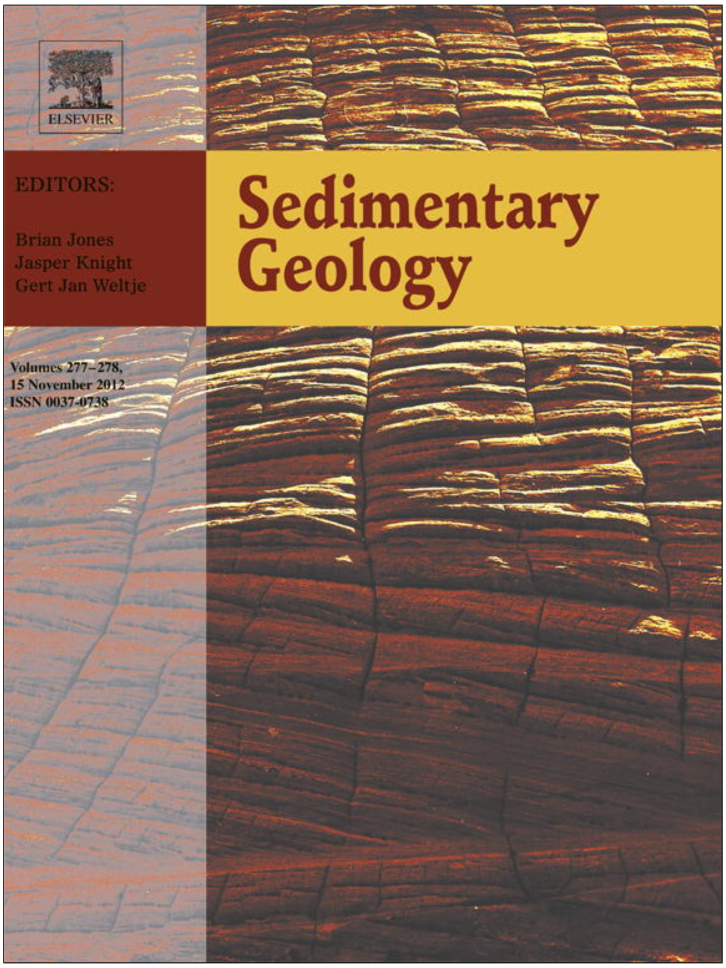
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Substrate-controlled ichnofacies along a marine sequence boundary: The Intra-Valanginian Discontinuity in central Neuquén Basin (Argentina)

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ABSTRACT

The Intra-Valanginian Discontinuity in the Neuquén Basin (Argentina) marks a dramatic sea-level fall within Lower Cretaceous strata, and can be mapped for tens of kilometers both along depositional strike and dip. In the proximal region of the lowstand configuration, the subaerial segment of the sequence boundary is demarcated by alluvial conglomerates (basal Mulichinco Formation) onto deep-marine black shales (Vaca Muerta Formation). In the distal marine realm, the time-equivalent marine sequence boundary separates black shales and marls beneath from shallow-marine carbonate deposits above. This paper documents and discusses substrate-controlled trace fossils demarcating the marine sequence boundary across more than 30 km in a proximal–distal transect in order to shed light onto processes affecting the sea-floor during the generation, biogenic modification, and preservation of this regionally extensive omission surface.

The downdip expression of the marine sequence boundary is well-exposed across a 20-km long, strike-oriented outcrop. Everywhere in this region the discontinuity is demarcated by robust *Thalassinoides* with well-defined walls and circular cross-sections, suggesting that the marly substrate was relatively firm during excavation. The burrow system is filled with bioclasts of echinoids and bivalves not present in underlying strata, up to pebble-size intraclasts that were eroded from the underlying succession, and authigenic minerals (glauconite, phosphates). This trace-fossil suite illustrates the *Glossifungites* Ichnofacies. The updip expression of the marine sequence boundary in the study area was recorded in a cored well located about 20 km from the outcrops. As in the distal region, a first generation of passively filled *Thalassinoides* excavated into a firm marly substrate is attributed to the *Glossifungites* Ichnofacies. However, this suite is cross-cut at the top by *Gastrochaenolites* and other unidentified borings. Bored intraclasts also occur above the omission surface. This trace-fossil suite represents the *Trypanites* Ichnofacies.

The Intra-Valanginian Discontinuity records a complex history after the onset of the dramatic sea-level fall. Extensive erosion and exhumation of previous sediments, as well as early cementation, combined to produce different types of substrates during the generation of the omission surface (firmgrounds and hardgrounds). Colonization of firm substrates probably started firstly in proximal regions, when relative sea-level was still falling. During early transgression, firmgrounds were occupied in distal regions and borers colonized the hardgrounds developed in proximal regions. Thus, the surface demarcates a composite surface, involving a sequence boundary plus a transgressive surface, draped in turn by a mixing of sediments suggesting siliciclastic starvation. The generation and preservation of the features associated with the Intra-Valanginian Discontinuity are thought to result from the combination of a ramp-type pre-existing morphology, coupled with a high-amplitude sea-level fall and a relatively deep-marine setting prior to the formation of the omission surface.

1. Introduction

During the generation of a marine discontinuity, the underlying succession might undergo different episodes of erosion, deposition and/or cementation, which in turn can result in the formation of different types of substrates. These softgrounds, firmgrounds, and/or hardgrounds, which can replace each other, both along depositional dip and along strike, would be in turn colonized by different types of organisms (MacEachern et al., 2007; Buatois and Mángano, 2011). Thus, any individual discontinuity across a basin could be demarcated by different substrate-controlled trace fossils (*Teredolites*, *Glossifungites*, and *Trypanites* Ichnofacies). Although these statements are fairly logical, ancient examples supporting this concept have not been widely reported (MacEachern et al., 2007 and references therein). In a few examples, a downdip change from palimpsest softground suites (developed on exhumed sandstones) into firmground suites attributable to the *Glossifungites* Ichnofacies (developed in dewatered muds) has been

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documented (Peterson, 1995; MacEachern and Løseth, 2003). Most notably, the variable expression of a single omission surface, from softground to firmground, hardground and rockground, was documented in detail by Lewis and Ekdale (1992). Cross-cutting vertical relationships between different substrate-controlled suites as a result of progressive hardening of the substrate (e.g., Bromley, 1975; Mángano and Buatois, 1991), and lateral variations within a single substrate-controlled ichnofacies (e.g., Gingras et al., 2001; Carmona et al., 2007) are comparatively better understood.

The applications of ichnology in carbonate sequence stratigraphy have hardly been explored (e.g., Hanken et al., 1996; Wilson et al., 1998; Rodríguez Tovar et al., 2007; Buatois and Mángano, 2011; Christ et al., 2012), and there is a surprising lack of studies of carbonate ichnofaunas based on cores. Carbonate sequence stratigraphy shows notable departures with respect to the siliciclastic paradigm (Bosence and Wilson, 2003; Schlager, 2005; Catuneanu, 2006). The most important of these differences resides in the fact that, in contrast to siliciclastic settings, substrate-controlled ichnofacies can be formed in carbonates without erosional exhumation, simply as a result of early diagenetic changes in the substrate (Bromley, 1975; Buatois and Mángano, 2011). Consequently, the *Glossifungites* and *Trypanites* Ichnofacies can develop during periods of reduced depositional rates or breaks in sedimentation. Examples include drowning unconformities formed due to shutdown of the "carbonate factory" during rapid sea-level rise and maximum flooding surfaces associated with condensation (see review in Buatois and Mángano, 2011). Nevertheless, substrate-controlled ichnofacies do occur in erosional surfaces also, including transgressive and composite surfaces, the latter being discontinuities produced during a relative sea-level fall, subsequently remodeled during initial transgression. For example, spectacular examples of the *Glossifungites* Ichnofacies due to wave ravinement of carbonate substrates have been documented by Rodríguez Tovar et al. (2007). In practice, the origin of any discontinuity surface (both in carbonates and siliciclastic successions) should be carefully evaluated by describing the underlying and overlying sediments, as well as by assessing its characteristics in detail and its sequence-stratigraphic context (e.g., Schwarz, 2012). This, eventually, will allow for detection of whether the surface is erosive in nature (e.g., transgressive surface of erosion, composite surface) or if it represents sediment condensation (e.g., drowning surface, maximum flooding surface).

In this paper, we address the ichnology of a major stratigraphic discontinuity that represents a second-order sea-level fall within the Lower Cretaceous of the Neuquén Basin, Argentina. This sequence boundary, referred to as the Intra-Valanginian Discontinuity, can be mapped for tens of kilometers both along depositional strike and dip (Schwarz et al., 2006). This study, integrating outcrop and subsurface datasets, describes the discontinuity and the substrate-controlled ichnofacies developed both along depositional dip and strike in the marine environment. The outcrop data represent the relatively distal segment of the marine depositional profile, and the discontinuity is demarcated there by the *Glossifungites* Ichnofacies (well exposed across several kilometers of along-strike outcrops). A cored well, located about 30 km updip, also shows the stratigraphic location of the studied discontinuity, confirmed by a regional outcrop–subsurface correlation using several supplementary boreholes. As in the distal region, a first generation of burrows excavated in a firm substrate is attributed to the *Glossifungites* Ichnofacies. However, this suite is in turn cross-cut by a second suite of trace fossils developed in a cemented hardground and therefore referable to the *Trypanites* Ichnofacies.

