioturbated lower-shoreface sandstones developed seaward from the studied inclined packages. (F) Schematic model showing two-dimensional attributes (length, height [*h*], and gradient; mean values between brackets) of tangential beds (white frames) and erosional surfaces (black frames); foreset packages represent a group of inclined beds between successive erosional surfaces. (G) Paleocurrent data obtained from inclined beds and erosional surfaces.

shoreface. Seaward of the breaker zone (i.e., in the distal upper shoreface), onshore-migrating asymmetric ripples and small dunes were commonly formed and preserved (Fig. 3B), most likely under oscillatory-dominant flows (Cummings et al., 2009). Further seaward, in the lower-shoreface setting, symmetrical and combined-flow ripples were probably created during fair-weather and storm conditions, but the depositional structures were most likely destroyed by intense bioturbation (Fig. 2E). Two additional criteria suggest that the studied shoreline was, for most of the time, a nonbarred system (Fig. 3B). First, there is a gradual vertical transition from lower-shoreface to upper-shoreface deposits, without the development of a surf diastem (Swift et al., 2003), which commonly marks the base of the upper shoreface in prograding shoreline settings with a bar-trough morphology (Clifton, 2006). Second, the consistent seaward accretion of foresets and foreset packages for hundreds of meters with no landward-dipping surfaces (Figs. 2B and 2F) implies that, if a bar-trough configuration was ever developed in the breaker zone example, the associated deposits were eroded during the prevailing high-gradient, nonbarred conditions.

While successive seaward-dipping foresets represent the accretion of upper-shoreface and foreshore deposits during shoreline progradation, regularly spaced erosional surfaces recognized within the reported example are interpreted as stages of beach retreat. These surfaces represent significant sediment erosion and export to the lower shoreface, which can be triggered by exceptional storms, high-energy wave periods, or beach rotation (Buynevich et al., 2007; Lindhorst et al., 2008; Fruergaard et al., 2018; Green et al., 2019).

IMPLICATIONS FOR HOLOCENE EXAMPLES

The architecture of the nonbarred coastline reported in this study shares many similarities with the architecture reconstructed from GPR surveys of several Holocene, wave- and storm-dominated, prograding sandy coasts (Fig. 4A; Bristow and Pucillo, 2006; Fruergaard et al., 2015). These studies typically show radar facies with tangential, seaward-dipping reflections, 2–5 m in height, which are considered the continuum expression of foreshore and upper-shoreface settings (Rodríguez and Meyer, 2006; Bristow and Pucillo, 2006; Lindhorst et al., 2008; Fruergaard et al., 2015; Hein et al., 2016). In these studies, individual reflections are closely spaced and are relatively steep, with maximum dip between 3° and 12° (Fig. 4A). Significantly, as in the Pilmatué Member, foresets are also bounded by high-amplitude, scarp-like reflections that can be traced further than

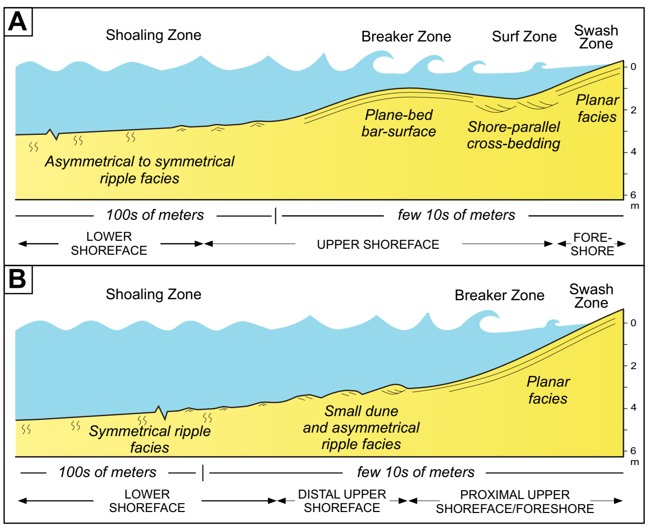

Figure 3. (A) Depositional model for a low- to moderate-gradient, barred shoreline system, commonly associated with a wide surf zone and waves breaking far from the shoreline. Dunes in troughs and plane bed in the swash zone are preserved as trough cross-bedded upper-shoreface deposits and planar-laminated foreshore deposits, respectively (modified from Clifton, 2006). (B) Depositional model reconstructed for investigated succession, characterized by a steep gradient (>5°) and inferred nonbarred morphology. Planar-laminated sands would be the dominant sedimentary facies both in the foreshore and proximal upper shoreface of these nonbarred shoreline systems.

