Architecture and controls of thick, intensely bioturbated, storm-influenced shallow-marine successions: an example from the Jurassic Neuquén Basin (Argentina)

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ABSTRACT

Thick (>100 m-thick), highly bioturbated storm-influenced shallow-marine deposits are not frequent in the stratigraphic record, but they tend to be unusually common in aggradational to retrogradational successions. Individual storm-event beds have typically low preservation in these successions, yet depositional settings are characterized on the basis of storms processes. We present a sedimentological study of a thick, bioturbated exhumed succession deposited during the early post-rift stage of the Neuquén Basin (Argentina) and compare its stratigraphic record with examples developed worldwide, in order to discuss controlling factors on the total destruction of storm-event beds during several million years.

The Bardas Blancas Formation (170-220 m thick) is dominated by muddy sandstones and sandy mudstones, but it also includes subordinate proportions of clean sandstones and pure mudstones, collectively representing different environments of a storm-influenced shoreface-offshore system. The offshore transition and proximal offshore strata invariably comprises intensely bioturbated deposits, with only a few preserved HCS-sandstone beds. The unit shows a long-term aggradational pattern involving ca. 7-10 Myr and is associated with low riverine influence.

By combining the observations and interpretations of the Bardas Blancas Formation with other subsurface and exhumed intensely bioturbated, shallow-marine successions we dispute the general assumption that they can be associated to low frequency or low magnitude of storms. Alternatively, we propose that the long-lived efficiency of benthic fauna on destroying most if not all the storm-event beds that reached the offshore-transition sector, results from the combination of two or three factors: deposition in relatively confined marine depocentres, persistent low riverine influence, and long-term aggradational stacking pattern. As these conditions can be recreated in a variety of basin styles, such as rift, early post-rift, and foreland settings, the recognition of thick, bioturbated successions as the ones discussed here can be used to infer more realistic constrains for depositional models and better predict facies distribution in these storm-influenced systems.

Key words: storm events, biogenic destruction, shallow-marine strata, Jurassic, Bardas Blancas Formation, Neuquén Basin.

1. INTRODUCTION

The deposition and preservation of individual storm-related event beds in shallow-marine settings have been reported and extensively discussed in the literature (Niedoroda et al., 1989; Wheatcroft, 1990; Snedden and Nummedal, 1991; MacEachern and Pemberton 1992; among many others). MacEachern and Pemberton (1992) characterized three types of shorefaces based on the intensity and frequency of storms: intense, moderate, and weak (low-energy) shorefaces. It is typically assumed that a thoroughly bioturbated succession with little or no preserved storm-event beds within a storm-influenced shoreface-offshore system would represent weakly storm-affected shorefaces dominated by fair-weather deposits (MacEachern and Pemberton 1992; MacEachern et al., 1999, Pemberton et al., 2012).

Thick successions (>100 m-thick) of storm-influenced, shallow-marine deposits characterized by highly bioturbated strata are not frequent in the stratigraphic record. However, they tend to be unusually common in rift to early post-rift stages of the Central Graben (Fraser et al., 2003; Gowland, 1996; Howell et al., 1996; Baniak et al., 2014), in rift stages of the Viking Graben (Råvnas et al., 1997; Løseth et al., 2009), and in early post-rift stages of the Neuquén Basin (Veiga et al., 2013). Other unusual examples of highly bioturbated, storm-influenced successions include the Bridport Sand Formation in the extensional Wessex Basin (Morris et al., 2006) and the Late Cretaceous Emery Sandstone Member of the Mancos Shale in the Western Interior foreland basin (Edwards et al., 2005). However, a thorough analysis of all these examples to test if they can be simply placed in the low-energy shoreface end-member of the MacEachern and Pemberton (1992) spectrum, or if there are other controlling factors that contribute to produce thick bioturbated storm-influenced successions, has not yet been attempted.

In this study, we present a detailed sedimentological study of a thick, highly bioturbated succession exposed in the northern Neuquén Basin (Lower-Middle Jurassic, Bardas Blancas Formation) with the following objectives: a) to describe and analyse an intensively bioturbated, storm-influenced shallow-marine succession, b) to compare the stratigraphic record of the Bardas Blancas Formation with thick, intensely bioturbated units from other basins, c) discuss combination of several depositional controls that contribute to the complete destruction of original sedimentary structures and storm-event beds during several million years.

2. GEOLOGIC AND STRATIGRAPHIC SETTING

The Neuquén Basin is located on the eastern side of the Andes in west-central Argentina, between latitudes 32º and 40º South, covering an area of over 150,000 km^2 (Fig. 1). It comprises a nearly continuous record of up to 6,000 m of stratigraphy from the Late Triassic to the Early Cenozoic and is one of the most important petroleum provinces of the country (e.g. Uliana and Legarreta, 1993). The sedimentary record of the Neuquén Basin includes continental and marine siliciclastics, carbonates, and evaporites, deposited under a variety of basin styles (Legarreta and Uliana, 1991; Howell et al., 2005).

During the Late Triassic to Early Jurassic, the western border of Gondwana was characterized by large transcurrent fault systems. This led to extensional tectonics within the Neuquén Basin and the formation of a series of narrow, relatively isolated depocentres (Franzese and Spalletti, 2001), which were filled mostly with volcanic and continental successions (Franzese et al., 2006; D´Elía et al., 2015). Due to continuous subduction at the proto-Pacific margin of Gondwana, a transition from syn- to post-rift conditions occurred in the late Early Jurassic (Vergani et al. 1995), marked by the first marine incursion in the basin (Gulisano et al., 1981; Veiga et al., 2013). The Neuquén Basin became a back-arc depocentre characterized by regional, slow subsidence (sag/post-rift phase) that lasted to the end of the Early Cretaceous (Legarreta and Uliana, 1991). In the earliest stage of the post-rift phase, sediment gravity flows and mass movements were particularly common in marine settings, and this has been related to steep gradients (e.g., Legarreta and Uliana, 1996; Burgess et al., 2000; Privat et al., 2020). In this context, low-amplitude eustatic fluctuations, as well as short-lived events of tectonic inversion, probably had a strong influence during the entire post-rift evolution (Legarreta and Uliana, 1991; Howell et al., 2005), but inherited topography and differential compaction had been invoked as potential local factors in the development of early post-rift strata in different sectors of the basin (Burgess et al. 2000; Cristallini et al., 2009; Veiga et al., 2013; Privat et al., 2020).

The Cuyo Group represents the early post-rift sedimentation all across the Neuquén Basin (Figs. 1, 2). It commonly overlies the Precuyano volcanic and volcaniclastic succession deposited during the syn-rift stage (Gulisano et al. 1984), but it can also rest directly upon Paleozoic volcanic or plutonic rocks (e.g., Choiyoi Group, Fig. 2). The Cuyo Group spans from Early to Middle Jurassic and comprises deep-marine to continental deposits in different proportion depending on the position in the basin, with a general east (proximal)-distal (west) depositional trend (Gulisano et al. 1984; Arregui et al., 2011). In the west-central sector of the Neuquén Basin (Fig. 1), the succession represents continuing deep-water sedimentation, strongly influenced by sediment gravity flows and mass-transport processes (Burgess et al. 2000, Hodgson et al., 2018), and is collectively known as the Los Molles Formation (Gulisano and Gutiérrez Pleimling, 1994). In the study area, in the east-central sector of the basin (Fig. 2), early post-rift sediments deposited mostly in shallow-marine settings (Veiga et al., 2013), and accumulation started in the Late Toarcian–Aalenian (Riccardi 2008; Spalletti et al. 2012). Lithographically, in this region the Cuyo Group includes the Bardas Blancas, Los Molles and Lajas formations (Gulisano and Gutiérrez Pleimling 1994; Spalletti et al. 2012; Veiga et al., 2013) (Fig. 2). The Bardas Blancas Formation is the focus of this contribution.

3. STUDY AREA AND PREVIOUS WORK

Veiga et al. (2013) provided a detailed architectural and sequence stratigraphic analysis of the Bardas Blancas Formation in the study area, integrating outcrop and subsurface information from a 3,000 km^2 area. They included two outcrop sections in the western and eastern sectors of the Sierra de Reyes anticline and several wells in the eastern subsurface region (Fig. 2). This study provides a framework in which to place the detailed sedimentological and ichnological analysis of the western outcrops of the Bardas Blancas Formation in the Sierra de Reyes anticline (Fig. 3A).

The Sierra de Reyes anticline is located in the southernmost sector of the Malargüe fold and thrust belt, which is the product of tectonic inversion during Late Cretaceous-Neogene time (Giambiagi et al., 2009). The inversion in this region is related to reactivation of Mesozoic normal faults and new reverse structures that transferred shortening to the east (Giambiagi et al., 2009; Sagripanti et al., 2014). The study area in the western flank of the Sierra de Reyes anticline is about 5 by 1.5 km, and strata is mostly dipping 30-20 degrees to the east. The Bardas Blancas Formation is exposed through a series of west-east gullies in which the main sedimentary sections were measured (Fig. 3B). A few reverse faults affect the stratigraphy but for the most part the outcrop is laterally continuous and allows reconstruction by means of key stratigraphic markers.

The Bardas Blancas Formation (170-220 m thick) is dominated by muddy sandstones and sandy mudstones, but it also includes subordinate proportions of coarser deposits (up to pebbly sandstones) and pure mudstones. The unit unconformably overlies the syn-rift volcaniclastic deposits of the Remoredo Formation all across the area (Figs. 3B, 4A), but the tops shows different vertical relationships. In the southern sector of the study area (and in the Quebrada de la Estrechura section, Figs. 2, 3A), the Bardas Blancas Formation rapidly grades into a pure mudstone, organic-rich unit defined as Los Molles Formation (Gulisano and Gutiérrez Pleimling, 1994; Spalletti et al., 2012) (Fig. 4B, C). The thickness of the Los Molles reaches 20 m in the Agua del Ñaco section, and it thins and pinches out to the north. In the Agua del Campo section, the Bardas Blancas strata are sharply overlying by bioclastic and pebbly sandstones of the La Estrechura Member of the Lotena Formation (Veiga et al., 2011; Veiga et al., 2013). Biostratigraphic data based on ammonites of the study succession indicates that the Bardas Blancas Formation in the study area spans from the Late Toarcian to the Early Bathonian (Spalletti et al. 2012) (Fig. 2). According to present numerical ages this time span would represent no less than 7 Myr and as much as 10 Myr. Further to the west of the study area, time-equivalent deposits of the Bardas Blancas Formation would be dominantly composed of mudstone strata of the Los Molles Formation, but they occur mostly in subsurface (e.g., well BjDC.x-1 in Fig. 2).

The sedimentology and stratigraphy of the Bardas Blancas Formation and its transition to Los Molles Formation in the study area was recorded by detailed logging of two main sections (Agua de Heredia and Agua del Ñaco sections, Figs. 3B, 4) and complemented with information extracted from the Agua del Campo section of Veiga et al. (2013). Sedimentological data were recorded in each section (texture, sedimentary structures, palaeocurrents), along with ichnofaunal, macrofaunal and taphonomic information. Bioturbation intensity was characterized using the Bioturbation Index (BI 0-6) defined by Taylor & Goldring (1993). Sand-silt-mud content in bioturbated facies was visually estimated by X10 lenses.

4. FACIES ASSOCIATIONS AND DEPOSITIONAL MODEL

The facies and facies associations of the Bardas Blancas Formation and its transition to Los Molles Formation are presented in Table 1. Six facies associations have been defined for the study interval including: FA1 - Delta front, FA2 - Upper shoreface, FA3 - Lower shoreface, FA4 - Offshore transition, FA5 - Proximal offshore, and FA6 - Distal offshore. The definition and interpretation of these facies associations is broadly in agreement with the proposed by Veiga et al. (2013), except for FA1 and FA2 that are presented differently. Hereby we present a short description of facies associations and their interpretation and subsequently describe the inferred depositional model.