The aims of this paper are threefold: (1) to describe and interpret the sediments and the substrate-controlled ichnofacies developed along depositional dip and strike of a ramp-type marine environment during and immediately after a major relative sea-level fall, (2) to discuss types and timing of processes associated with the development of a major omission surface, and (3) to analyze and discuss factors controlling discontinuities in carbonate marine settings. In addition, this study represents one of a few reports in documenting bioerosion structures in cores.

2. Geologic setting

From the Middle Jurassic to the Early Cretaceous, the Neuquén Basin was a back-arc basin located inboard of the proto-Andean emergent magmatic arc, in the western margin of southern Gondwana (Fig. 1). Whereas a predominantly extensional stress regime associated with volcanism and deep-marine sedimentation was dominant in the westward intra-arc setting during that time (Ramos, 1999), the back-arc Neuquén Basin developed under regional thermal subsidence punctuated by several episodes of structural inversion (Vergani et al., 1995; Howell et al., 2005).

Between the Late Jurassic and Early Cretaceous (Neocomian), the epeiric sea of the Neuquén Basin was characterized by a ramp-type profile in the east and south margins (Legarreta and Uliana, 1991), but a steeper depositional profile toward the west (Spalletti et al., 2008). The Mendoza Group, the basin fill during this period, records deposition from basinal marine settings to continental subenvironments (Fig. 2A) (Gulisano et al., 1984; Legarreta and Uliana, 1991). Long-live periods of highstand conditions (Tithonian–early Valanginian and late Valanginian–Hauterivian) were interrupted by significant events of relative sea-level fall, followed by rapid transgression (Fig. 2A). Relative sea-level drops triggered partial disconnection of the epeiric sea from the Proto-Pacific, as well as the exposure and erosion of large areas of the basin (Howell et al., 2005). These in turn produced extensive second-order unconformities, respectively the Intra-Valanginian and the Intra-Hauterivian sequence boundaries (Fig. 2A, B). The Mulichinco Sequence developed directly on top of the Intra-Valanginian unconformity (Schwarz and Howell, 2005; Schwarz et al., 2006).

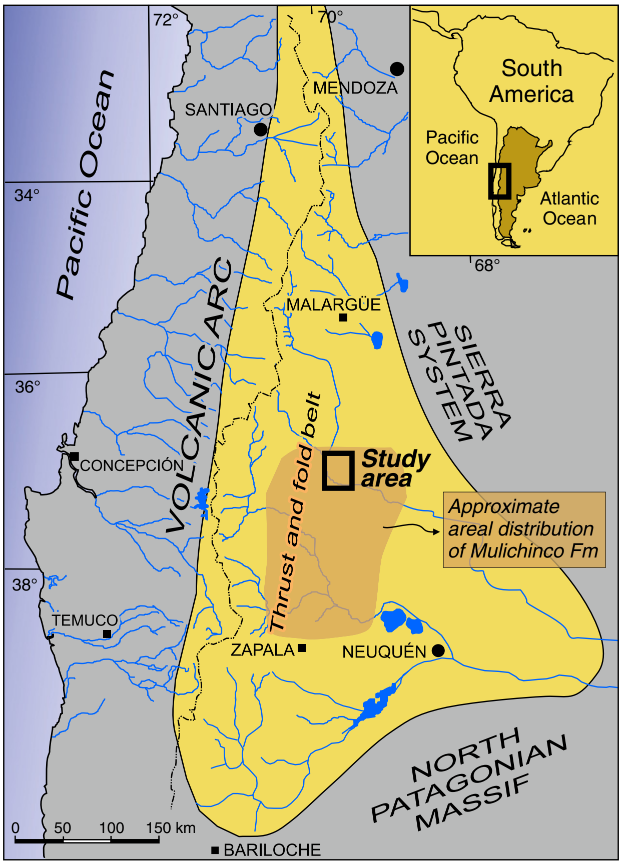

Fig. 1. Location map of the Neuquén Basin. Study area (Fig. 3) is boxed. Also depicted is the areal distribution of the Mulichinco Formation.

3. The Intra-Valanginian Discontinuity

The Intra-Valanginian Discontinuity, originally recognized by Gulisano et al. (1984), marks a relative sea-level fall of at least 100 m within the Early Cretaceous evolution of the Neuquén Basin (Schwarz and Howell, 2005). The sea-level drop, probably tectonically induced (Vergani et al., 1995; Schwarz et al., 2006), triggered a basinward shift of depositional belts (Fig. 2A, B) and exposed extensive proximal regions of the basin. The Intra-Valanginian Discontinuity is the basal unconformity of a second-order lowstand wedge, the so-called Mulichinco Lowstand Sequence (Schwarz and Howell, 2005; Schwarz et al., 2006). This lowstand sequence developed immediately after accommodation resumed across the basin (Fig. 2B). The underlying Tithonian–Lower Valanginian succession, mostly known as the Vaca Muerta and Quintuco formations, represents a second-order highstand systems tract (Fig. 2, Schwarz et al., 2006).

The Intra-Valanginian Discontinuity or basal sequence boundary can be mapped unambiguously across the present-day exposures of the Mendoza Group in southern and central Neuquén Basin (~60 km south–north, Fig. 1). There, continental deposits of the Mulichinco Formation directly overlie a >700 m-thick succession of basinal black shales and shallow-marine clastics and carbonates of the Vaca Muerta and Quintuco formations (Gulisano et al., 1984; Legarreta and Gulisano, 1989; Schwarz and Howell, 2005). As the discontinuity represents a subaerial sequence boundary (Fig. 2B), no colonization by elements of the *Glossifungites* and *Trypanites* Ichnofacies took place, and erosion probably removed any potential substrate-controlled excavation suite that might have formed during the formation of the regressive surface of marine erosion.

Farther to the north, terrestrial deposits of the Mulichinco Lowstand Sequence grade into river-dominated deltaic deposits and storm-dominated shallow-marine deposits (Fig. 2B, Schwarz and Howell, 2005). In this region, the discontinuity is also demarcated by a major facies change (from basinal shales beneath to shallow-marine deposits on top), without any preservation of substrate-controlled trace-fossil suites. The Intra-Valanginian Discontinuity was here interpreted as a regressive surface of marine erosion coeval of the sequence boundary (Schwarz et al., 2006).

In the central sector of the Neuquén Basin, the study area, the Mulichinco Lowstand Sequence is composed of siliciclastic and carbonate deposits developed in a low-gradient (i.e., ramp) shoreface-to-offshore depositional system (Schwarz, 1999; Schwarz and Howell, 2005). The