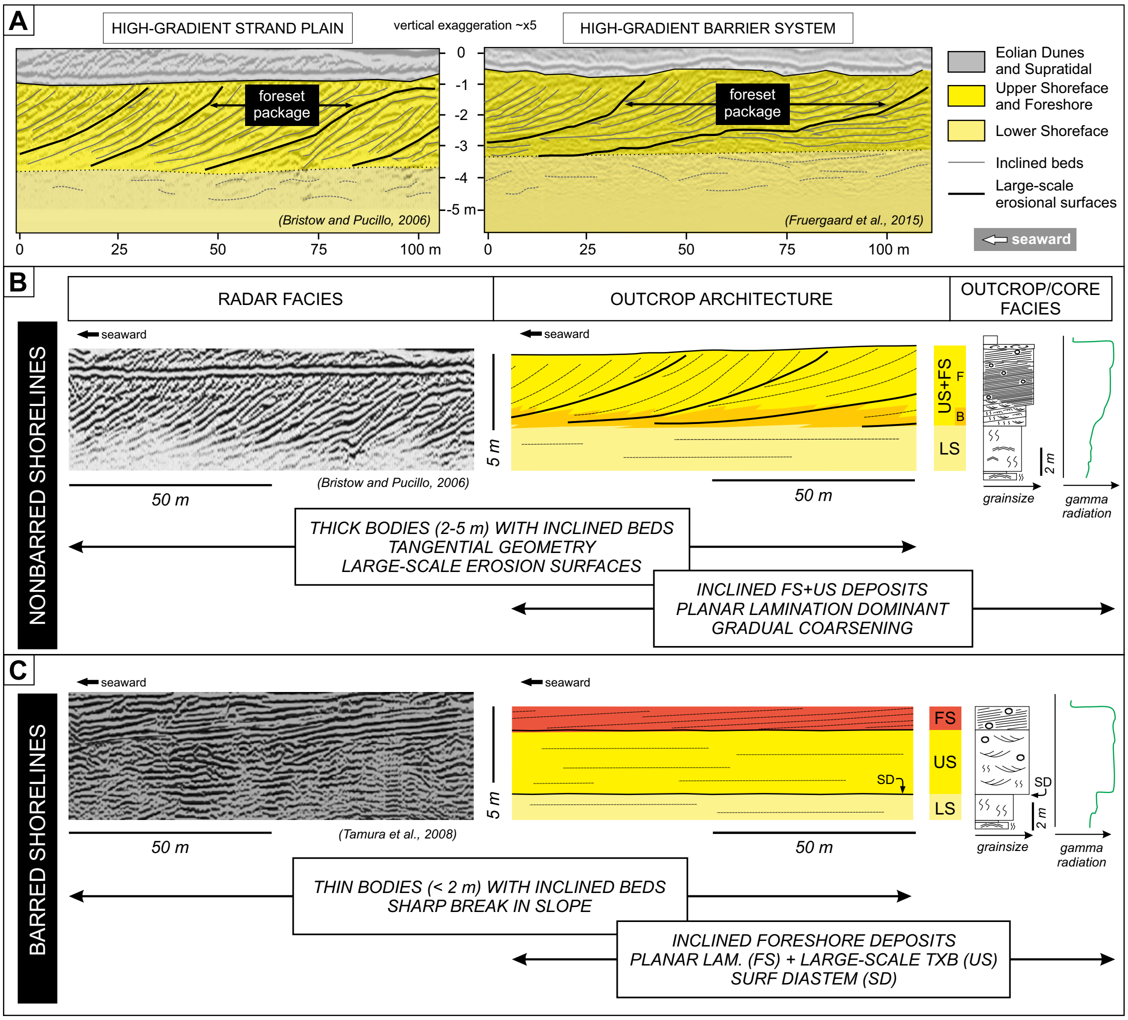

Figure 4. (A) Interpreted ground-penetrating radar (GPR) sections of a prograding Holocene strand plain in Australia (left; modified from Bristow and Pucillo [2006]) and a barrier island in Denmark (right; modified from Fruergaard et al. [2015]). In both cases, inferred upper-shoreface and foreshore deposits are dominated by closely spaced, tangential radar reflections separated by more extensive erosional surfaces. Discontinuous and subhorizontal reflections are interpreted as lower-shoreface deposits. Based on marked similarities with the studied example (Figs. 2A, 2B, and 2F), these Holocene high-gradient clastic shorelines could suggest some stages of nonbarred morphology and/or complete destruction of longshore bars if barred morphology occasionally dominated. (B) Diagnostic criteria proposed for the interpretation of nonbarred shorelines in the rock record (Fig. 3B). Criteria can be obtained from GPR sections, outcrop-based architecture, facies successions in outcrop and cores, and/or grain-size trends in well-log suites. Thick (2–5 m) bodies composed of seaward-dipping, tangential beds (or radar facies) passing gradually to shallowly dipping beds, mostly composed of planar lamination, would be the main indicators of a nonbarred shoreface (GPR section modified from Bristow and Pucillo [2006]). (C) Comparison with a record of barred configurations, characterized by thin bodies (<2 m) of inclined foreshore beds sharply separated from upper-shoreface deposits (GPR section modified from Tamura et al. [2008]). FS—foreshore; US—upper shoreface; LS—lower shoreface; SD—surf diastema; TXB—trough cross-bedding.

individual foresets. The resulting foreset packages are a few tens of meters wide and commonly grade downward to semicontinuous, gently dipping reflections (Fig. 4A). Where information is available, sedimentary facies within inclined strata show a dominance of fine- to medium-grained sands with trough cross-bedding and planar lamination (Fruergaard et al., 2015).