4.1. Delta front (FA1)

Facies association FA1 occurs only at the base of the unit and only locally along the strike of the study area. This FA is dominated by conglomerates with quartz and volcanic pebbles (up to 5 cm-long), mudstone rip-up clasts and bioclasts in a chaotic to organized fabric, interbedded with pebbly sandstones with planar cross-stratification or horizontal lamination (Table 1, Fig. 5A). This association is interpreted to represent a high-energy nearshore setting, heavily influenced by coarse terrestrial input of river-related hyperpycnal flows, and partly reworked by subordinate coastal processes (Veiga et al., 2013).

4.2. Upper shoreface (FA2)

Facies association FA2 is composed of amalgamated fine- to medium-grained sandstones mostly with trough cross-stratification and occasional lenses of highly fragmented bioclasts (Fig. 5B). Bioturbation is absent to low with sparse *Ophiomorpha* (Table 1). This association is thought to reflect a wave-dominated, upper-shoreface setting, intensely affected by longshore currents (Walker and Plint, 1982; Isla et al., 2020).

4.3. Lower shoreface (FA3)

Facies association FA3 mostly comprises tabular very fine- to fine-grained sandstones with HCS, and subordinated SCS, plane bed, and symmetrical ripples (Fig. 5C). Bioturbation intensity ranges significantly (BI 2-5) and is dominated by *Skolithos* ichonofacies (Table 1). This association is interpreted as a lower-shoreface setting dominated by deposits related to storm-surge, purely oscillatory or combined flows (Walker and Plint, 1992, Dumas and Arnott, 2006) with high re-mobilitation potential, and associated low preservation of fair-weather sediments.

4.4. Offshore transition (FA4)

Facies association FA4 is mostly composed of tabular and massive muddy sandstones and subordinated sandy mudstones (Fig. 5D). Bioturbation is mostly high (BI 5-6), locally moderate (BI

4), and is dominated by a highly diverse *Cruziana* ichnofacies (Table 1) in which *Teichichnus* and *Chondrites* are dominant (Fig. 6A, B). Infrequently, medium- to thin-bedded, very-fine gained sandstones with HCS are recorded in this association. These beds invariably show an increment of bioturbation at the top, passing abruptly to bioturbated muddy sandstones. This association represents an offshore-transition setting, immediately below the fair-weather wave base (Reading & Collinson, 1996). Storm-derived flows delivered sand to distal marine settings, but post-depositional bioturbation homogenized muds and sandy event beds into muddy sandstones in almost all cases.

4.5. Proximal offshore (FA5)

Facies association FA5 is dominated by massive sandy and silty mudstones forming tabular beds with diffuse bedding planes (Fig. 5E). Bioturbation is systematically high (BI 5-6) and represented by a distal expression of the *Cruziana* ichnofacies (Table 1). Burrows of *Chondrites*, *Rhizocorallium*, and *Zoophycos* are sporadic in outcrops (Fig. 6C, D), whereas smaller traces such as *Phycosiphon* or *Helminthopsis* are commonly observed in cores of these sandy and silty mudstones (Veiga et al., 2013, their figure 9c). As in FA4, very uncommon discrete sandstone beds occur interbedded in this association, but they are finer grained and thinner (Table 1). Due to the relatively lower proportion of sand material in this association than in FA4, FA5 is interpreted to represent a proximal-offshore setting, i.e. the distal end of the running-distance of most storm-derived flows (Veiga et al., 2013).

4.6. Distal offshore (FA6)

Facies association FA6 includes mudstone-dominated successions that are common at the base and top of the study interval (Fig. 2, 5F). At the base they consist of grey, massive mudstones with moderate bioturbation, represented by a *Zoophycos* ichnofacies commonly in cores (Veiga et al., 2013, their figure 9D). Medium- to thin-bedded conglomerates with extraformational pebbles and mudstone rip-up clasts are commonly interbedded in these massive mudstones. At the top of the unit FA6 is mostly represented by black, fissile (platy), unbioturbated shales, in which cm-thick tuffaceous layers occur. This section represents the transition to the Los Molles Formation. FA6 is interpreted to reflect the distalmost conditions of the marine system, i.e., a distal offshore to shelf, but under two different conditions. Firstly, oxic sea-bottom conditions as well as sediment gravity flows depositing coarse material were common in the distal offshore of the early Bardas Blancas Formation. Conversely, inferred high organic contents and original lamination in the Los Molles Formation mudstones at the top of the study interval probably suggest long-lived dysoxic to anoxic conditions, in a saturated water–sediment interface (Doyle et al. 2005, Veiga et al., 2013).

4.7. Depositional model

Except for FA1 that is solely recorded at the base of the Bardas Blancas Formation (Table 1), the remaining facies associations are commonly registered forming shallowing-upward successions that are up to a few 10s of m thick (Fig. 7). Thus, a well-defined storm- and wave-dominated shoreface-offshore depositional system is reconstructed for the unit. The upper-shoreface was dominated by migrating dunes and bars associated with long-shore currents (FA2), whereas the adjacent lower-shoreface setting mostly preserved event beds with hummocks sculpted by the development of storm-surge combined flows (FA3, Fig. 7). The shoreface bioturbation intensity and its distribution along dip follows normal patterns for wave-dominated shoreface-offshore systems, increasing downdip (Walker and Plint, 1992; Gowland, 1996; Hampson, 2000; MacEachern et al. 2007; Schwarz et al., 2018).

In marked contrast, the preservation motifs and inferred conditions in the offshore transition (FA4) and proximal offshore (FA5) seems to be quite peculiar. These two adjacent settings record depositional conditions between the fair-weather wave base and storm wave base (Fig. 7), and reflect a gradual increment in the proportion of mud versus sand fraction in the resulting sediments, likely associated with the decreasing inability of storm-surge flows to export sand to more distal areas (Aigner et al., 1982). But as post-depositional homogenization of muds and sands is concerned, these two environments behave very similarly, providing a similar capacity of deposit-feeder organisms to rework almost 100% of the sands during inter-event periods. The fact that this condition prevailed for several million years (7-10 Myr) is not a commonly reported motif for examples worldwide and is further discussed in this contribution.

As for the distalmost segment of the shoreface-offshore system for most Bardas Blancas Formation, accumulation of muds is considered to have been dominantly from settling out of suspensions in very low-energy hydrodynamic settings (FA6). Debris flows transporting gravel were common in early stages of the system (Fig. 7), but probably became infrequent later in its evolution, allowing to produce a mud-rich, distal offshore, occasionally colonized by *Zoophycos*-producing organisms. Distal offshore settings prevailed further to the west of the study area were substrate conditions probably remained constant during most of the Bardas Blancas deposition (Figs. 2, 7). But when a distal offshore setting was installed in the southern sector of the study area (Los Molles Formation), a shift to prevailing dysoxic-anoxic conditions appear to have dominated in a soupy substrate.

5. ARCHITECTURE OF AN INTENSELY BIOTURBATED SUCCESSION

The most distinctive feature of the Bardas Blancas Formation is that most of the proximal offshore (FA5) and offshore transition (FA4) strata comprises intensely bioturbated deposits (BI 5-6). Complete bioturbation (BI 6) is dominant, providing a complete structureless appearance of the beds in outcrop (Fig. 8A), due to total biogenic homogenization of the original deposits (Taylor and Goldring, 1993). It also typically prevents the identification of individual trace fossils. In these two facies associations, beds are defined by subtle variation in the sand-silt-mud content, usually aided by the weathering profile, where the muddier facies is less resistant (Fig. 8A). The relative dominance of muddy sandstones versus sandy and silty mudstones in a given interval places it in FA4 or FA5 (Fig. 8A, B). Individual beds range from 0.15 m up to 1.5 m and they almost invariably show planar, horizontal lower and upper contacts defining tabular beds at different scales, from a few 10s to 100s of meters in length (Fig. 8B, C).

The preserved volume of un-modified storm-generated deposits in these two facies associations is small, but still provides a window for interpreting the primary depositional processes and products. Where observed, these sandstone beds commonly have hummocky cross-stratification and are laterally continuous for up to a few 10s of meters (Fig. 9A, D). They have sharp, irregular bases overlying silty mudstones and invariably show irregular (indented), transitional to sharp tops into muddy sandstones (Fig. 9B, E). In these overlying muddy sandstones, biotubation intensity is moderate to high (BI 4-5), and an ichonofabric dominated by *Chondrites* can be recognized in outcrop (Fig. 9C), but a more diverse assemblage including *Phycosiphon,* and *Zoophycos* has also been recorded in cores of the unit (Veiga et al., 2013). The overlying muddy sandstone becomes the “full bed” laterally from where the discrete storm-generated deposit is recognized (Fig. 9A, D).

The vertical distribution of facies associations in the study area allows to recognize shallowing-upward, 10s of meters-thick genetic units in the study interval of the Bardas Blancas Formation, identified as parasequences (Fig. 2). Shell beds mark flooding surfaces in places, and internally these parasequences are composed of bedsets with subtle stratigraphic boundaries (Fig. 8D). Parasequences in the lower interval of the unit show a complete transition from mudstones of FA6 (distal offshore) to clean, trough cross-bedded sandstones of FA2 (upper shoreface)(Fig. 4), whereas in the middle and upper segments of the study interval, they are mostly composed of sandy mudstones and muddy sandstones of FA5 and FA4 (proximal offshore and offshore transition), sometimes with the presence of lower-shoreface HCS-sandstones at their top (FA4) (Figs. 8D, 9). Bioturbation intensity in the lower-shoreface deposits is either similar or lower than the one recorded in the underlying offshore-transition facies (Fig. 8D).

The vertical staking pattern and sequence architecture of the Bardas Blancas Formation in the study area was investigated by Veiga et al. (2013). Integrating outcrop and subsurface data they identified three parasequence sets within the study interval (Figs. 2, 4), individually representing alternating conditions from retrogradational (PS Sets I and III) to aggradational (PS Set II, Fig. 2) stacking patterns. Collectively these three units were interpreted as representing a long-term transgressive event (about 7-10 Myr) during the early post-rift stage of the basin, where sustained accommodation was probably provided by a combination of thermal subsidence, differential compaction of syn-rift deposits and eustatic rise (Veiga et al., 2013). The observed changes in the stacking patterns were attributed to the effect of inherited topography from the underfilled syn-rift hemigrabens, as sedimentation areas were expanding during progressive flooding and sediments were depositing in partially filled hemigraben-segments with different gradients.

The aggradational to retrogradational stacking pattern of Parasequence Sets II and III has a major impact in the resulting distinctive nature of the study succession. As a result of these particular conditions, about 100 m of the Bardas Blancas Formation in the study area are dominated by a vertical stacking of almost completely homogenized deposits of FA4 and FA5 (Figs. 4, 8 and 9). The resulting stratigraphy is a storm-generated, but highly bioturbated, thick monotonous succession, with very little grain size variation (muddy sandstones to sandy mudstones), virtual absence of preserved primary physical (depositional) structures, bedding contacts that are invariably horizontal, and scattered fossil remains that rarely produce distinct shell concentrations.

The potential combination of factors allowing for such exceptional resultant stratigraphy is discussed below.

6. DISCUSSION

6.1. Thick bioturbated storm-influenced shallow-marine successions: where?

The preservation potential of individual storm-related event beds (or tempestites) in shallow-marine settings and the lam-scram textures resulting from partial to total destruction of these event beds have been extensively reported and discussed (Wheatcroft, 1990; MacEachern and Pemberton 1992; among many others). MacEachern and Pemberton (1992) characterized three types of shorefaces based on the intensity and frequency of storms: intense, moderate, and weak (low-energy). It is typically assumed that a thoroughly bioturbated succession with little or no preserved tempestites within a storm-influenced shoreface-offshore system would represent weakly storm-affected shorefaces dominated by fair-weather deposits. On the contrary, shorefaces with stacked, well-preserved tempestites would be interpreted as storm-dominated shorefaces (MacEachern and Pemberton 1992; MacEachern et al., 1999, Pemberton et al., 2012).