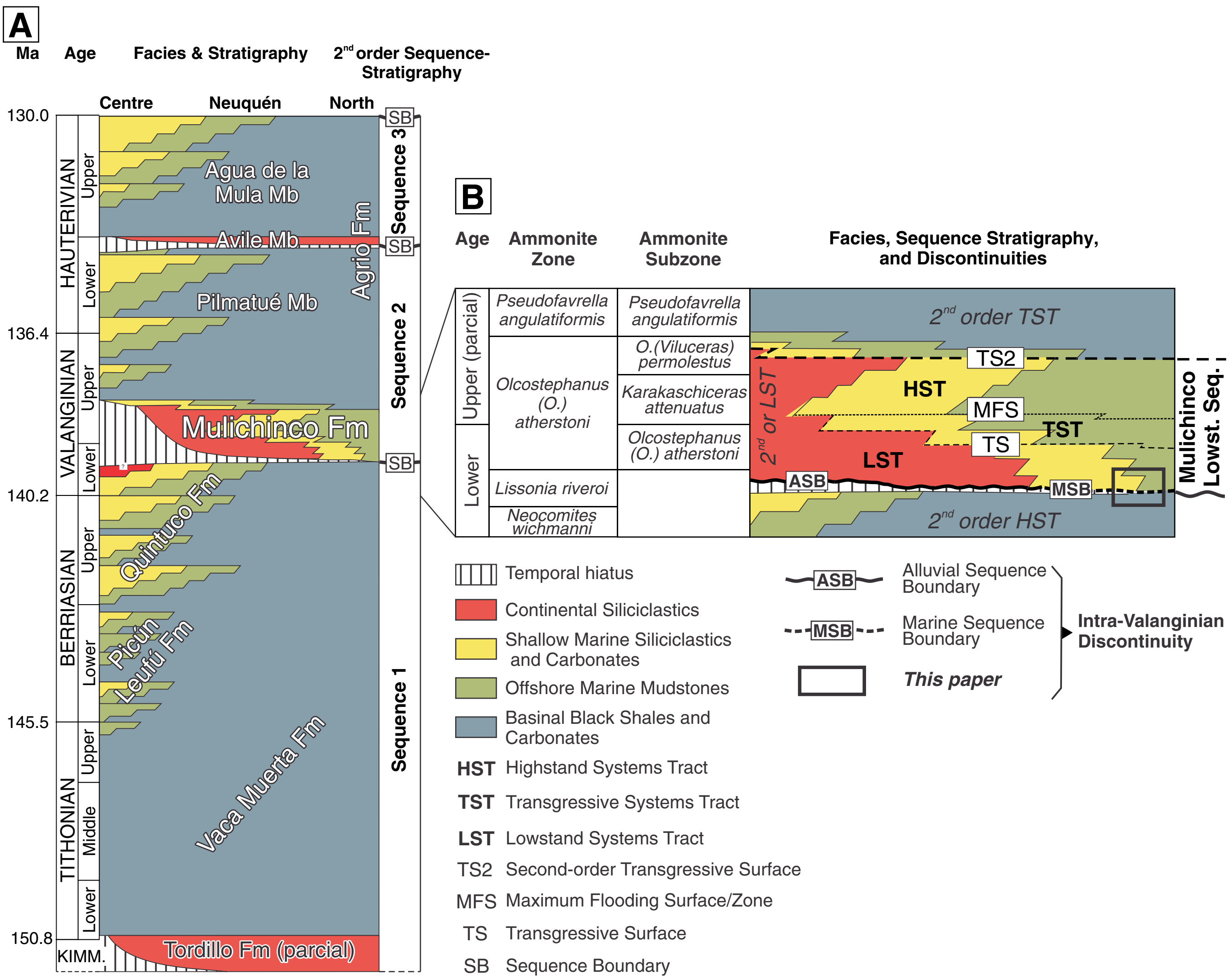

Fig. 2. A: Chronostratigraphic chart for the Tithonian–Hauterivian of the Neuquén Basin. The Mulichinco Formation represents a second-order lowstand wedge developed during a tectonically-enhanced relative sea-level drop. B: Third-order systems tracts and key stratigraphic surfaces recognized within the Mulichinco Lowstand Sequence. Note that the sequence boundary or Intra-Valanginian Discontinuity can be divided in an alluvial segment and a marine segment. The study area represents a distal sector of the marine sequence boundary. Panel A is modified from Schwarz et al. (2006). Time scale after Ogg et al. (2004). Panel B is simplified from Schwarz et al. (2006). Ammonite biostratigraphy from Aguirre-Urreta et al. (2005).

Intra-Valanginian Discontinuity overlies the Vaca Muerta Formation, which here comprises more than 500 m of bituminous dark shale, with subordinated marl and wackestone (Spalletti et al., 1999). In this region, ammonite horizons belonging to the *Lissonia riveroi* zone (Fig. 2B) occur within the topmost section of the Vaca Muerta Formation and at the base of the Mulichinco Formation. These data allow for accurately dating the Intra-Valanginian Discontinuity as middle Early Valanginian (Fig. 2B). In this distal sector of the depositional realm, the Mulichinco Sequence begins with a thin carbonate package (<6 m thick) followed by green offshore mudstone. This less dramatic vertical facies change (fine-grained deposits representing basinal setting beneath to offshore conditions above) without apparent evidence of erosion was interpreted to represent the correlative conformity (Fig. 2B) of the Intra-Valanginian sequence boundary (Schwarz and Howell, 2005; Schwarz et al., 2006). However, the new sedimentologic and ichnologic data presented in this paper indicate that even in the distal part of the marine system significant erosion occurred during sea-level fall.

4. Study area and data base

The study area is located in the northern part of the Neuquén Basin (west-central Argentina), covering the southernmost part of Mendoza Province and the northern sector of Neuquén Province (Figs. 1 and 3). The area, ~40 km wide by 40 km long, is divided east–west by the Andean fold and thrust belt front. The western sector of the area comprises north–south running anticlines with excellent exposures of the Mendoza Group (Figs. 3 and 4). The Intra-Valanginian Discontinuity was investigated in two sections (named respectively Portezuelo de las Minas and Arroyo del Ñaco), located over the flank of one of these anticlines and separated 15 km from each other (Fig. 3). Up to 80 m of the underlying Vaca Muerta Formation was investigated in those locations and in nearby locations (e.g., Casa de Piedra section, Schwarz et al., 2006). The overlying Mulichinco Formation, which is 135–250 m thick, was measured in these localities but for this contribution only the basal 20 m are described and discussed (Fig. 5).

Eastward of the tectonic front, the studied succession is found only in the subsurface (Fig. 3), where it is penetrated by more than 100 wells. The Mulichinco Formation contains several reservoir horizons with moderate to good petrophysics properties, and has been in production since the 1970s. The stratigraphic location of the Intra-Valanginian Discontinuity is clearly identified in well logs (Fig. 6A). A cored interval (130-m thick) in one well (called Well-1 thereafter) recovered strata of the topmost Vaca Muerta Formation and the discontinuity itself (Fig. 6A, B), allowing for a detailed description and interpretation of the Intra-Valanginian Discontinuity in the area. Well-1 is presently located about 20 km away from the nearest outcrops (Fig. 3), but taking into account local shortening during Andean deformation (Zamora Valcarce et al., 2006), it could be as far as 27 km from them. In comparison with the westerly outcropped study area, this eastern sector represented a relatively proximal region of the epeiric sea during the Neocomian times and the Intra-Valanginian Discontinuity formation (Schwarz and Howell, 2005).

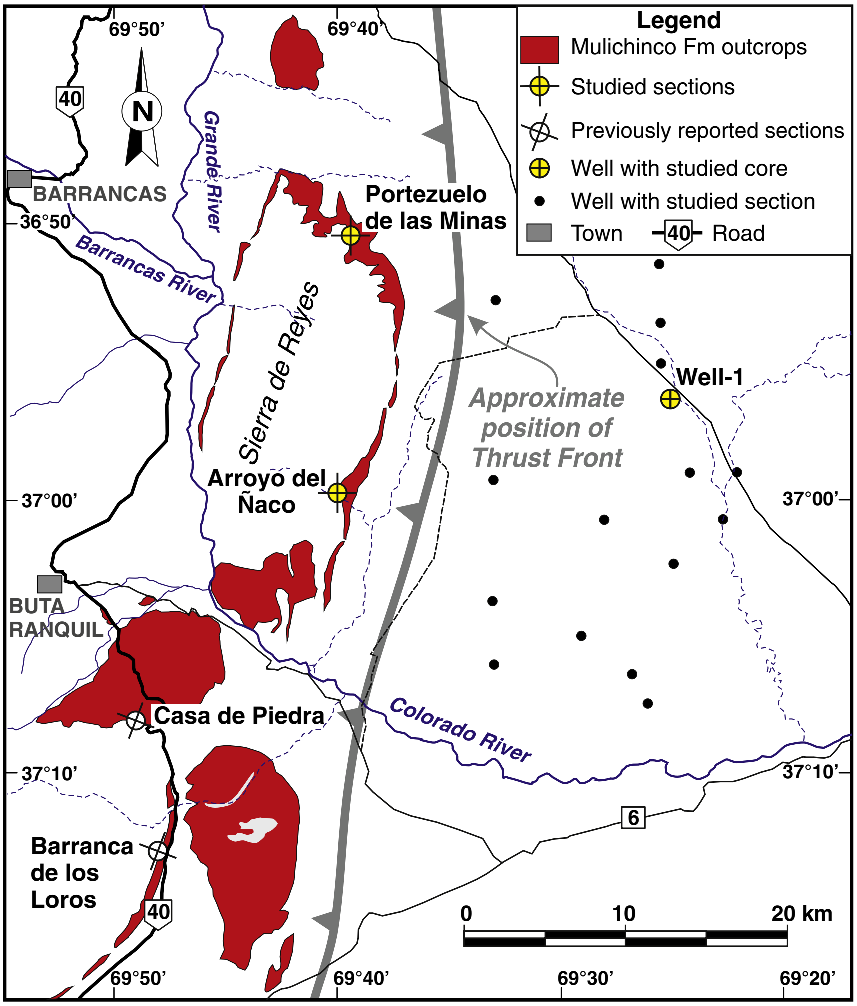

Fig. 3. Simplified geologic map with distribution of Mulichinco outcrops and locations of studied sedimentary sections and cores. The Andean Thrust Front represents the boundary between the outcropped area to the west and the subsurface region to the east.

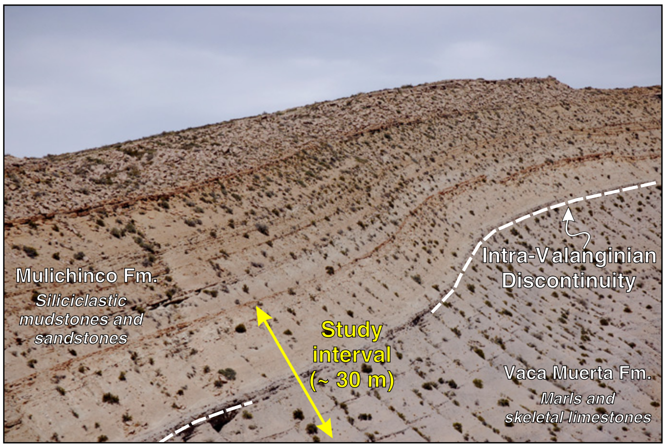

Fig. 4. Stratigraphic location of the Intra-Valanginian Discontinuity between the basinal marls and shales of the Vaca Muerta Formation and the shallow-marine deposits of the Mulichinco Formation at the Portezuelo de las Minas locality. View to southeast.