The marked resemblance between the architecture of the reported outcrops from the Pilmatué Member (Fig. 2F) and the radar-based Holocene examples (Fig. 4A) suggests that the resulting sedimentary record of prograding steep clastic shorelines could be interpreted as representing a dominant nonbarred morphology. Longshore bars probably developed in these high-gradients shorelines but were removed by storm surges (Fruergaard et al., 2013), leaving behind a punctuated and nonbarred stratigraphic record as the shoreline prograded seaward.

CONCLUSIONS AND PERSPECTIVES

We conclude that the Lower Cretaceous example reported here represents the record of a prograding, high-gradient, wave-dominated shoreline with predominantly nonbarred morphology. Comparison of these results with Holocene observations allows us to provide diagnostic criteria for identifying such systems in the rock record. These criteria include (Fig. 4B): (1) relatively thick (2–5 m) sandy bodies composed of seaward-dipping inclined beds or radar facies; (2) inclined beds or radar facies with tangential geometry, passing gradually to subhorizontal beds, (3) predominance of planar lamination over trough cross-bedding in sandy facies, and (4) foreset packages bounded by dipping erosional surfaces. The resulting combination of facies and architecture contrasts with classical models of barred shoreline systems (Fig. 4C), which consist of thinner foreshore bodies with inclined, planar-laminated facies transitioning onto gently dipping upper-shoreface deposits, dominated by large-scale trough cross-bedding, and with a surf diastem at the base (Tamura et al., 2008).

As wave-dominated clastic shorelines occur in several depositional environments, such as deltas, strand plains, barriers, and spits, the proposed criteria can be used to refine our understanding of all these systems, as well as to revisit previous interpretations of inclined beds worldwide. Additionally, as some of these criteria are based on 2-D quantitative attributes of inclined surfaces and beds (Fig. 4B), this paper highlights the need to incorporate a high-resolution analysis of upper-shoreface and foreshore deposits into shoreline clinoform analysis.

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