The Bardas Blancas Formation deposits interpreted to represent offshore-transition (partially equivalent of the "distal lower shoreface" of MacEachern et al. (1999) and proximal offshore settings are invariably composed of highly bioturbated muddy sandstones and sandy mudstones, and very few preserved tempestites. We demonstrate that all the preserved deposits in those settings are in fact the total biogenic homogenization of sediments (sand, silt, and mud) laid down by storm-surge flows. If other transport processes, such as hyperpycnal flows or turbidity currents were common in the system, the biogenic destruction removed all the evidence. Following the MacEachern and Pemberton (1992) characterization, the Bardas Blancas system would therefore fall in the low-energy category of the storm-influenced shoreface systems.

Thick monotonous successions (>100 m-thick) of storm-influenced, shallow-marine deposits formed by persistent combination of processes that resulted in highly bioturbated strata are not common in the stratigraphic record, but they tend to be restricted to certain geological conditions (Figs. 10, 11; Table 2). The Upper Jurassic Farsund Formation in the Norwegian Central Graben (distal equivalent of the Ula Formation, Bergan et al., 1989; Fraser et al., 2003), the Upper Jurassic Heather and Lower Kimmeridge Clay formation in the UK Central Graben (distal equivalents of the Fulmar

Formation, Donovan et al., 1993; Gowland, 1996), and the transition from the Middle Jurassic Tarbert to Heather Formations in the North Viking Graben (Råvnas et al., 1997; Råvnas and Steel, 1998; Løseth et al., 2009) are all subsurface examples showing facies and bioturbation patterns that are remarkably similar to the ones observed in outcrops and subsurface for the Bardas Blancas Formation (Fig. 10D). The Early to Middle Jurassic Bridport Sand Formation in the Wessex Basin (Morris et al., 2006) and the Late Cretaceous Emery Sandstone Member of the Mancos Shale (Edwards et al., 2005), are partial or total exhumed examples of highly bioturbated shallow-marine successions.

Strata of the Farsund Formation in the Norwegian Central Graben are dominated by intensely bioturbated muddy sandstones and sandy mudstones that reach 200 m of thickness in Well 2/1-6 (Fig. 10A). The more proximal equivalent Ula Formation is mostly composed of highly bioturbated sandstones, overall characterized as reflecting the weak to moderate shoreface profiles (Baniak et al., 2014, 2015) following the model from MacEachern and Pemberton (1992). The sedimentology and ichnology of the Fulmar Formation in the UK Central Graben has been reported in detail by Howell et al. (1996) and Gowland (1996). They concur on the long-lived development of a storm-influenced shoreface-offshore system, in which biogenic complete destruction of depositional structures largely prevailed in lower shoreface and offshore-transition settings (Fig. 10B). As in the Ula Formation example, total bioturbation in the offshore transition zone of the Fulmar Formation was interpreted as the result of low magnitude and/or low frequency of storm events (Howell et al., 1996). Collectively, these Upper Jurassic units of the Central Graben developed in a rifting tectonic stage and show long-term (several million years) aggradational to retrogradational stacking patterns (Howell et al., 1996; Mannie et al., 2014; 2016) (Fig 11).

The facies association and stacking patterns of the Tarbert and Lower Heather succession, in the North Viking Graben, were described by Løseth et al. (2009), based on cores and several key wells including well 30/9-14 (Fig. 10C). In this well the gamma-ray log for most of the Lower Heather interval suggests very uniform response, whereas cores display relatively homogenous, highly bioturbated muddy sandstones (Fig. 10C) grading to bioturbated sandstones with little preservation of HCS-beds. This uppermost succession has been interpreted to represent a parasequence with progradation from offshore, into offshore-transition settings and lowermost shoreface, within a long-term retrogradational stacking pattern (Løseth et al., 2009) (W3 in Fig. 11). As suggested by the authors, bioturbation intensity increases from W2 to W3 within the retrogradational stacking pattern (Løseth et al., 2009, their figure 4). This net transgressive trend was developed within a synrift setting during the Bathonian and probably lasted 1-2 Ma (Mannie et al., 2016).

The Early to Middle Jurassic Bridport Sand Formation in the Wessex Basin (UK) is another example of storm-influenced, intensely bioturbated succession (Morris et al., 2006). According to the high degree of biogenic reworking, the dominant siltstones and silty sandstones with uncommon preserved storm beds were interpreted as reflecting low-energy lower-shoreface and offshore-transition settings (Morris et al., 2006). Interestingly, no evidence of nearby river influence or river-mouth processes were recorded, and sand supply to the shoreface settings was related to along-shore transport. Moreover, a well-defined, long-term aggradational stacking pattern was defined for the unit in extensional fault-bounded depocentres, and related to localized, relatively higher tectonic subsidence (Morris et al., 2006) (Table 2). One fully exhumed example of thick, highly bioturbated storm-influenced shallow-marine successions occurs within Late Cretaceous strata of the Book Cliffs, Utah (USA). The Emery Sandstone Member of the Mancos Shale is up to 250 m and represents the aggradational stack of storm-dominated shoreface parasequences developed in a foreland basin setting (Edwards et al., 2005) (Table 2).

All of these examples suggest that the Bardas Blancas Formation is a good analogue for thick bioturbated shallow-marine successions occurring in a variety of basinal settings, but preferentially in those having storm-surges as main across-offshore transport process in relatively confined or small depocentres, low to moderate riverine influence and a long-term balance between sediment supply and accommodation (i.e., aggradational stacking patterns) (Fig 11). Thus, it seems an oversimplification to assume that these basin conditions would be overruled by the frequency and magnitude of atmospheric processes (i.e. storms), which would also vary significantly across the long time periods some of these successions encompass.

6.2. Possible controls on thick bioturbated storm-influenced shallow-marine successions

Based on the occurrence of similar, thick storm-generated shallow-marine successions sharing more geological attributes than just their highly bioturbated nature, we propose to relate the total destruction of original storm beds and sedimentary structures over several million years to a suite of factors, rather than assuming that what they have in common is just a similar frequency and/or magnitude of atmospheric processes (i.e., storms).

Firstly, most of the examples discussed above (section 6.1) are related to complex syn-rift or early post-rift topography that define relative small depocentres during long-term marine transgressions (Howell et al., 1996; Veiga et al., 2013). These depocentres were mostly elongated and a few kms to 10s of kms wide (Fig. 11). It would be possible to relate this depositional context to the ability of the benthic fauna to recolonize almost the entire extent of these small depocentres, to produce not only total vertical bioturbation (as seen in 1D cores, Fig. 10), but also generating destruction of original beds for several kilometers laterally, as recorded in the outcrops of the Bardas Blancas Formation. In other words, we relate the relatively small size of the depositional setting to the high efficiency of re-colonization fauna to destroy most of the individual storm deposits, independently of how fast new colonization occurred, or the storm recurrence (or frequency). This destruction efficiency is steadily high across the recorded segments of the depositional environment (from the lower shoreface to proximal offshore), and does not necessarily follow the trend observed in modern shelves, in which the degree of bioturbation decreases in an offshore direction (Snedden and Nummedal, 1991). Howell et al. (1996) already used this basin-scale factor to support their process-realistic depositional model for the bioturbated, sand-dominated deposits of the Fulmar Formation. Moreover, Morris et al. (2006) suggested that small areas of accumulation in the Bridport Formation could have been more prone to extensive biotic proliferation, increasing the destruction success of storm-event beds. Going further, it could be speculated that the relatively small size of depocentres would allow a more homogenous distribution of the food source for the benthic fauna, which would ultimately account for its success in re-colonizing the entire depositional setting at all times.

An additional, long-term control on these thick bioturbated successions is related to the potential riverine influence (i.e., water and sediment input) to the marine realm. Modern studies have shown that individual, hurricane-related storm-event beds have high probability to be completely destroyed by bioturbation when riverine influence is relatively low and water depth is shallow (< 30 m), for example in the Texas inner shelf (Snedden and Nummedal, 1991). Likewise, it has also been recently demonstrated that amalgamated storm beds can be biogenically destroyed fairly rapidly (< 10 years) under conditions of high riverine influence, such as several hurricane-event layers described immediately downdrift of the Missisippi River delta in similar water depths (Walsh et al., 2018). The stratigraphic record of the intensely bioturbated succession reported in our study suggests a sustained biogenic destruction efficiency close to 100% during several million years (Fig. 11). It follows that stress factors for benthic fauna typically associated with nearby, high riverine influence (such as high turbidity or significant salinity fluctuations) were short-lived or uncommon episodes in the reported depositional settings. Therefore, for most of the Bardas Blancas Formation we infer a low riverine influence, with poorly integrated fluvial systems and significant along-shore sand supply. This seems to be the case for other examples discussed in section 6.1 and shown in Table 2. Howell et al. (1996) inferred absence of large deltas and poorly developed fluvial systems as clastic suppliers to the marine sandstones of the Fulmar Formation, whereas Morris et al. (2006) related the highly bioturbated succession to the lack of nearby river-mouth processes and significant along-shore transport. The intensely bioturbated Emery Member was also related to a moment of small rivers draining the Sevier Orogen, rather than a large integrated fluvial system as inferred for the shoreface settings of its underlying and overlying units (Edwards et al., 2005).

Another evident similarity between all the aforementioned examples is associated with the long-term stacking pattern (Fig. 11). The early post-rift Bardas Blancas Formation and the rift to early post-rift successions of the Central Graben show a consistent aggradational to retrogradational stacking involving ca. 7 to 20 Myr (Fig. 11) (Table 2). The transition from the fluvial to estuarine deposits of the Tarbert Formation, and then into the marine deposits of the lower Heather Formation, represents first a net retrogradational trend that becomes more aggradational-to-retrogradational (W2 and W3, Fig 11). Interestingly, the overall bioturbation index in the offshore-transition deposits increases in the W3 interval (Løseth et al., 2009), suggesting the maximum destruction efficiency of storm-event beds occurred at that time. The Emery Sandstone succession represents another unusual record of long-term aggradational stacking pattern (ca. 1.7 Myr, Table 2), in which the sedimentation rates were low compared to those of underlying and overlying units (Edwards et al, 2005). Coincidently, the offshore-transition to lower-shoreface deposits of the Emery Sandstone reflect one of the highest destruction efficiency of storm-event beds in the Upper Cretaceous record of the Wasatch-Book Cliff section. This shows a marked difference with less bioturbated, environment-equivalent deposits, for example the younger Kenilworth Member (Eide et al., 2015) and the Grassy Member (Onyeanu et al., 2018) of the Blackhawk Formation, both units developed in progradational stacking patterns. Thus, a delicate long-lived balance between sediment supply and accommodation to create thick successions with highly aggradational (to slightly retrogradational) stacking patterns could be linked to sedimentation rates across the shoreface-offshore system. The offshore-transition and proximal offshore sectors of the system would have experienced low net sedimentation rates that -- if all other variables remained fairly constant-- would have produced a similar effect than low frequency of storm-surge flows reaching those regions. The lack of significant progradational events (basinward facies shifts) also contributed to create thick, fairly homogenous strata, without major sedimentation breaks or sequence boundaries, and representing one or two segments of the depositional system. In the case of the investigated examples those segments correlated approximately with areas below the fair weather wave base and storm wave base, in which the highest destruction efficiency of storm-event beds took place.

In summary, by combining the observations and interpretations of different thick, intensely bioturbated, shallow-marine successions we dispute the common assumption that the final bioturbated product can be associated to low frequency or low magnitude of storms. Alternatively, we propose that the long-lived efficiency of benthic fauna on destroying most if not all the storm-event beds (that reached the offshore transition sector), results from the combination of two or three factors: deposition in relatively confined marine depocentres, persistent low riverine influence, and/or a long-term, aggradational to slightly retrogradational stacking pattern. As these conditions can be recreated in a variety of basin styles, such as rift, early post-rift, and foreland settings, the recognition of thick, bioturbated successions as the ones discussed here can be used to infer more realistic constrains for depositional models and better predict facies distribution in these storm-influenced systems.