Sedimentary sections in the exposed localities (decimeter-scale detail) and the core (centimeter-scale detail) were measured describing facies attributes (e.g., texture, physical sedimentary structures), invertebrate fauna, and trace fossils. Thin sections, X-ray diffractometry, and SEM-EDAX analyses of key beds helped to better characterize the sedimentary texture and composition. The physical sedimentologic, ichnologic, taphonomic and sequence-stratigraphic datasets were integrated. Selected wells were used in the construction of an east–west cross section from the investigated cored well to the outcrops (i.e., down system) to accurately confirm the location of the Intra-Valanginian Discontinuity (Schwarz et al., 2011, their Fig. 6). Correlation between the exposed localities is fairly simple (Fig. 5).

5. Results

5.1. Pre-discontinuity succession

5.1.1. Characteristics of the pre-discontinuity succession

The Intra-Valanginian Discontinuity in all the studied localities lies within a carbonate-dominated interval (Figs. 5 and 6). In the exposed sections, the underlying deposits corresponding to the uppermost part of the Vaca Muerta Formation are composed of massive marl interbedded with subordinated skeletal floatstone and wackestone (Figs. 5 and 7A). Skeletal floatstones are dominated by pebble-size bioclasts of a cemented oyster (*Ceratostreon*) in a micritic matrix, showing low fragmentation, uncommon articulation and high density (Fig. 7B). Bioclastic wackestones are mostly composed of sand-size fragments having higher fragmentation and a higher diversity of skeletal remains (Fig. 7C). Shells of small thin-shelled bivalves (?*Entolium* sp.), oysters, epibenthic foraminifera (*Epistomina*) and radiolarians are common. Burrow systems assigned to *Thalassinoides* ichnospecies occur near the top of the formation.

The Vaca Muerta cored succession (5.30 m thick) is also dominated by dark gray, massive marl (Figs. 6B and 7D), with typically low contribution of thin-shelled bivalves and oysters, but ostracods and foraminifers are common. Within the marl, carbonate content varies from 40 to 70%. Quartz and clays are common, and pyrite is commonly observed within shells. Skeletal floatstones (<0.30 m thick) with significant proportion of oyster-derived bioclasts and abundant micritic matrix intercalate within the marl (Fig. 7E). They are demarcated at their bases by *Thalassinoides* isp. penetrating into the underlying marl (Fig. 7F); burrows are passively filled with bioclastic debris. Taphonomically, the oyster-rich floatstones are similar to the ones described in outcrops, with shells having low fragmentation, random distribution, and some specimens with both valves (Fig. 7E). In one case, however, valves are intensely broken, and they lie concordant to bedding. All these bioclastic beds fine at the top (mostly because specimens become smaller), and they grade upward into marl.

5.1.2. Interpretation of the pre-discontinuity succession

The topmost section of the Vaca Muerta Formation represents accumulation in a carbonate-dominated marine ramp (Spalletti et al., 1999; Doyle et al., 2005). Massive marl deposited from suspension fall out in a basinal to outer-ramp setting. Massive appearance of marl suggests that the sea floor was at least temporally colonized by burrowers, and the presence of pyrite within shells points toward oxic conditions at the water/sediment interface (Canfield and Raiswell, 1991). On the other hand, the presence of *Epistomina*, an opportunistic epifaunal suspension-feeder commonly found in dysaerobic environments of the Neuquén basin (Sagasti and Ballent, 2002), could suggest periods with reduced oxygen concentration at the sea floor. Skeletal floatstone, with low taphonomic indexes suggest low to null lateral transport, and therefore the shell concentrations can be regarded as parautochthonous to autochthonous fossil associations (Kidwell et al., 1986). These monospecific shell beds representing the development of epibenthic opportunistic communities were likely developed during periods of relatively low net sedimentation (Schwarz and Howell, 2005; Schwarz, 2012). The passively-filled *Thalassinoides* galleries demarcating their bases indicate incipient consolidation of the lime-dominated mud below the water–sediment interface (i.e., firmgrounds), which may have taken place during short-term non-depositional periods, and therefore are regarded as minor omission surfaces (e.g., Hillgärtner, 1998). In turn, skeletal wackestone and floatstone with high taphonomic indexes and preferentially-oriented shells could be the product of distal storm flows in distal mid-ramp settings (Doyle et al., 2005; Kietzman et al., 2008).

In terms of depositional systems, and considering that there are no significant facies changes in the Vaca Muerta Formation between the outcrops and subsurface studied localities, it is reasonable to assume that the study area (~1600 km^2) represented a single outer-ramp depositional system before the Valanginian major sea-level fall. In addition, in terms of the sequence-stratigraphic framework, most of the Vaca Muerta Formation represents a second-order highstand systems tract (Fig. 2) (Legarreta and Uliana, 1991; Schwarz et al., 2006). To the south of the study area, it has been documented that the uppermost 80-m-thick strata of the unit, early Valanginian in age, is largely dominated by basinal shale and marl (Fig. 3, Casa de Piedra section), without any evident stacking pattern (Schwarz and Howell, 2005; Schwarz, et al., 2006). In the study region, the occurrence of the reported coarser-grained facies at the topmost part of the unit may represent a regressive pattern (third-order highstand systems tract/falling stage systems tract?), truncated by the Intra-Valanginian Discontinuity.

5.2. Discontinuity surface

5.2.1. Ichnologic and sedimentologic characterization of the discontinuity

Although in outcrops the Intra-Valanginian Discontinuity separates two carbonate packages without any significant facies changes across it (Figs. 5 and 6B), its stratigraphic location is well demarcated by an irregular surface associated with a distinct trace-fossil suite (Fig. 8). The surface has a highly irregular morphology with up to several centimeters of relief and is characterized by rounded protuberances separated by pits and grooves (Fig. 8A, B). In some cases, apparent "intraclasts" of the underlying skeletal wackestone lay a few millimeters above the surface (Fig. 8A). However, as protruding knobs can have very narrow necks (Fig. 8A, B), it is more probable that these apparent "intraclasts" are in fact connected in three dimensions with underlying sediments (i.e. in or out of the observed 2D cross-section).

The trace-fossil suite is composed exclusively of robust *Thalassinoides paradoxicus*. The burrow system occurs as endichnia, penetrating up to 25 cm into the underlying wackestone (Fig. 8A). The system typically comprises horizontal and inclined burrows (Fig. 8B), but vertical shafts

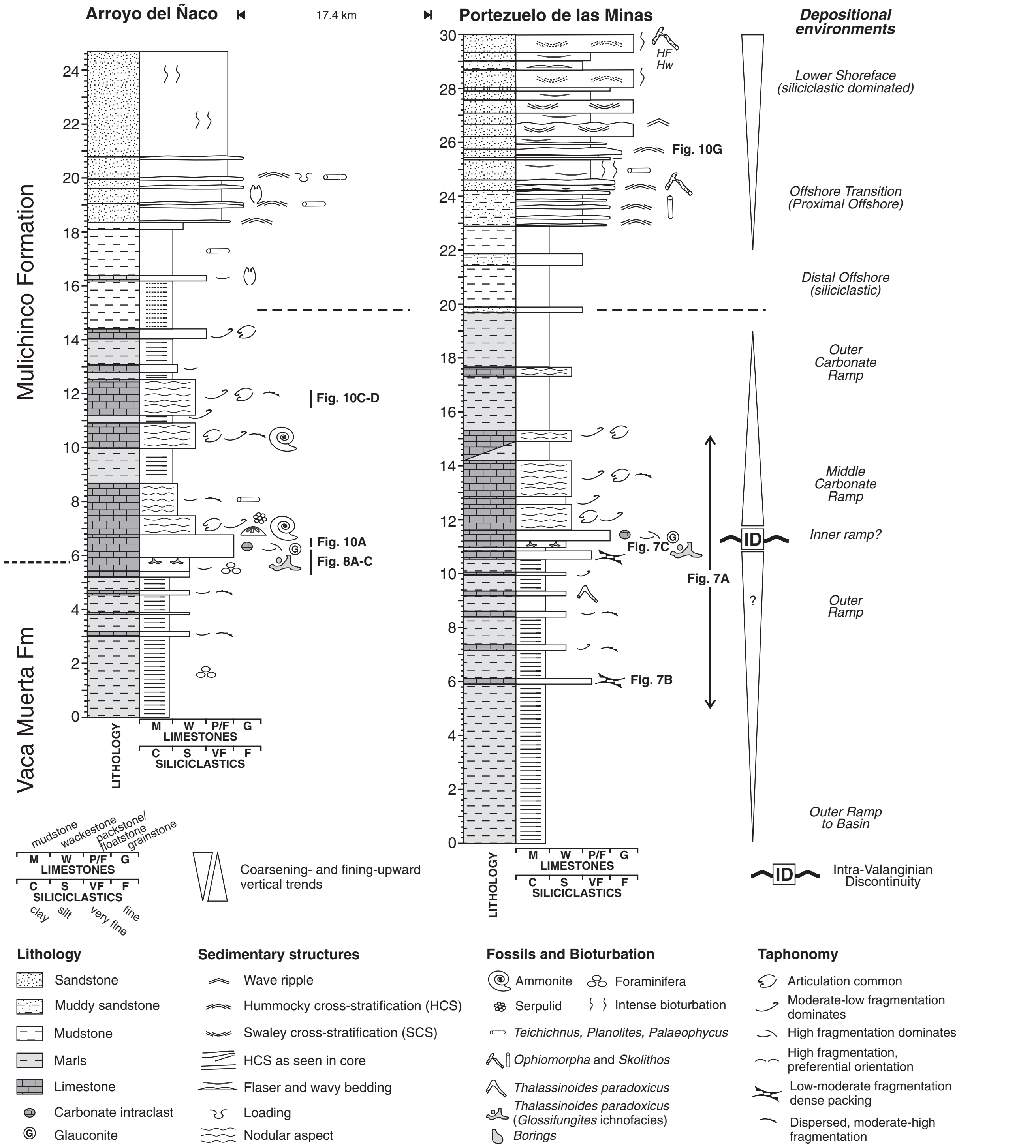

Fig. 5. Bed-by-bed sedimentologic sections measured in the study localities and general correlation between sedimentary units discussed in this study. Stratigraphic location of several illustrations is also shown in drawn sections.

are also present. Irregular and "Y" branching are dominant (Fig. 8C, D), and burrows up to 2 cm in diameter and 20 cm long are common. Significantly, excavations have well-defined walls and circular to sub-circular cross-sections, suggesting little compactional deformation (Figs. 7C and 8A, B). The burrow system is filled with sediment from the overlying bed (which is described in detailed in Section 5.3.1), and comprises highly fragmented shells of echinoids, infaunal bivalves, and oysters, as well as carbonate intraclasts and glauconite (Fig. 8C, E).

In the core (or proximal location), the Intra-Valanginian Discontinuity occurs on top of a skeletal wackestone containing a complex array of trace-fossil suites (Figs. 6B and 9A). Interestingly, an unusual yellowish color characterizes the upper 15 cm of the bed, but it rapidly changes to a more common dark gray color below that. The surface has an irregular geometry with up to 5 cm of relief, and both knobby and sharp upper boundaries are present.

The most abundant biogenic structures are *Thalassinoides* isp. systems, 2–3 cm wide and up to 22 cm deep, circular to subcircular in cross-section, and increasing upwards in abundance and size (Fig. 9A). Burrows have a lighter yellowish rim in the internal walls and are filled with shelly sediment. Well-developed vertical to inclined clavate borings

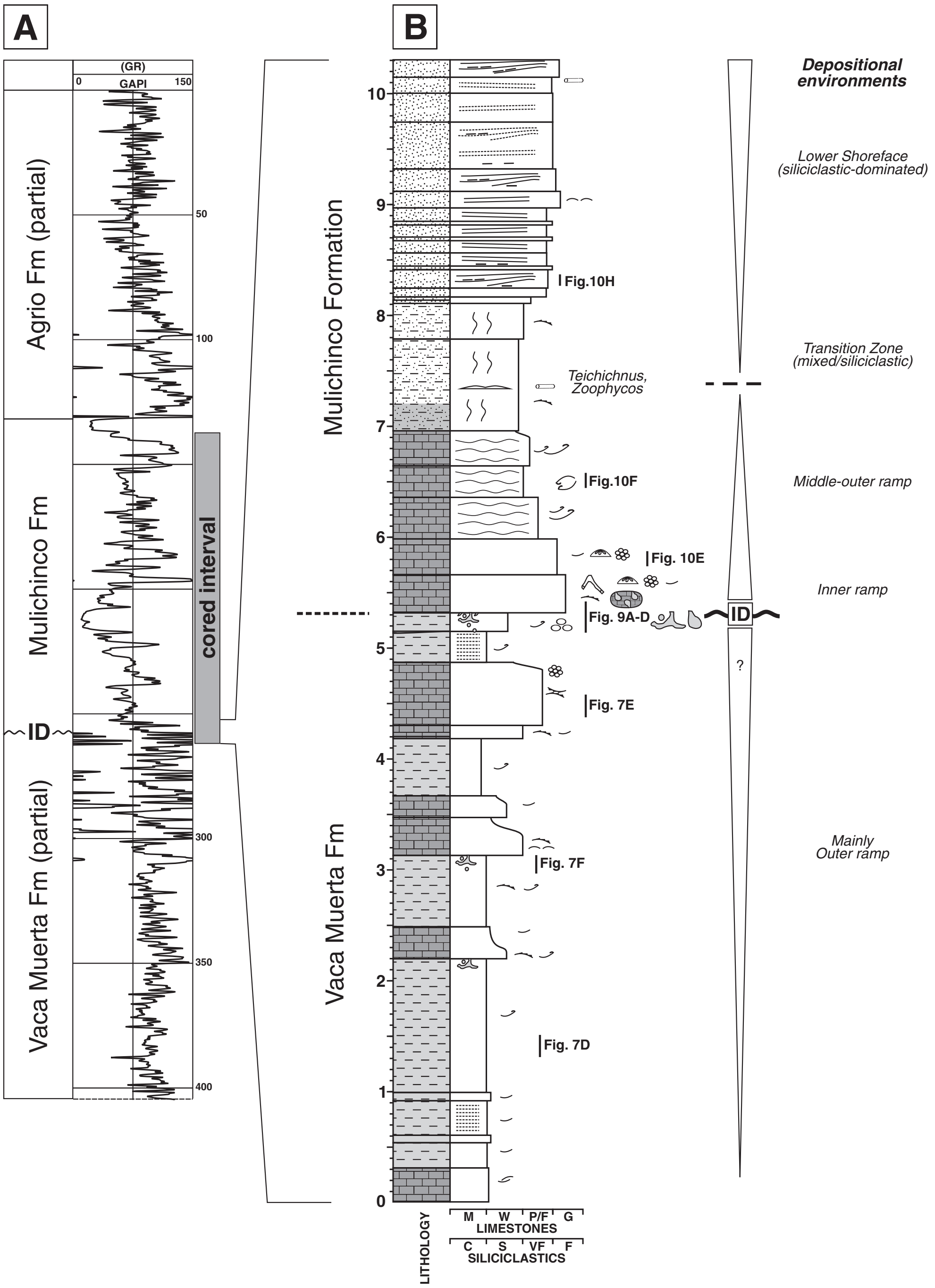

Fig. 6. A: Gamma-ray log of Well-1 and main stratigraphic units. B: Detailed sedimentologic section measured of studied interval. For legend on section see Fig. 5. Stratigraphic location of several illustrations is also shown in drawn sections. Panel A is modified after Schwarz et al. (2011).

attributed to the bivalve ichnogenus *Gastrochaenolites* occur below the surface, either penetrating from the surface itself or from the *Thalassinoides* specimens (Fig. 9). Inverted roof borings have not been observed. *Gastrochaenolites torpedo* consists of one inclined specimen, which penetrates downwards from the discontinuity surface. It has a 0.5 cm wide neck and a 0.9 cm wide chamber; its length is 2.3 cm. The aperture cannot be observed. *Gastrochaenolites turbinatus* is represented by a single inclined specimen that penetrates from a *Thalassinoides* specimen (Fig. 9B). The boring is up to 0.3 cm wide and 1.6 cm long. Various vertical to strongly inclined clavate borings displaying indistinct morphologies have been included in *Gastrochaenolites* isp. A (Fig. 9A). They commonly penetrate from the discontinuity surface, but in some cases they do so from *Thalassinoides* specimens. Other vertical structures display a poorly defined clavate morphology, and are referred to as *Gastrochaenolites*? isp. (Fig. 9B, C). Also common in connection with the surface are smaller structures, 0.3–0.5 cm wide, represented by circular to sub-circular cross-sections of uncertain origin (Fig. 9B). They may represent a different *Thalassinoides* population, but they are considerably smaller than this ichnogenus. Also, they differ from the sponge boring *Entobia* in their larger size and the fact that they occur as isolated structures rather than forming multichamber structures. The possibility that these represent cross section of inclined *Gastrochaenolites* specimens cannot be discounted.

In addition to these borings, a clast occurring above the surface is intensely bioeroded (Fig. 9D). Two different forms have been recognized.