7. CONCLUSIONS

1 - The Lower-Middle Jurassic Bardas Blancas Formation represents a thick (up to 230 m), highly biorturbated, storm-influenced shallow-marine succession developed during the early post-rift stage of the Neuquén Basin.

2 - Most of its stratigraphic record is dominated by muddy sandstones and sandy to silty mudstones deposited in offshore-transition to proximal-offshore settings, in which benthic- fauna efficiency to destroy individual storm-event beds was persistently close to 100 % during a time spam ranging from 7 to 10 Myr. This highly efficient biogenic reworking was mostly associated to deposit-feeder organisms of the *Cruziana* ichnofacies.

3 - The Bardas Blancas Formation shears several attributes with other thick (> 100 m) intensely bioturbated successions including: deposition in relatively confined marine depocentres, persistent low riverine influence, and long-term (2- 20 Myr) aggradational stacking pattern. Yet,

all these biogenically reworked successions are developed in a variety of structural styles, including rift, early post-rift, and foreland settings.

4 - We question the assumption that the resulting architecture of these unusual thick, bioturbated shoreface-offshore successions at different scales should be directly associated to low frequency or low magnitude of storms. Alternatively, we propose that the long-lived efficiency of benthic fauna on destroying almost all the storm-event beds accumulated in these depositional environments during several million years was more likely controlled by the co-occurrence of the following depositional factors: a) relatively small depocenters with infaunal colonization evenly distributed in intermediate to distal sectors of the marine system, b) benthic fauna very rarely affected by physico-chemical stress factors in those regions due to overall low riverine influence, and c) delicate balance between sediment supply and accommodation producing relatively low net sedimentation rates across the system.

5 - These depositional conditions can be recreated in a variety of basin styles, so the results of this contribution on the controls of thick, highly bioturbated successions can be used to infer more realistic constrains for depositional models and better predict facies distribution in these distinct storm-influenced systems.

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FIGURES AND FIGURE CAPTIONS

Fig 1. A. Map of the Neuquén Basin with approximate location (red square) of the study area (Fig. 2). **B.** Paleogeographic reconstruction of the Neuquén Basin during the Jurassic – Early-Cretaceous. The onset of subduction on the western margin of Gondwana and the early development of the Andean arc led to development of a large triangular-shape epicontinental basin, partially connected to the proto-Pacific Ocean through a volcanic arc. Modified after Howell et al. (2005).

Fig. 2. Cross section (integrating outcrop and well data) showing the stratigraphic setting and overall depositional architecture of the early post-rift succession (Bardas Blancas, Los Molles and Lajas formations) in central Neuquén Basin, as well as the older Remoredo Formation (syn-rift volcaniclastic deposits) and Choiyoi Group (basement) units. Inset shows detailed map of the cross section. Modified from Veiga et al. (2013). Chronostratigraphy based on ammonite dating from Spalletti et al. (2012).

Fig. 3. A. Geologic map of the Sierra de Reyes region, showing the different locations studied in Veiga et al. (2013) (black stars) and this study (white stars). **B**. Satellite image of the study area, in the eastern flank of the Sierra de Reyes anticline, showing the location of the sections studied in the Cuyo Group.

Fig. 4. Field panoramas of Agua del Campo (**A**) and Agua de Heredia (**B**), showing the location of main stratigraphic units, and their bounding surfaces. **C.** Simplified stratigraphic section showing the overall aggradational-to-retrogradational stacking of the Bardas Blancas Formation, and its vertical relationships with the underlying and overlying lithostratigraphic units. Parasequence sets (PSS's) after Veiga et al. (2013).

Fig. 5. Outcrop examples of the different facies associations defined in this study. **A.** Cross-bedded, organic-rich and poorly-sorted pebbly to medium-grained sandstones (FA1- Delta Front). Parasequence Set I, Agua de Heredia. **B.** Amalgamated, trough cross-bedded, well-sorted fine-grained sandstones (FA2 – Upper shoreface). Parasequence Set I, Agua de Heredia. **C.** Tabular to

slightly undulate, medium-bedded fine-grained sandstones, with hummocky cross stratification (HCS) (FA3- Lower shoreface). Parasequence Set II, Agua del Campo. **D.** Moderate to highly bioturbated sandstones and muddy sandstones, with local preservation of HCS (FA4- Offshore transition). Parasequence Set II, Agua del Campo. **E.** Highly bioturbated sandy and silty mudstones, with subordinate muddy sandstones (FA5- Proximal offshore). Parasequence Set II, Agua de Heredia. **F.** Massive to crudely laminated gray mudstones with occasional diagenetic nodule-rich horizons (FA6- Distal offshore). Parasequence Set II, Agua de Heredia. See Table 1 for more details about their main attributes, and Figs. 2 and 4 for location in stratigraphy.

Fig. 6. Selected examples of trace fossils found in offshore transition (FA4) and proximal offshore (FA5) facies associations.

Fig. 7. General depositional model of the Bardas Blancas Formation in the study area, showing the distribution of different facies associations (FA's) and their associated depositional environments. Note the influence of inherited and under-filled rift topography in the stratigraphic architecture of early post-rift deposits. Not to scale.

Fig. 8. Examples of tabularity and bioturbation at different scales. **A.** Highly bioturbated, dm-scale muddy sandstones and sandy mudstones in offshore transition deposits (FA5). Parasequence Set III, Agua del Ñaco. **B.** Bioturbated offshore transition deposits (FA5), stacked in m-scale, well-defined bedsets. Parasequence Set III, Agua de Ñaco. **C.** General view of several m-scale bedsets, showing the homogeneous and tabular nature of the studied deposits. Parasequence Set II, Agua de Heredia. **D.** Stratigraphic section, containing the interval shown in **C**, with the lithological, sedimentary and bioturbation trends of a 10's of m-thick, shallowing-up succession (parasequence), made by several m-scale bedsets, and bounded by regional-scale flooding surfaces. Parasequence Set II, Agua de Heredia. See Figs. 2 and 4 for location in stratigraphy.

Fig. 9. Two examples of preserved HCS in storm-event beds. **A.** General view of the gradual vertical transition from proximal offshore (FA5) to offshore transition deposits (FA4). **B.** Example of partially preserved HCS in dominantly highly bioturbated proximal offshore deposits (FA5). Parasequence Set II, Agua de Heredia. **C.** Detail view of the contact between the fully bioturbated (*Chondrites* ichnofabric) upper part and the non-bioturbated lower part (preserving the original sedimentary structures) of the same event bed. Parasequence Set II, Agua de Heredia. **D.** Outcrop view of offshore transition deposits (FA4). **E.** Example of preserved HCS in a partially homogenized event bed, overlain and underlain by highly bioturbated muddy sandstones and sandy mudstones (offshore transition, FA4). Parasequence Set III, Agua del Campo Sur.

Fig. 10. GR well logs and core examples of highly bioturbated, storm-dominated shallow-marine successions comparable to the studied deposits. **A.** Upper Jurassic Farsund Formation, interpreted as the equivalent offshore transition deposits of the bioturbated, sand-rich Ula Formation in the Norwegian Central Graben. **B.** Heather and Intra-Heather Sandstone Formation, the offshore transition deposits overlying the transgressive shallow-marine sandstones of the Tarbert Formation, in Northern Viking Graben/Western Horda Platform. **C.** Heather Formation, also the equivalent offshore transition deposits of the highly bioturbated, Fulmar Formation, in the UK Central Graben. **D.** Lower-Middle Jurassic Bardas Blancas Formation, Neuquén Basin (this study).

Fig. 11. Structural setting, overall stratigraphic architecture and stacking pattern of the different highly bioturbated, storm-dominated shallow-marine successions shown in Fig. 10, and the Bardas Blancas Formation.

Table 1. Facies association classification, description and interpretation of the main processes and environments of deposition. Trace fossil content is listed in relative order of abundance. FWWB: Fair-weather wave base; SWWB: Storm-weather wave base.

Table 2. Main characteristics of the thick intensely bioturbated successions discussed in this contribution.

Figure 1

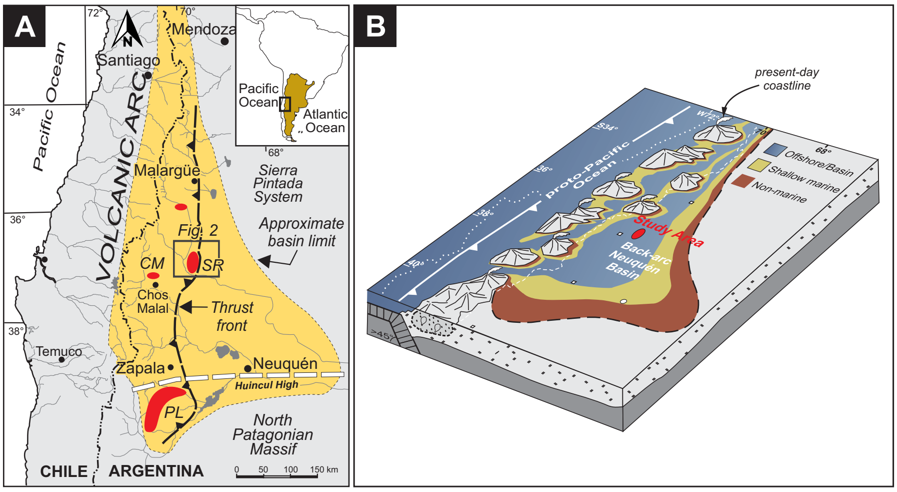
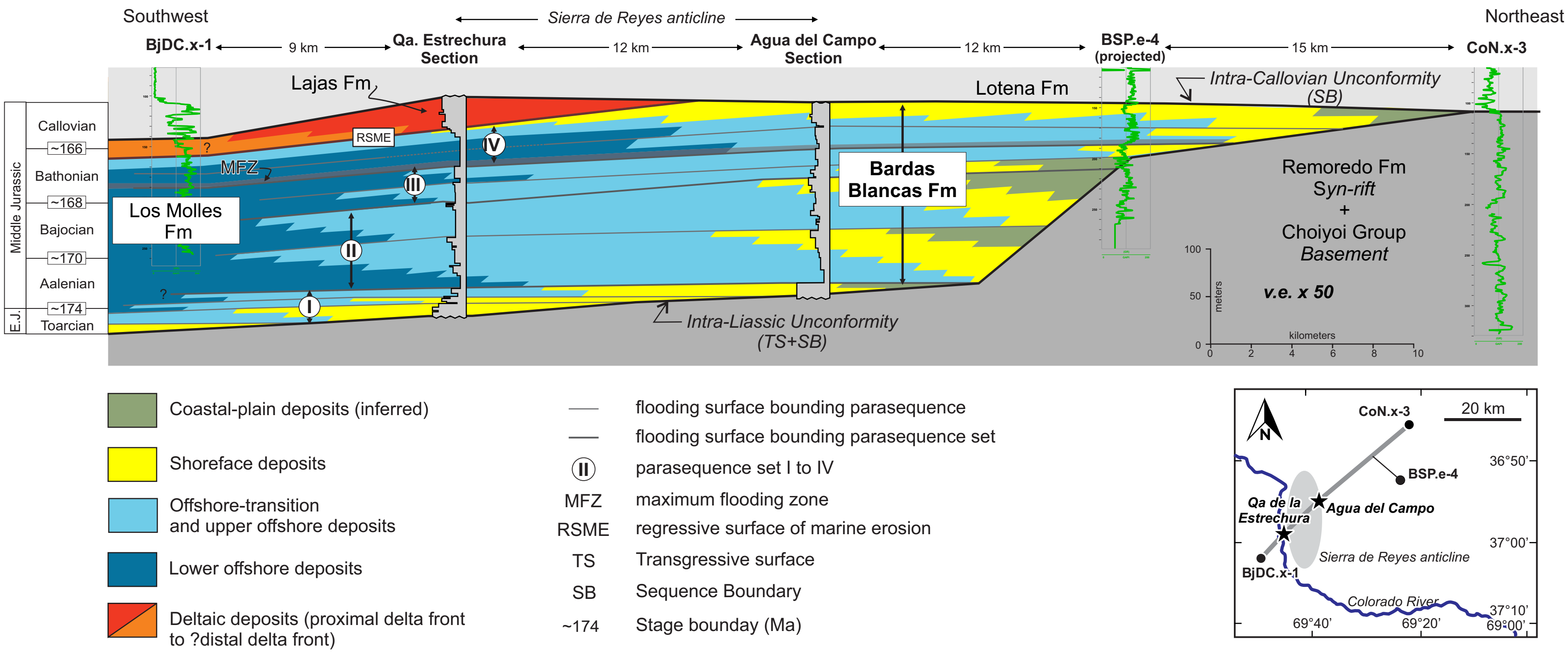