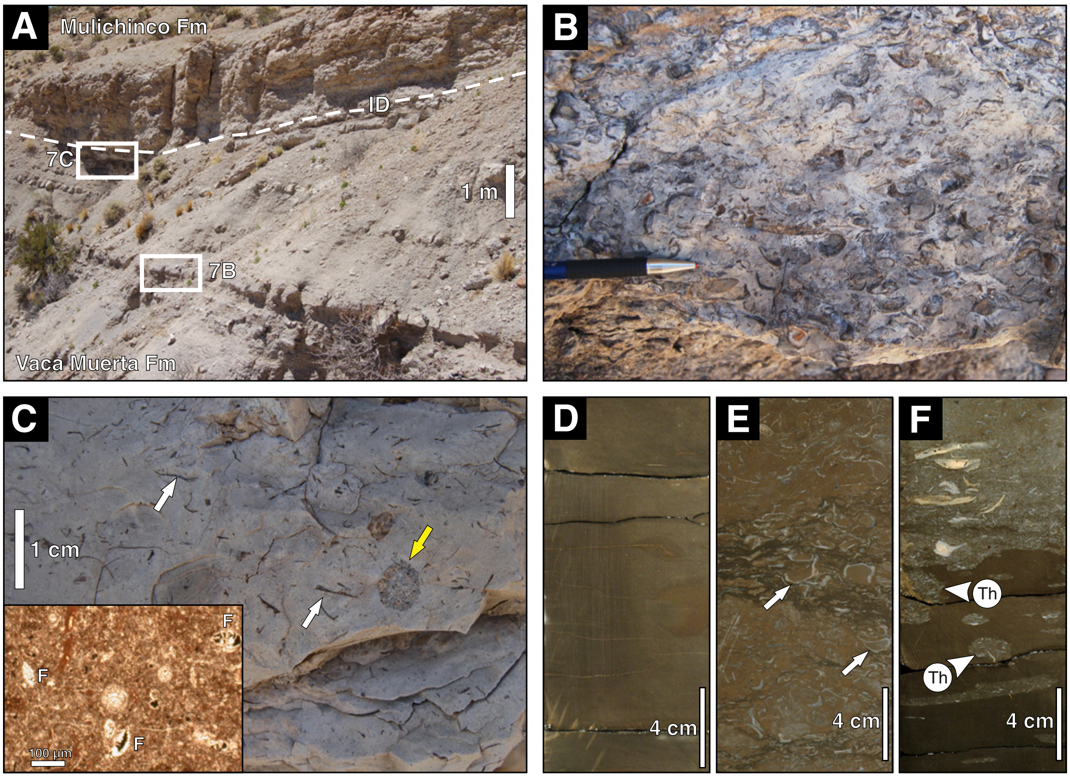

Fig. 7. Pre-discontinuity deposits of the topmost part of the Vaca Muerta Formation. A: Carbonate-dominated package at the Portezuelo de las Minas locality. The Intra-Valanginian Discontinuity (ID) occurs within it. Rectangles show locations of figures A and B. B: Cross-sectional view of a massive skeletal floatstone, typically dominated by bioclasts of the epifaunal oyster *Ceratostreon*. Shells are commonly a few centimeters long and they show relative low fragmentation and non-preferential orientation (pencil for scale). C: Skeletal wackestone directly underlying the unconformity in this section. White arrows show fragmented shells (mostly from thin-shelled bivalves), whereas yellow arrow point out to the cross-section of an undeformed burrow with coarser bioclastic fill (from overlying sediments). Inset: Thin section photograph (cross polarized) of wackestone texture showing foraminifers (F) and thin shells in a micrite matrix. Bar for scale. D: Brownish to dark gray massive marl as seen in core. E: Muddy floatstones to wackestones as seen in cores, dominated by high concentration of epifaunal *Ceratostreon* (arrows) showing low taphonomic indexes. F: Sharp-based skeletal wackestone/packstone in core with *Thalassinoides* (Th) penetrating the underlying marls. They are passively filled with bioclastic debris and attributed to the *Glossifungites* Ichnofacies.

The first type is represented by a single elongate specimen attributed to *Gastrochaenolites lapidicus*. Its neck is 0.1 cm wide, its chamber is up to 0.5 cm wide, and its length is 1 cm. This clast is also covered by several specimens displaying the bases of borings, which have been included in *Gastrochaenolites* isp. B. One of these borings penetrates from the *G. lapidicus* specimen (Fig. 9D).

All the trace fossils (burrows and borings) are invariably filled with coarse-grained shelly material coming from the overlying strata as in the outcropped sections (Fig. 9). This coarse-grained fill locally continues into fractures (<1 cm long) parallel to bedding. These fractures are parallel also to the main fractures that cross the core.

5.2.2. Interpretation of the discontinuity and associated trace fossil suites

The *Thalassinoides* demarcating the Intra-Valanginian Discontinuity in outcrop is undeformed (uncompacted) and passively filled with coarser-grained carbonate particles from the overlying bed. Preferential stain at burrow walls could be the result of differential cementation of a finer-grained fecal lining (Gingras et al., 2007). It is interpreted that the burrows were excavated in a firmground and are attributable to the *Glossifungites* Ichnofacies (MacEachern et al., 1992). However, considering that the firmground developed on a sea floor dominated by lime mud, it should be evaluated whether the stiffness was a product of (a) early diagenesis in deep-water marine conditions and normal sedimentation; (b) early diagenesis due to non-deposition; and/or (c) extensive erosional exhumation, as in the case of fine-grained siliciclastics, with or without the involvement of diagenetic processes.

The outer-ramp setting represented by the pre-Discontinuity succession indicates relatively low-energy, deep-water conditions with sporadic, storm-related current action. Therefore, early diagenesis would probably have negligible effect on the fine-grained sediments formed under those conditions (Shinn, 1969), and in contrast, would have been more effective in inner ramp regions, where high-energy currents typically force sea water through sediments and favor early cementation (James, 1997). Early diagenesis developed during a prolonged stage of condensation, starving and non-deposition (e.g., Buatois and Mángano, 2011) seems also unlikely. The studied succession at the topmost part of the Vaca Muerta Formation does not show evidence of significant transgression to account for a long-term non-depositional hiatus and the generation of an omission surface (e.g., Hillgärtner, 1998; Sattler et al., 2005). On the contrary, if anything, this uppermost section with relatively coarser deposits suggests a regressive trend (Fig. 5).

On the other hand, extensive erosion associated with the Intra-Valanginian Discontinuity has been recognized elsewhere in the Neuquén Basin (Schwarz and Howell, 2005), as well as in the study area. It has been suggested that at a regional scale, subaerial erosion could have been significant, leaving as a final product a low-relief sequence boundary (i.e., without incised valleys; Schwarz et al., 2006). In the study area, the irregular geometry of the discontinuity suggests at least several centimeters of vertical erosion locally. Additionally, the burrow fills contain abundant carbonate intraclasts derived from erosion of previous skeletal wackestone and mudstone. This evidence suggests that the area underwent significant mechanical erosion, and therefore exhumation of previously dewatered lime muds was conducive to firmground development. Under these conditions, which imply long-lived sediment bypass and high-energy currents affecting the sea floor, the idea that early cementation could have helped in the consolidation of these sediments with low initial porosity cannot be rejected. In any case, the

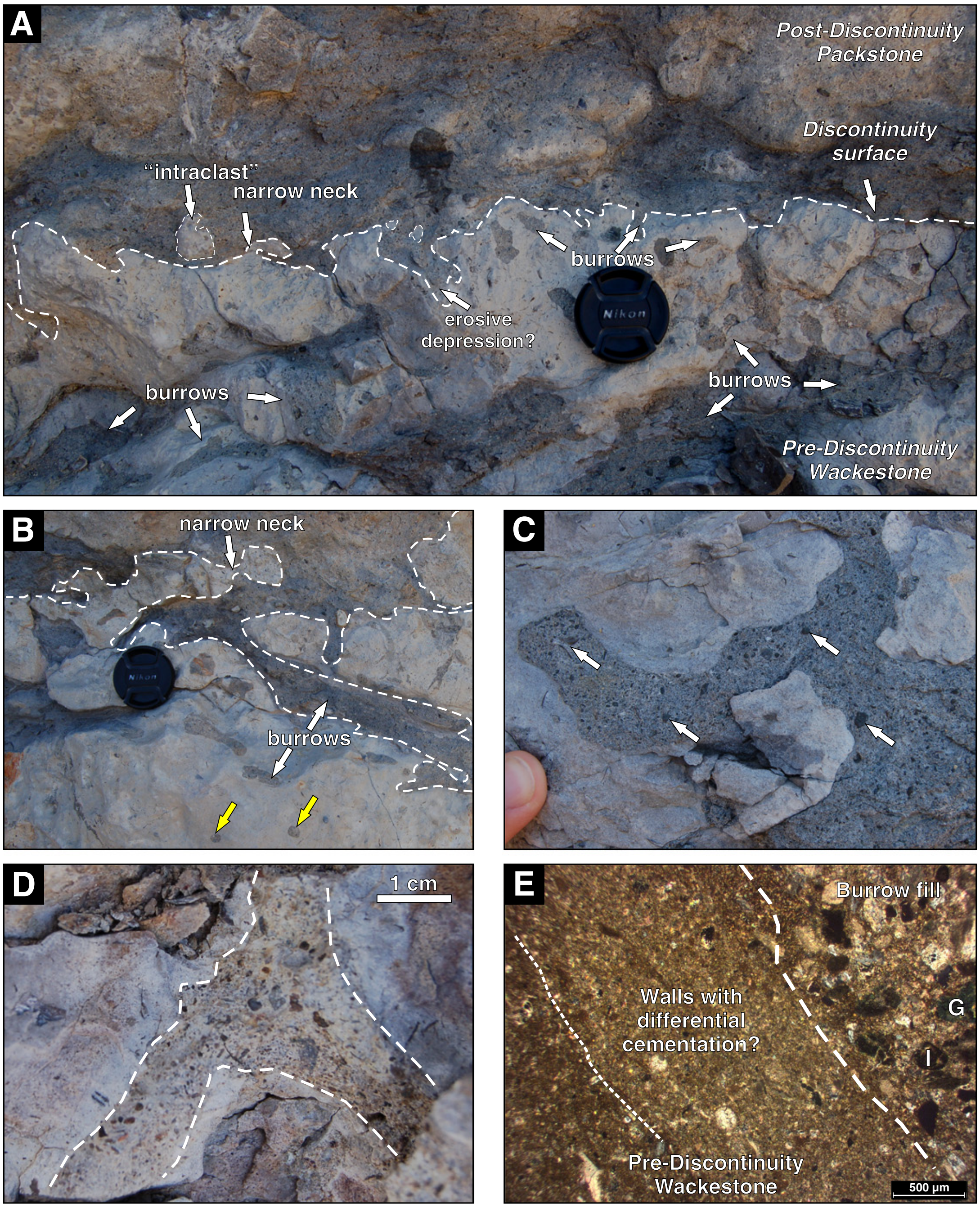

Fig. 8. The Intra-Valanginian Discontinuity in outcrop. A: Detailed view of the surface at Arroyo del Ñaco locality. Below the dashed line the skeletal wackestone is observed, penetrated by a complex system of *Thalassinoides paradoxicus*. The surface is highly irregular with knobby protuberances, having narrow necks. Some of them are appear to be detached ("intraclasts") from the underlying bed. B: Robust, gently inclined and horizontal *Thalassinoides*. Note sub-circular cross-sections (yellow arrows). Lens cap in A and B is 5 cm across. C: Sharp-walled shaft with irregular branching. Note the presence of up to 3 mm long carbonate intraclasts (arrows). Finger for scale. D: Y-branched burrow of *Thalassinoides* at Portezuelo de las Minas. Bar for scale. E: Thin section photograph showing a pre-discontinuity wackestone and the infill of a burrow. Note the intense cementation that seems to be preferentially developed at the margins (walls) of burrow. Carbonate intraclasts (I) and glauconite (G) are seen within the post-discontinuity sediments.

firmground was subsequently colonized by a crustacean fauna leaving open burrows that eventually were filled with coarser-grained material during renewed deposition.

The picture emerging from the core analyzed is much more complex. The *Thalassinoides* suite reported from the core shares almost all the features with the suite recorded in outcrop despite the fact that they are about 20 km apart (Fig. 3). Accordingly, the suite in the core also records the generation of a firmground and illustrates the *Glossifungites* Ichnofacies. As in the case of the outcrop, the carbonate intraclasts in the burrow fills suggest that erosional exhumation, potentially coupled with early diagenesis, was a key mechanism in producing the firmground conditions. However, in contrast with the outcrop locality, the firmground *Thalassinoides* suite is overprinted by a hardground suite dominated by *Gastrochaenolites*. This situation is typical of omission surfaces in hardgrounds, in which two omission suites are recognized, pre- and post-lithification suites (Bromley, 1975, 1996). The former contains burrows and hosts the *Glossifungites* Ichnofacies, whereas the latter contains borings of the *Trypanites* Ichnofacies, resulting in a palimpsest surface (e.g., Mángano and Buatois, 1991; Lewis and Ekdale, 1992; Bertling, 1999). This scenario is further supported by the presence

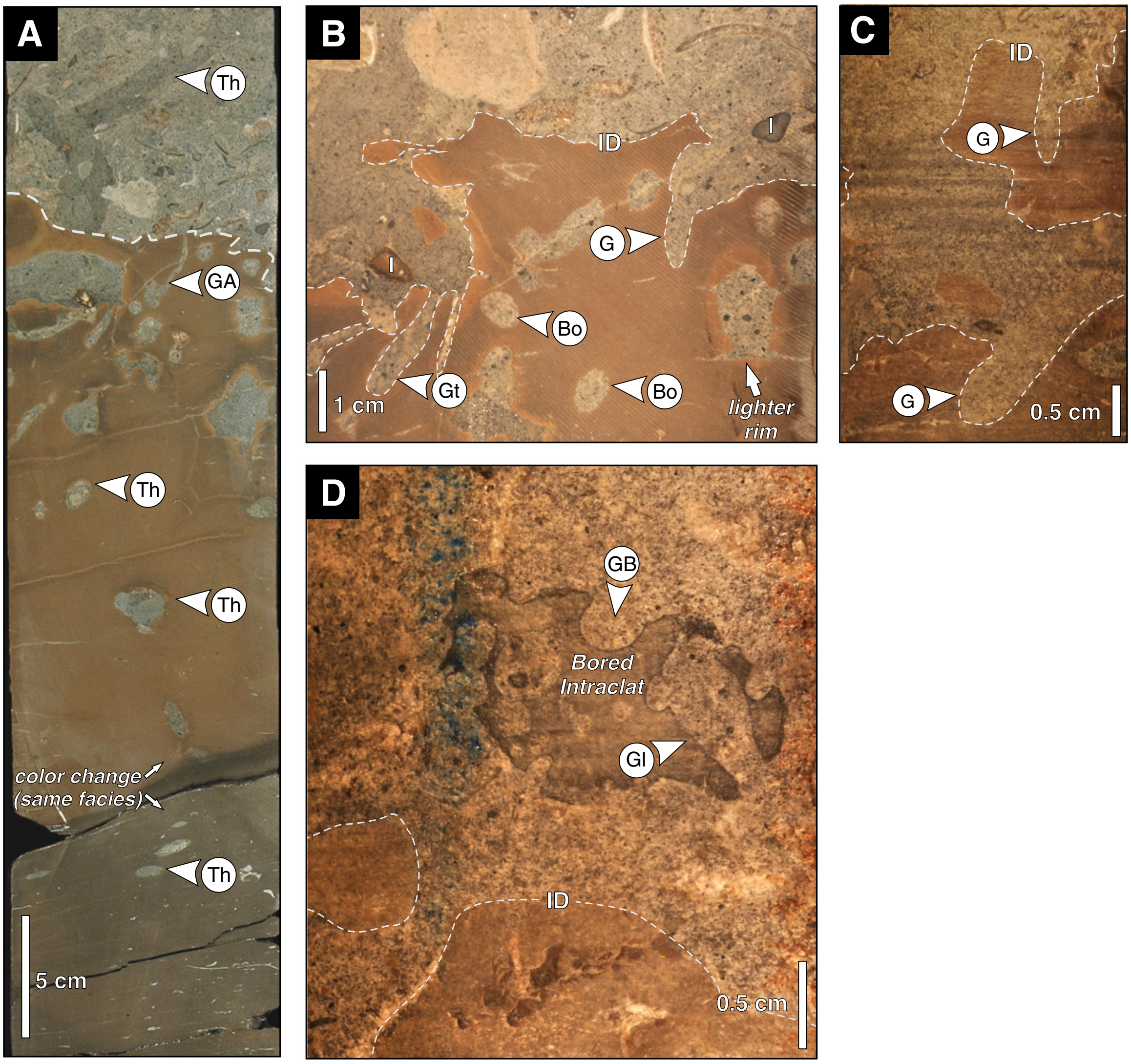

Fig. 9. Ichnologic and sedimentologic attributes of the Intra-Valanginian Discontinuity (ID) in Well-1. A: The 45-cm thick core interval showing pre- and post-sediments as well as the discontinuity (dashed line). *Thalassinoides* (Th) occurs up to 20 cm beneath the surface and increases in abundance upwards. Also note gradual upward change in burrow cross-sections. B: and C: The discontinuity surface is demarcated by well-developed vertical to inclined clavate borings attributed to the bivalve ichnogenus *Gastrochaenolites*. Gt: *Gastrochaenolites turbinatus*; GA: *Gastrochaenolites* isp. A; G: *Gastrochaenolites*? isp. (vertical structures with poorly defined clavate morphology); Bo: Circular to sub-circular cross sections of uncertain origin. D: A carbonate intraclast on top of the discontinuity which is heavily bored. Gl: *Gastrochaenolites lapidicus*; GB: *Gastrochaenolites* isp. B (smaller borings unidentified). All the illustrations come from different sections of the same core: A and B from polished sides, whereas C and D from unpolished (back) sides (bar for scale in all cases).

of bioeroded clasts immediately above the surface, a feature which seems to be commonly associated with lithification suites (de Gibert et al., 1998). The ichnogenus *Gastrochaenolites* has also been documented in firmgrounds (e.g., Carmona et al., 2007). However, the overall morphology of the structures and their remarkably sharp boundaries suggest that the latter possibility is quite unlikely, and that the structures are actually borings in a hardground. In addition, the presence of similar bivalve-generated structures in associated intraclasts is consistent with colonization of cemented horizons.

5.3. Post-discontinuity succession

5.3.1. Characteristics of the post-discontinuity succession

Both in the studied outcrops and core, the Mulichinco Formation above the discontinuity begins with a massive, intraclastic-skeletal packstone (Figs. 5, 6B, 8A and 9A), which infill the burrows and borings associated with the discontinuity. Carbonate intraclasts typically range from granule to sand size and are derived from erosion of fine-grained skeletal deposits (Fig. 10A). They are subrounded, but with irregular edges. Uncommon pebble-size intraclasts present in core are typically bored on all sides (Fig. 9D). In turn, bioclasts are moderately well-sorted due to intense fragmentation and abrasion. They are mostly from plates and spines of echinoids and infaunal bivalves (Fig. 10A), with subordinated fragments of oysters, microgastropods, serpulids, and foraminifers. Siliciclastic grains, mostly quartz and feldspar, represent ~20% of total detrital components and are up to fine sand. Glauconite, either as individual pelleted grains (<0.2 mm) or as coatings of carbonate intraclasts, is common (Fig. 10A). XRD and SEM-EDAX analyses suggest that glauconitic structure can be described as an interstratified glauconite–smectite, with up to 4% of K_2O. Phosphates (mostly apatite) and pyrite are also common, and they occur as individual specimens or having intergrowth relationships with glauconite (Fig. 10B), possibly suggesting a co-genetic origin.