A
B
Pacific Ocean
VOLCANIC ARC
Santiago
Mendoza
Malargüe
Sierra Pintada System
Approximate basin limit
Fig. 2
CM
SR
Chos Malal
Thrust front
Temuco
Zapala
Neuquén
Huincul High
PL
North Patagonian Massif
CHILE
ARGENTINA
Pacific Ocean
Atlantic Ocean
present-day coastline
proto-Pacific Ocean
Offshore/Basin
Shallow marine
Non-marine
Study Area
Back-arc Neuquén Basin

Figure 2



Southwest
Northeast
Sierra de Reyes anticline
BjDC.x-1
9 km
Qa. Estrechura Section
12 km
Agua del Campo Section
12 km
BSP.e-4 (projected)
15 km
CoN.x-3
Lajas Fm
Lotena Fm
Intra-Callovian Unconformity (SB)
Middle Jurassic
E.J.
Callovian
~166
Bathonian
~168
Bajocian
~170
Aalenian
~174
Toarcian
RSME
MFZ
Los Molles Fm
Bardas Blancas Fm
Remoredo Fm Syn-rift + Choiyoi Group Basement
I
II
III
IV
v.e. x 50
meters
kilometers
Intra-Liassic Unconformity (TS+SB)
Coastal-plain deposits (inferred)
Shoreface deposits
Offshore-transition and upper offshore deposits
Lower offshore deposits
Deltaic deposits (proximal delta front to ?distal delta front)
flooding surface bounding parasequence
flooding surface bounding parasequence set
parasequence set I to IV
MFZ maximum flooding zone
RSME regressive surface of marine erosion
TS Transgressive surface
SB Sequence Boundary
~174 Stage bounday (Ma)
N
20 km
CoN.x-3
BSP.e-4
Qa de la Estrechura
Agua del Campo
Sierra de Reyes anticline
BjDC.x-1
Colorado River
36°50'
37°00'
37°10'
69°40'
69°20'
69°00'

Figure 3

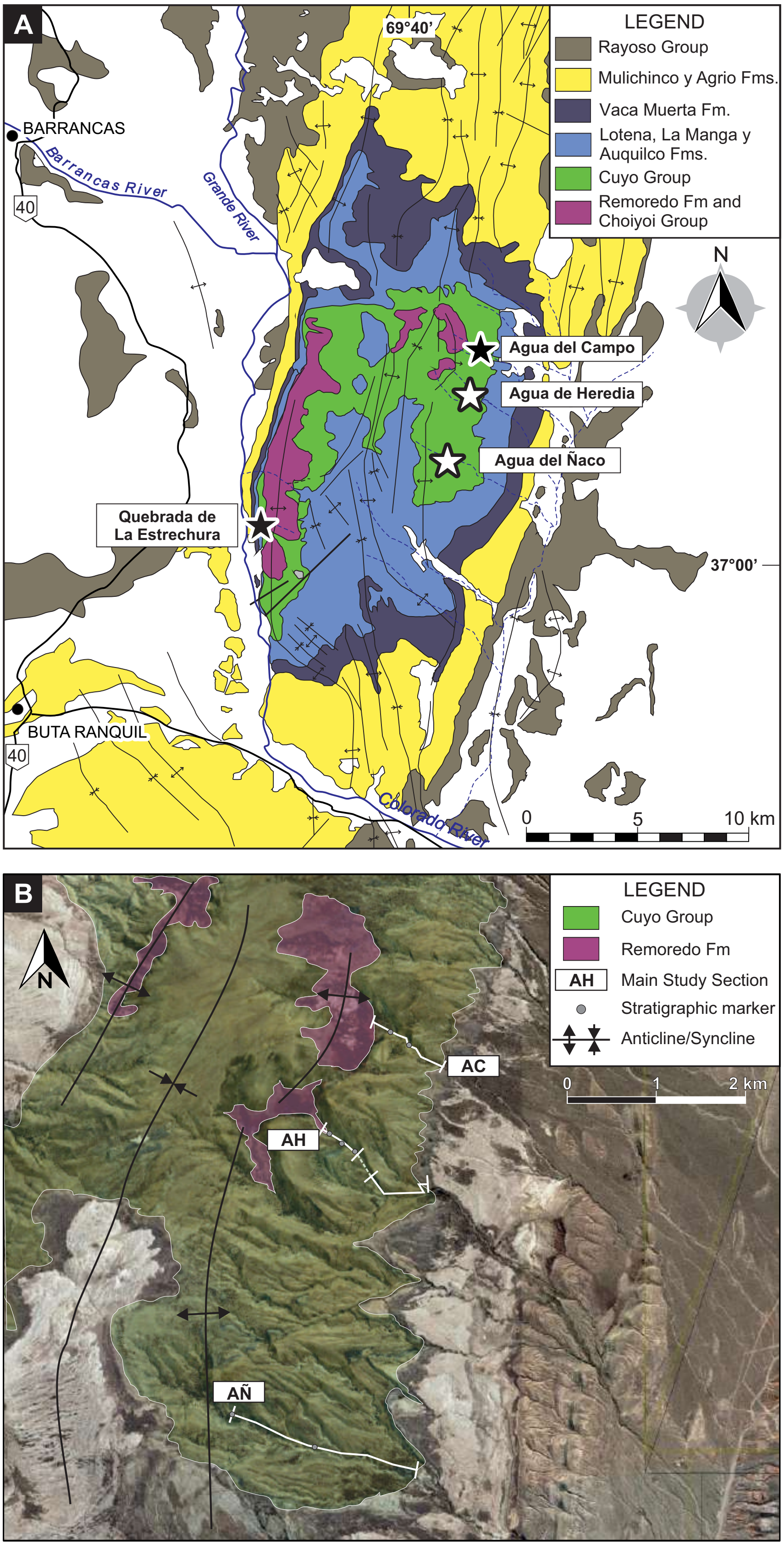

A
LEGEND
Rayoso Group
Mulichinco y Agrio Fms.
Vaca Muerta Fm.
Lotena, La Manga y Auquilco Fms.
Cuyo Group
Remoredo Fm and Choiyoi Group
69°40'
37°00'
BARRANCAS
Barrancas River
Grande River
Colorado River
BUTA RANQUIL
40
Agua del Campo
Agua de Heredia
Agua del Ñaco
Quebrada de La Estrechura
N
0 5 10 km
B
LEGEND
Cuyo Group
Remoredo Fm
AH Main Study Section
Stratigraphic marker
Anticline/Syncline
AC
AH
AÑ
N
0 1 2 km

Figure 4

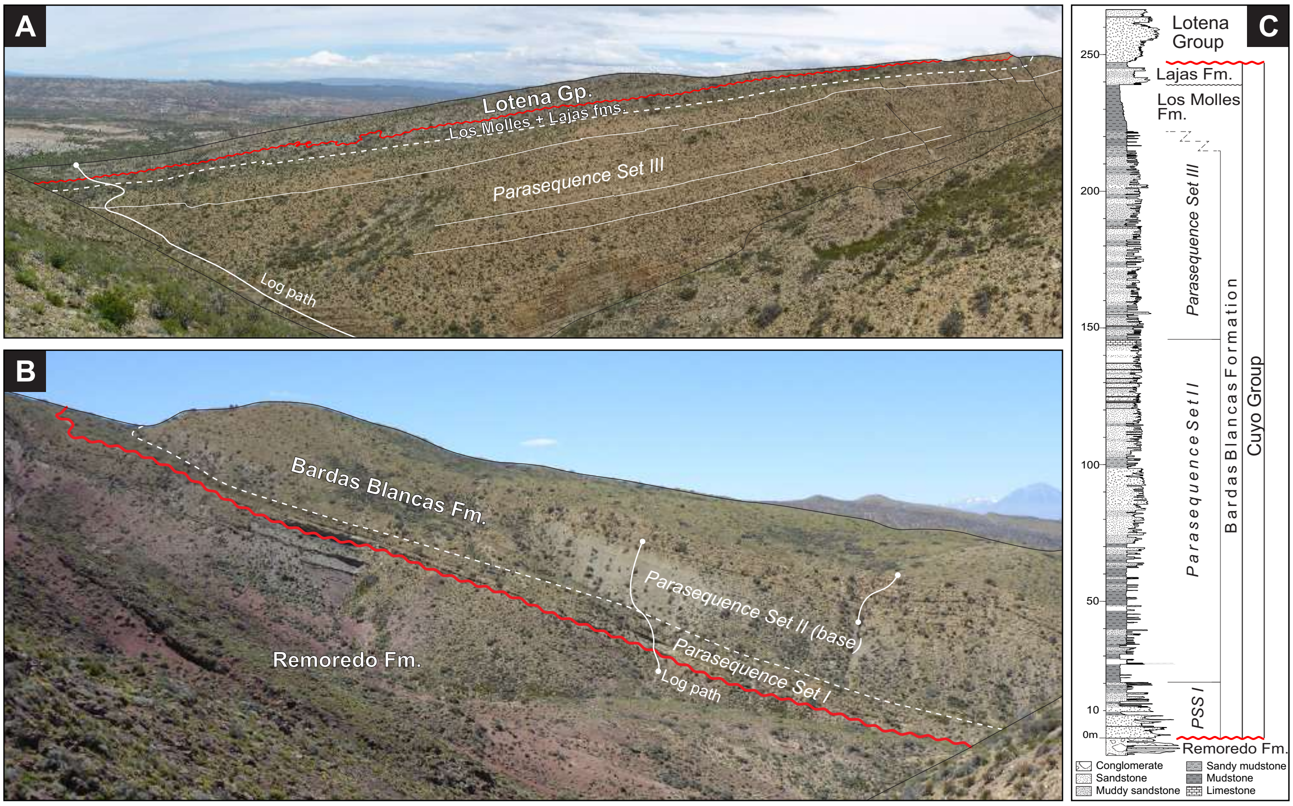

A
Lotena Gp.
Los Molles + Lajas fms.
Parasequence Set III
Log path
B
Bardas Blancas Fm.
Parasequence Set II (base)
Parasequence Set I
Remoredo Fm.
Log path
C
Lotena Group
Lajas Fm.
Los Molles Fm.
Parasequence Set III
Parasequence Set II
PSS I
Bardas Blancas Formation
Cuyo Group
Remoredo Fm.
250
200
150
100
50
10
0m
Conglomerate
Sandstone
Muddy sandstone
Sandy mudstone
Mudstone
Limestone

Figure 5

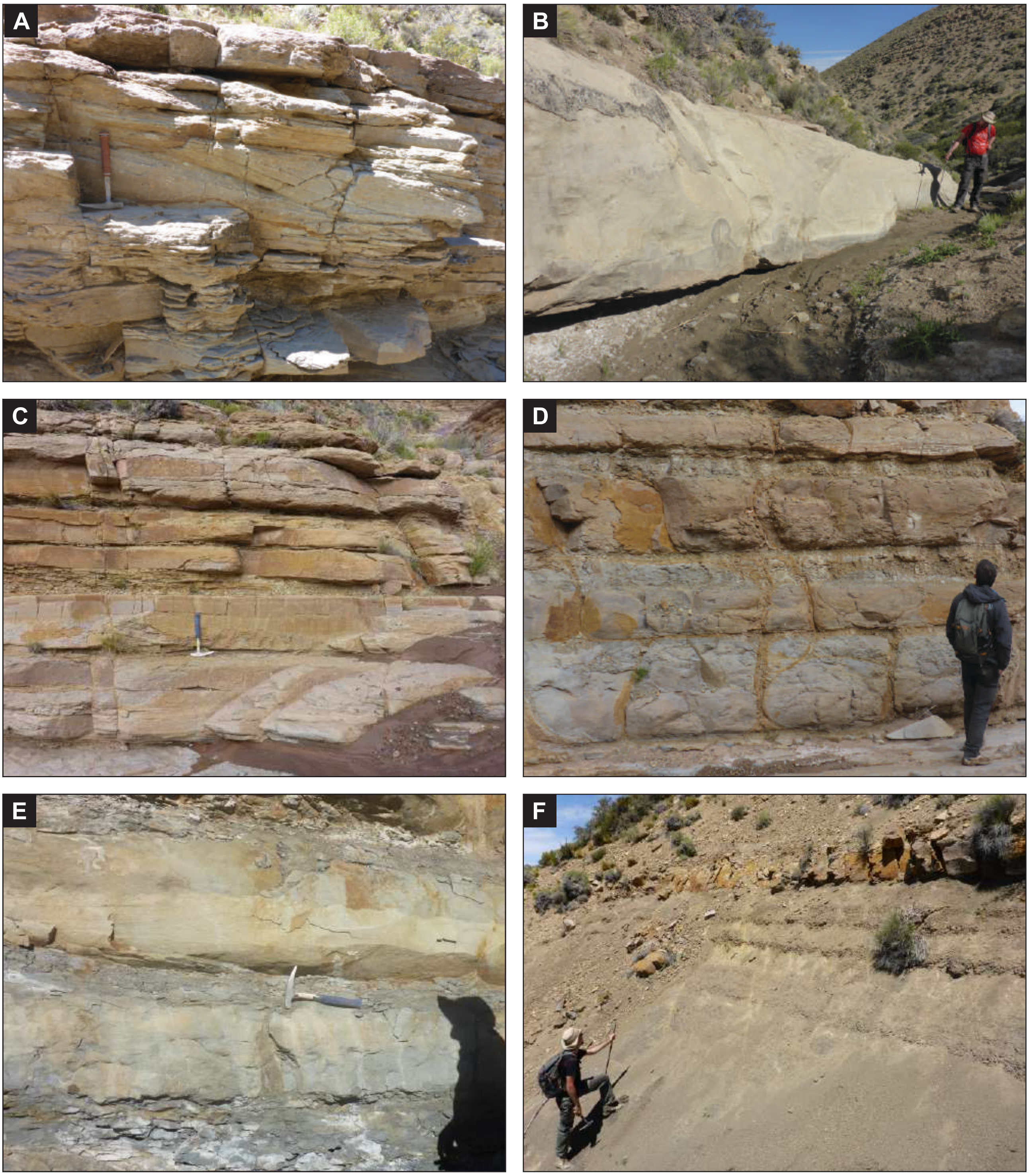


Figure 06


A
Chondrites
Muddy sandstone
B
Teichichnus
Muddy sandstone
C
Rhizocorallium
Sandy mudstone
D
Zoophycos
Zoophycos?
Rhizocorallium
Sandy mudstone

Figure 7

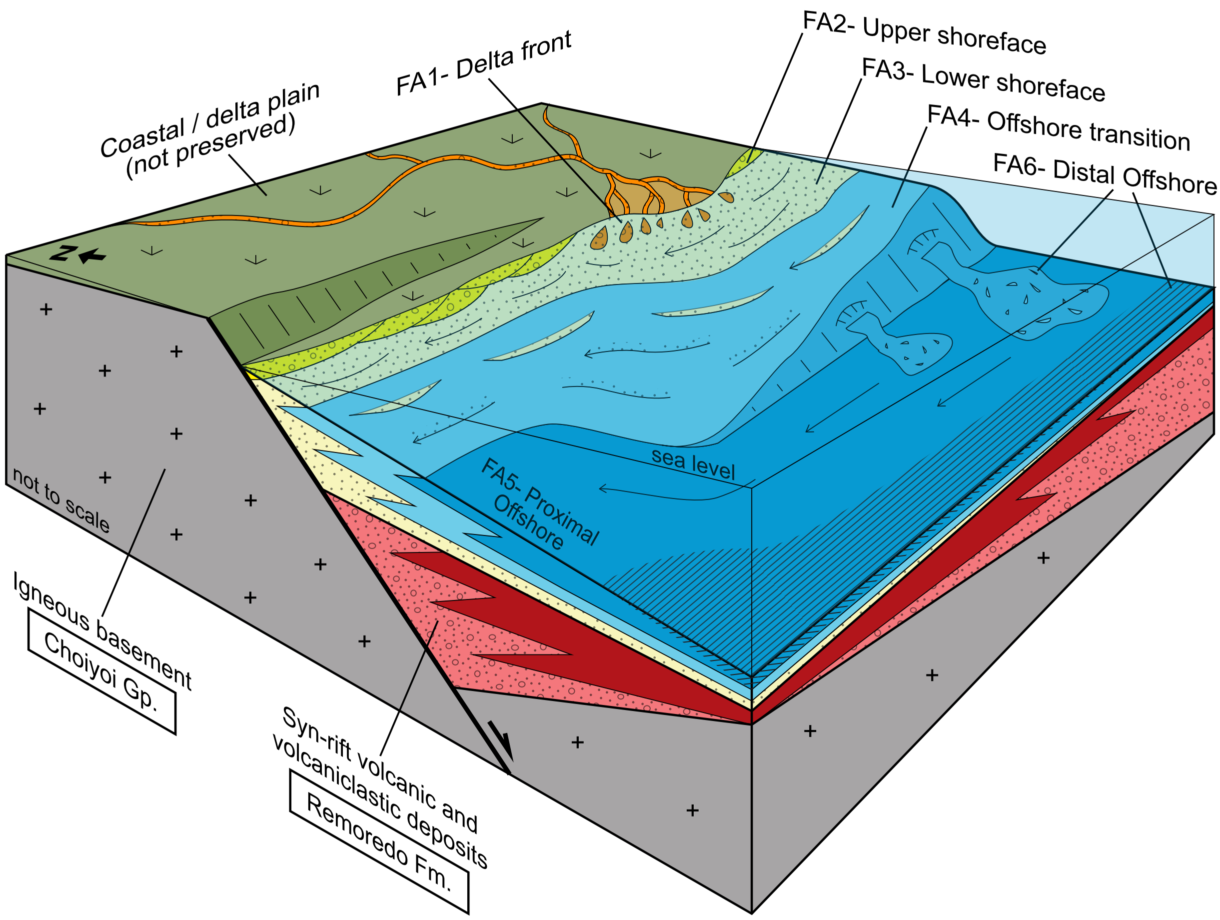

FA1- Delta front
FA2- Upper shoreface
FA3- Lower shoreface
FA4- Offshore transition
FA6- Distal Offshore
Coastal / delta plain
(not preserved)
N
not to scale
sea level
FA5- Proximal
Offshore
Igneous basement
Choiyoi Gp.
Syn-rift volcanic and
volcaniclastic deposits
Remoredo Fm.

Figure 8

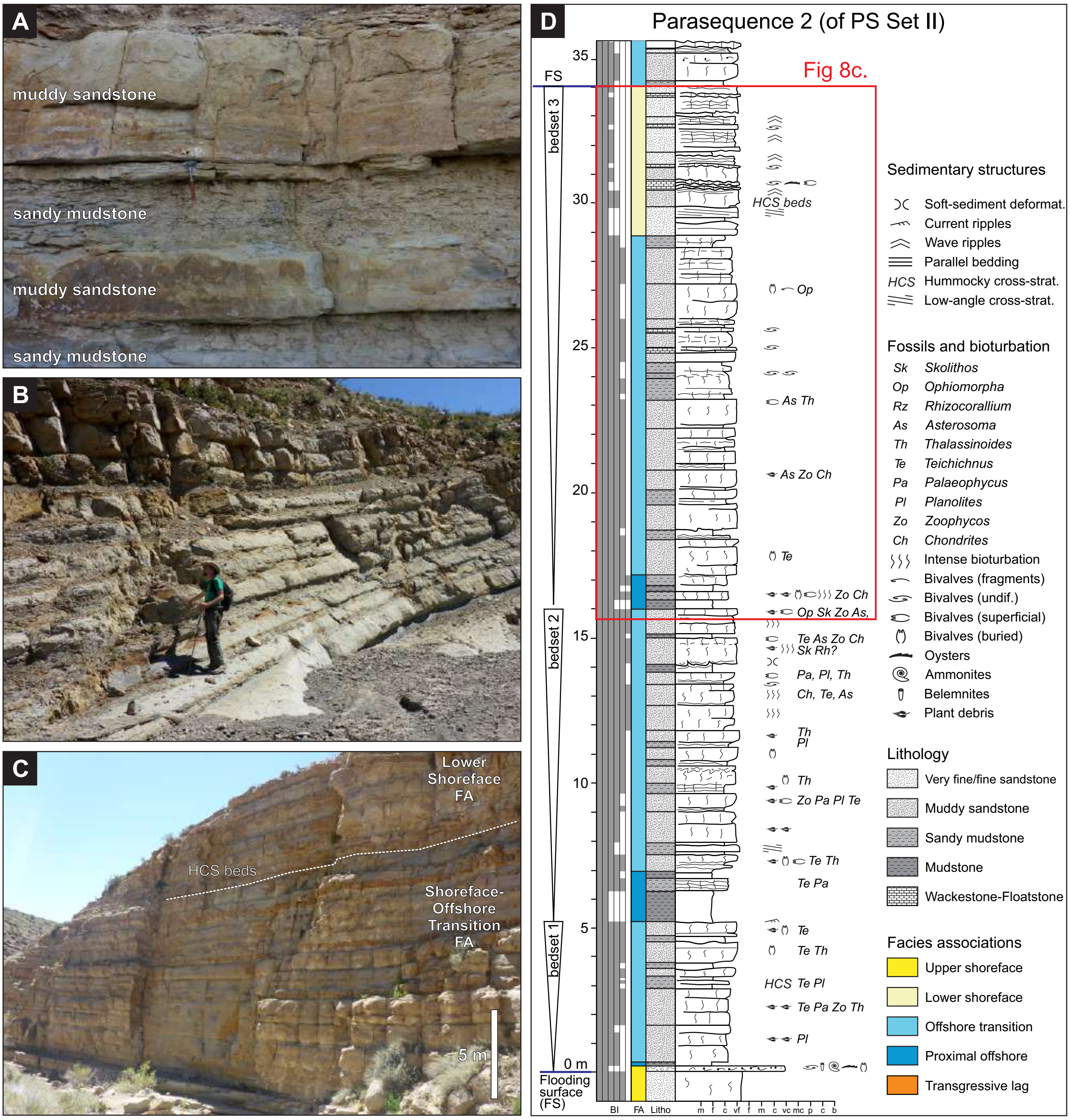
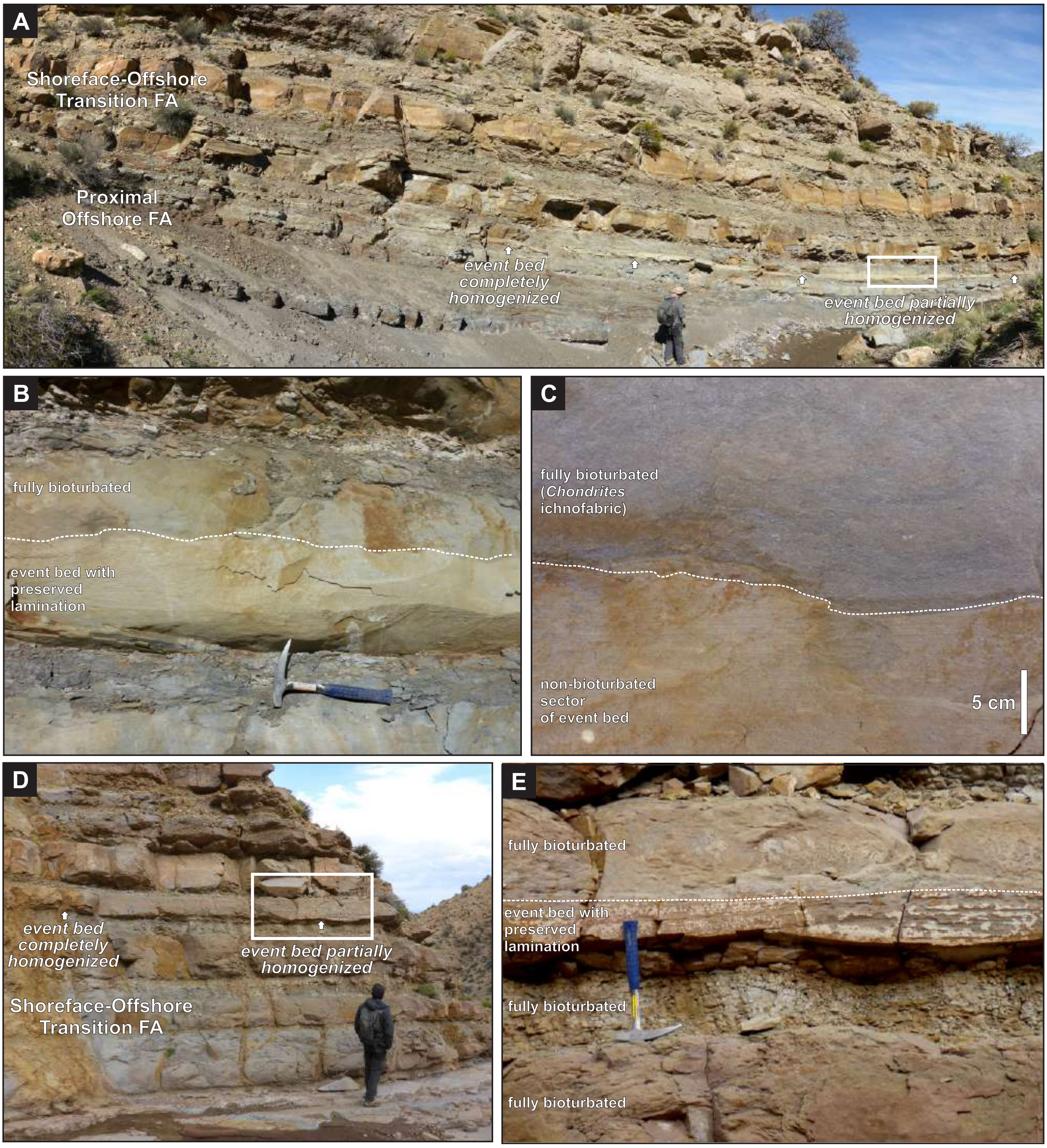

A
muddy sandstone
sandy mudstone
muddy sandstone
sandy mudstone
B
C
Lower Shoreface FA
HCS beds
Shoreface-Offshore Transition FA
5 m
D
Parasequence 2 (of PS Set II)
Fig 8c.
FS
bedset 3
bedset 2
bedset 1
Flooding surface (FS)
0 m
5
10
15
20
25
30
35
BI FA Litho
m f c vf f m c vc mc p c b
HCS beds
Op
As Th
As Zo Ch
Te
Zo Ch
Op Sk Zo As,
Te As Zo Ch
Sk Rh?
Pa, Pl, Th
Ch, Te, As
Th
Pl
Th
Zo Pa Pl Te
Te Th
Te Pa
Te
Te Th
HCS Te Pl
Te Pa Zo Th
Pl
Sedimentary structures
Soft-sediment deformat.
Current ripples
Wave ripples
Parallel bedding
HCS Hummocky cross-strat.
Low-angle cross-strat.
Fossils and bioturbation
Sk Skolithos
Op Ophiomorpha
Rz Rhizocorallium
As Asterosoma
Th Thalassinoides
Te Teichichnus
Pa Palaeophycus
Pl Planolites
Zo Zoophycos
Ch Chondrites
Intense bioturbation
Bivalves (fragments)
Bivalves (undif.)
Bivalves (superficial)
Bivalves (buried)
Oysters
Ammonites
Belemnites
Plant debris
Lithology
Very fine/fine sandstone
Muddy sandstone
Sandy mudstone
Mudstone
Wackestone-Floatstone
Facies associations
Upper shoreface
Lower shoreface
Offshore transition
Proximal offshore
Transgressive lag

Figure 9



A
Shoreface-Offshore Transition FA
Proximal Offshore FA
event bed completely homogenized
event bed partially homogenized
B
fully bioturbated
event bed with preserved lamination
C
fully bioturbated (*Chondrites* ichnofabric)
non-bioturbated sector of event bed
5 cm
D
event bed completely homogenized
event bed partially homogenized
Shoreface-Offshore Transition FA
E
fully bioturbated
event bed with preserved lamination
fully bioturbated
fully bioturbated

Figure 10

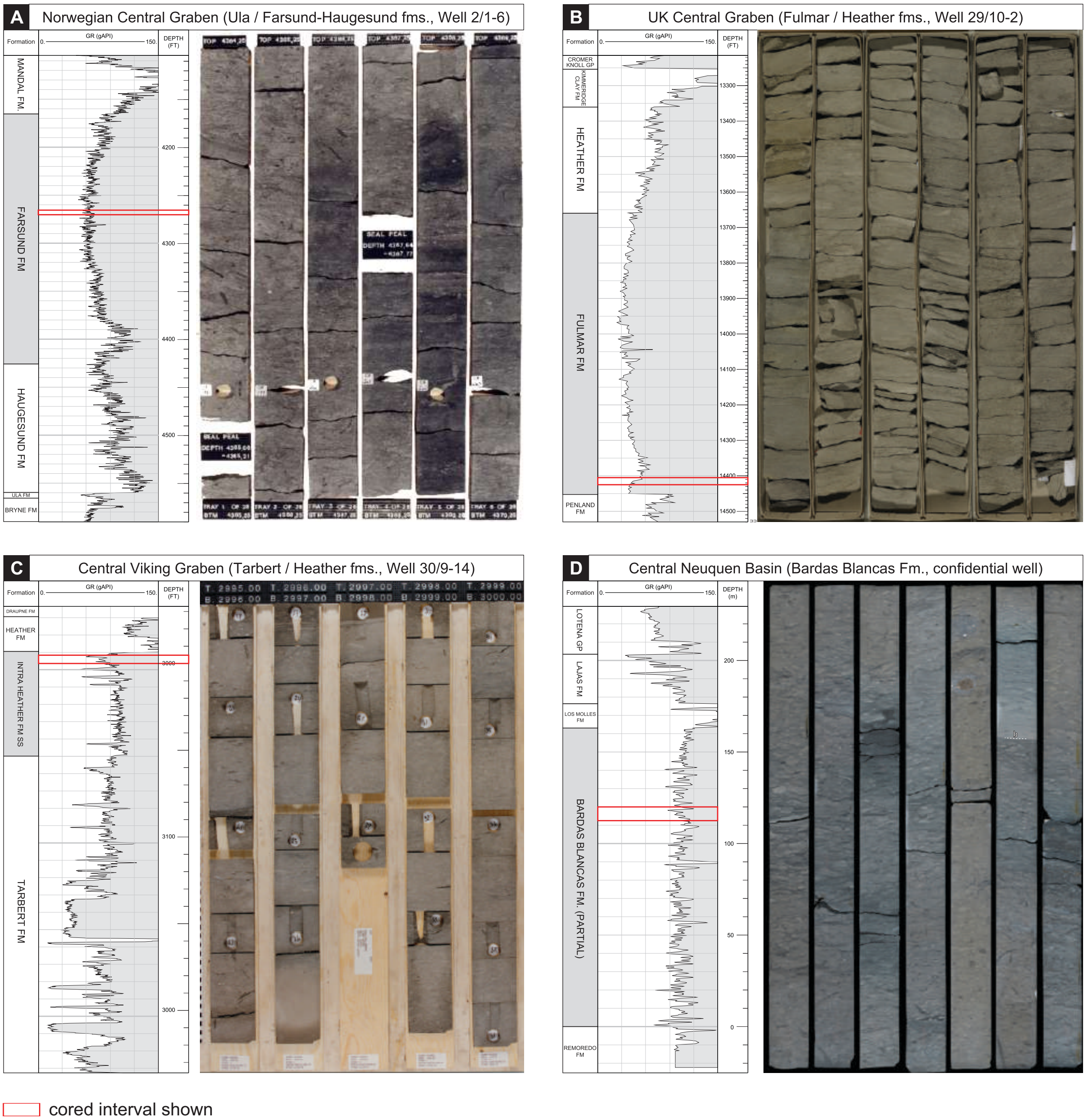
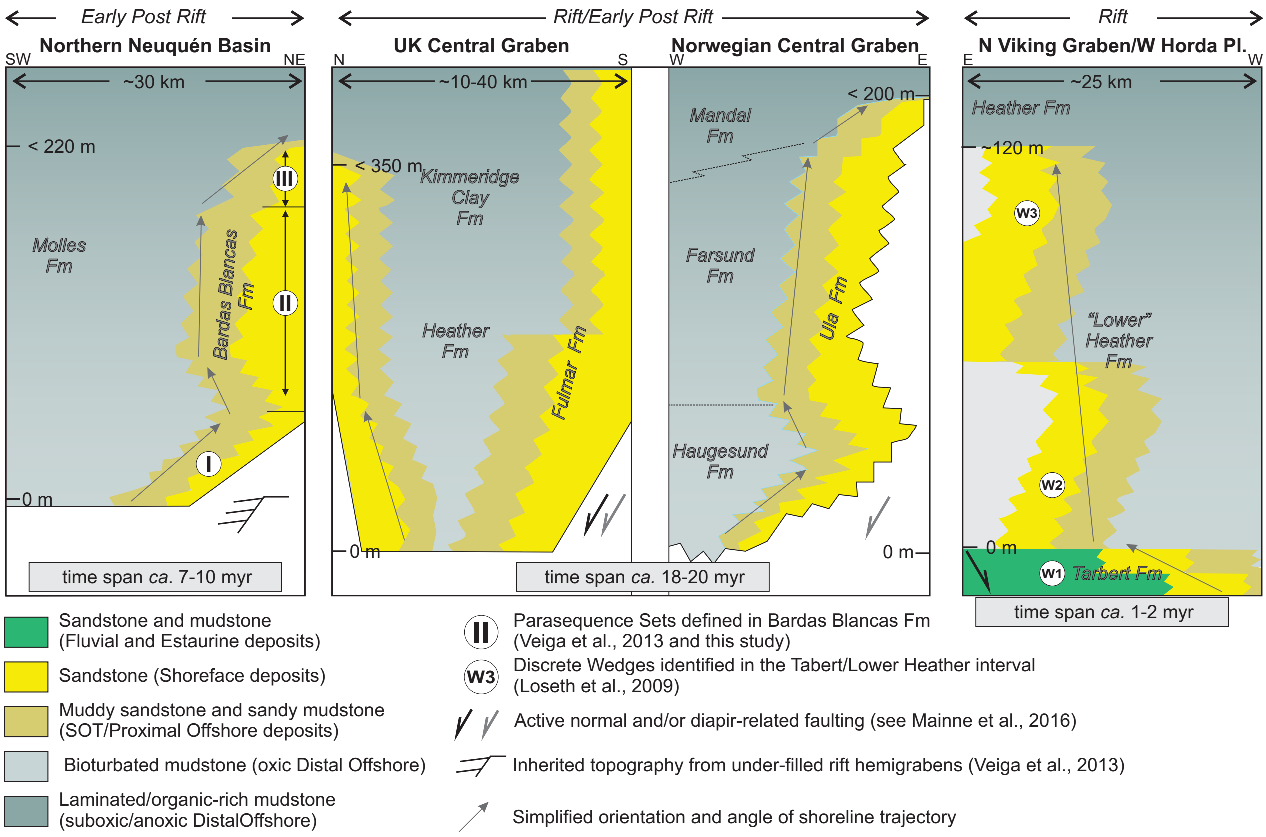

A
Norwegian Central Graben (Ula / Farsund-Haugesund fms., Well 2/1-6)
Formation
GR (gAPI)
DEPTH (FT)
MANDAL FM.
FARSUND FM
HAUGESUND FM
ULA FM
BRYNE FM
B
UK Central Graben (Fulmar / Heather fms., Well 29/10-2)
CROMER KNOLL GP
KIMMERIDGE CLAY FM
HEATHER FM
FULMAR FM
PENLAND FM
C
Central Viking Graben (Tarbert / Heather fms., Well 30/9-14)
DRAUPNE FM
HEATHER FM
INTRA HEATHER FM SS
TARBERT FM
D
Central Neuquen Basin (Bardas Blancas Fm., confidential well)
DEPTH (m)
LOTENA GP
LAJAS FM
LOS MOLLES FM
BARDAS BLANCAS FM. (PARTIAL)
REMOREDO FM
cored interval shown

Figure 11



Early Post Rift
Rift/Early Post Rift
Rift
Northern Neuquén Basin
SW
NE
~30 km
< 220 m
Molles Fm
Bardas Blancas Fm
III
II
I
0 m
time span ca. 7-10 myr
UK Central Graben
N
S
~10-40 km
< 350 m
Kimmeridge Clay Fm
Heather Fm
Fulmar Fm
0 m
Norwegian Central Graben
W
E
< 200 m
Mandal Fm
Farsund Fm
Ula Fm
Haugesund Fm
0 m
time span ca. 18-20 myr
N Viking Graben/W Horda Pl.
E
W
~25 km
Heather Fm
~120 m
W3
"Lower" Heather Fm
W2
0 m
W1
Tarbert Fm
time span ca. 1-2 myr
Sandstone and mudstone (Fluvial and Estaurine deposits)
Sandstone (Shoreface deposits)
Muddy sandstone and sandy mudstone (SOT/Proximal Offshore deposits)
Bioturbated mudstone (oxic Distal Offshore)
Laminated/organic-rich mudstone (suboxic/anoxic DistalOffshore)
II
Parasequence Sets defined in Bardas Blancas Fm (Veiga et al., 2013 and this study)
W3
Discrete Wedges identified in the Tabert/Lower Heather interval (Loseth et al., 2009)
Active normal and/or diapir-related faulting (see Mainne et al., 2016)
Inherited topography from under-filled rift hemigrabens (Veiga et al., 2013)
Simplified orientation and angle of shoreline trajectory

Code	Texture	Structures	Thickness	Fossil content	Bioturbation	Trace fossils	Other	Presence	Interpretation	Environment
FA1	Normally- to inversely-graded pebbly to medium-grained sandstones.	Plane bed, planar or trough cross-stratification (sets <0.3 m thick), oriented to W-SW.	0.3–1.5 m thick beds.	Sand-size bioclasts common, high degree of fragmentation. Mostly from bivalves, but ammonite and belemnite fragments also present.	Absent to moderate (BI 0-3).	*Skolithos* suite: *Palaeophycus, Ophiomorpha, Arenicolites.*	Thin (up to 40 cm-thick) extraformational conglomerate layers with quartz and volcanic lithic pebbles (up to 5 cm-long) with mudstone rip-up clasts, and chaotic to organized fabric. Rare detrital glauconitic grains. Tree trunks, micaceous and organic debris preserved in bedding planes.	Only observed at the base of Bardas Blancas Fm.	High-energy nearshore setting, influenced by terrestrial input of river-related hyperpycnal flows, and partly reworked by subordinate coastal processes.	**Delta front**
FA2	Amalgamated fine- to medium-grained sandstones	Structureless or trough cross-stratification (sets <0.5 m thick).	0.5-1.8 m thick beds.	Occasional lenses of shells with oriented bioclasts at bed bases.	Absent to low (BI 0-2).	Where observed, *Skolithos* suite: *Ophiomorpha.*	Very well-sorted, “clean” sandstones. Locally preserved coarser grained, bioclast-rich accumulations at the top (transgressive lags).	Uncommon, only observed towards upper part of some parasequences.	High-energy nearshore setting, intensely reworked by dominant longshore currents.	**Upper Shoreface**
FA3	Amalgamated to tabular very fine- to fine-grained sandstones.	HCS with subordinate SCS and plane bed. Symmetrical ripple tops uncommon.	0.15–0.80 m thick beds. Few m-thick bedsets.	Lenses of shells with common bioclasts oriented parallel to bed bases.	Low-moderate to high (BI 2-5).	*Skolithos* suite: *Arenicolites, Skolithos, Palaeophycus, Ophiomorpha,*	Parting lineation, micaceous and organic (plant) debris common. Occasional nodular carbonate horizons, associated with large bioclast accumulations.	Common in studied sections, mainly towards upper part of parasequences.	Moderate to high energy in marine environment, above FWWB. Common deposits of purely oscillatory and/or combined flows during storms. Amalgamation suggests erosion of fair-weather sediments.	**Lower shoreface**
FA4	Tabular very fine-grained sandstones and muddy sandstones, with subordinate sandy mudstones.	Typically massive due to very intense bioturbation. Occasional HCS or faint ripple cross-lamination.	Tabular beds from 0.10-0.40 m thick. Up to 1.50 m thick. Several m-thick bedsets.	Bioclasts of infaunal and semi-infaunal bivalves common. Low to moderate degree of fragmentation, articulated specimens common, occasionally preserved in life position. Belemnite and ammonite remains less common.	Mostly high (BI 5-6), occasionally moderate (BI 4).	*Cruziana* suite: *Teichichnus, Asterosoma, Rosselia, Chondrites, Planolites, Thalassinoides, Rhizocorallium, Palaeophycus, Phycosiphon, Zoophycos.*	Occasional preservation of sandstone beds (0.2-1.0 m thick), traceable for 100’s of m. They are fine- to very fine-grained, with HCS or less commonly massive grading upwards to planar-laminated. Shells can be concentrated at their bases. Bioturbation (lam-scram) increases from top downwards.	Broadly distributed in studied sections.	Moderate to low energy in marine environment, below FWWB. Lower proportion (or preservation) of storm deposits than lower shoreface deposits.	**Offshore transition**
FA5	Sandy mudstones and silty mudstones, with subordinate mudstones and muddy sandstones.	Diffuse grain-size changes, bedding contacts are diffuse, but roughly parallel.	Tabular beds from 0.20-0.80 m thick.	Fragments of ammonites and belemnites frequent, benthic macrofossils are uncommon (mostly oysters).	Mostly high (BI 5-6), occasionally moderate (BI 4).	*Distal Cruziana* suite: *Chondrites, Phycosiphon, Planolites, Teichichnus, Helminthopsis, Thalassinoides, Rhizocorallium,* diminute *Skolithos*, *Zoophycos.*	Discrete sandstone beds less common than in FA4. They show plane bed and bioturbation decreasing from top to bottom.	Broadly distributed in studied sections.	Low-energy conditions, with cohesive substrates and persistent oxic conditions. Relatively distal depositional setting, around SWWB.	**Proximal offshore**
FA6	Gray mudstones and/or black shales.	Massive to crudely laminated.	From cm- to several m-thick packages.	Foraminifera common.	Absent to moderate (BI 0-3).	*Zoophycos* suite: *Zoophycos, Phycosiphon, Chondrites, Scolicia (?).*	Occasional diagenetic nodule-rich horizons. In lower section, thin (up to 40 cm-thick) extraformational conglomerate layers, with mudstone rip-up clasts (up to 10 cm), chaotically distributed in sandstone beds or forming organized intraformational conglomerates. In upper section, remobilized or coherent black shales, typically platy, with absence of trace fossils and scarce fragments of small, thin-shelled bivalves. Cm-thick tuffaceous layers occur.	Relatively uncommon, mainly observed near base or top of unit.	Suspension settling in very low-energy conditions and devoid of bottom currents, below SWWB. Occasional gravity-flow deposits in the lower section. Dysoxic to anoxic conditions with soupy, organic-rich substrates in the upper section (and transition to Los Molles Fm).	**Distal offshore**

Table 1- Facies association classification, description and interpretation of the main processes and environments of deposition. Trace fossil content is listed in relative order of abundance. FWWB: Fair-weather wave base ; SWWB: Storm-weather wave base.

Table 2.

Units	Age; Duration; Thickness	Dominant facies (in lower shoreface and offshore-transition settings)	Long-term Stacking Pattern	Tectonic setting and subsidence	Sediment source	References
Emery Sandstone (Mancos Shale Fm., Utah, USA)	Upper Cretaceous; 1.8 Myr; < 250 m	Intensely bioturbated fine to medium grained sandstones; interbedded siltstones	Aggradational	High subsidence rates in foreland basin setting	Small rivers, little evidence of deltaic influence, low sedimentation rates compared to underlying and overlying units.	Edwards et al. (2005)
Ula and Farsund formations (Norwegian Central Graben)	Upper Jurassic; ca. 18.5 Myr; < 200 m	Intensely bioturbated very fine to fine grained sandstones (Ula Fm); intensely bioturbated muddy sandstones, sandy mudstones, silty mudstones, and shales (Farsund Formation)	Aggradational, retrogradational	Series of extensional fault-bounded basins and sub-basins, relative high mechanical subsidence	Not available	Baniak et al. (2014; 2015).
Fulmar Fm. and equivalent Header Fm. (UK Central Graben)	Middle- Upper Jurassic; ca. 21.1 Myr; < 360 m (typically 60-110 m)	Moderate to Intensely bioturbated fine to medium grained sandstones, uncommon HCS-sandstone beds; intensely bioturbated muddy heterolithics	Aggradational	Mechanical subsidence and/or diapir- related faulting, complex topography linked to sub-basins and intrabasinal highs.	Poorly developed river systems; lack large deltaic systems;	Gowland (1996); Howell et al. (1996)
Tarbert - Lower Heather formations (northern North Sea)	Middle Jurassic; < 4.2 Myr; < 200 m	Bioturbated and HCS-dominated very fine to medium grained sandstone; bioturbated silstones	Retrogradational	Series of extensional fault-bounded basins and sub-basins, relative high mechanical subsidence	Not available	Løseth et al. (2009)
Bridport Sand Fm. (Wessex Basin, UK)	Early Jurassic; ~ 7 Ma; < 200 m	Silty, very fine to fine grained sandstones	Progradational, aggradational	Extensional fault-bonded depocentres; high rates of mechanical subsidence	Lack of river-mouth processes; along-shore transport significant; high net siliciclastic sediment input	Morris et al., 2006
Bardas Blancas Fm. (Nequén Basin, Argentina)	Lower to Middle Jurassic; ~ 7-10; < 220 m	Intensely bioturbated sandy mudstones, muddy sandstones, very fine to fine grained sandstones	Aggradational, Retrogradational	Underfilled rift depocentres; inherited topography	Lack of river-mouth processes; along-shore transport significant	Veiga et al., 2013; **this study**