The basal bed is followed both in outcrop and core by a carbonate package with an upward-fining trend (Figs. 5 and 6B). In outcrops this interval (7–9 m thick) comprises nodular skeletal floatstone and wackestone (Fig. 10C, D), passing upwards to mudstone and marl. Siliciclastic grains are almost absent (<2%) marking a contrast with

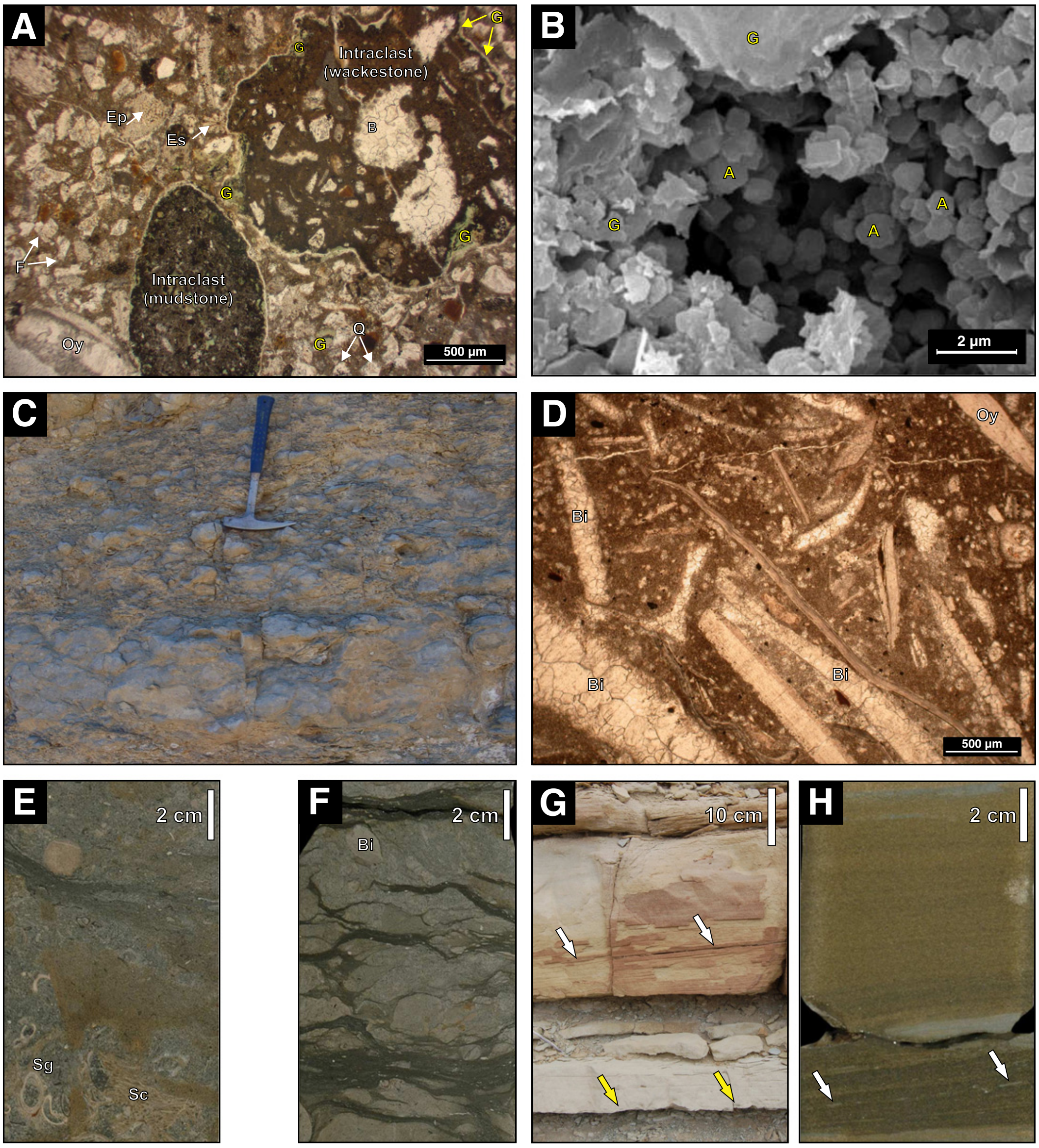

Fig. 10. Attributes of the carbonate-dominated package of the basal Mulichinco Formation above the Intra-Valanginian Discontinuity. A: Thin section photograph (cross-polarized light) of the basal intraclastic-skeletal packstone in outcrop, having limestone intraclasts (I), plates (Ep) and spines (Es) of echinoids, and skeletal fragments of oysters (Oy). Terrigenous grains of quartz (Q) and feldspars (F) are also common. Glauconite (G) is also present, as individual grains and forming crusts around the intraclasts. B: SEM photograph of a green grain, showing close relationship between authigenic minerals. EDAX analysis allows recognizing glauconite (G) and apatite (A). C: and D: Outcrop and thin section photograph, respectively, of nodular wackestone/floatstone facies that occur within the overlying carbonate-dominated interval. Bioclasts of unidentified bivalves (Bi) and oysters (Oy) are present in variable proportion. E: Skeletal packstone at the base of carbonate-dominated package as seen in core Well-1. Note the relative high fragmentation of bioclasts, as well as the presence of colonial (Sc) and gregarious (Sg) serpulids. F: Wackestone facies that characterized the top of carbonate unit in core. Note nodular aspect, as well as the possible presence of an articulated bivalve represented by an internal mold (Bi). G: and H: Sandstone beds at the top of the investigated succession, having hummocky cross-stratification both in outcrop (G) and core (H). Note convex-up, low-angle lamination (white arrows) and rip-up clasts (yellow arrows).

the underlying bed. Skeletal facies are dominated by variable abundance of endobenthic, suspension-feeding bivalves (e.g., *Panopea* and *Cucullaea*), microgastropods, epibenthic oysters (*Ceratostreon*) and serpulids. Layers with high concentration of reclined oyster (*Aetostreon*) and undetermined irregular echinoids also occur. In general, the degree of fragmentation is moderate to low, gravel-size fragments are abundant, and articulation is common. In the core, this package is only 2 m thick and comprises skeletal packstone grading upward to nodular wackestone (Figs. 6B and 10E, F), with a similar association of skeletal remains.

The carbonate package is overlain by a siliciclastic succession, characterized in outcrop by a gradual coarsening- and sandier-upward trend (Figs. 4 and 5). Massive mudstone grades vertically to silty sandstone and very fine-grained sandstone. Lenticular sandstone beds having hummocky cross-stratification are interbedded within the latter. The upper section is composed of fine-grained sandstone with well-developed hummocky and swalley cross-stratification (Figs. 5 and 10G). Rip-up clasts commonly occur at the base of sets, whereas rare *Skolithos linearis*, *Palaeophycus tubularis* and *Ophiomorpha* isp. locally disturbed the primary fabric. In the core, the basal carbonate package is overlain by a siliciclastic-dominated succession (Fig. 6B). A muddy sandstone with *Teichichnus rectus* and *Zoophycos* isp. occurs at the base. This grades upward to decimeter-scale sandstone beds where low-angle cross-stratification (Fig. 10H), likely representing hummocky cross-stratification, is the dominant physical structure.

5.3.2. Interpretation of post-discontinuity succession

The basal bed of the Mulichinco Formation, having a high proportion of intraclasts derived from fine-grained carbonate, suggests a widespread erosional episode of outer-ramp sediments prior to Mulichinco deposition. High taphonomic indices of skeletal fragments (e.g., high fragmentation and abrasion) point to an allochtonous fossil concentration (Kidwell et al., 1986), mostly composed of irregular echinoids, as well as endobenthic and epibenthic suspension-feeders that were not present in underlying sediments. Fossil preservation and textures suggest that this coarse-grained bed was subjected to intense reworking under relatively strong currents, likely in an inner-ramp setting (James, 1997). The glauconite-phosphate paragenesis present in the sediments is associated with stratigraphic condensation (Carson and Crowley, 1993; Gómez and Fernández-López, 1994; Hillgärtner, 1998), related to a significant resident time of the terrigenous and carbonate-derived grains in the sea floor. In turn, the relative high proportion of siliciclastics in this basal bed suggests a high sediment supply (either from pre-existing or newly-incorporated sediments), but which did not last very long (not present in overlying carbonate package).

The overlying carbonate-rich succession is considered to reflect a rapid change from middle- to outer-ramp conditions. Low taphonomic indices of skeletal limestone at the base suggest little physical reworking and current action, but likely well-oxygenated bottom waters. Overlying marls were deposited from sediment suspension fallout in low-energy environments, and they represent a fully outer-ramp depositional setting, as in the case of the Vaca Muerta Formation (Schwarz and Howell, 2005).

The siliciclastic-dominated succession at the top of the studied interval is interpreted to represent a low-gradient storm- and wave-dominated marine depositional environment (Schwarz, 1999; Schwarz and Howell, 2005). This dramatic change in depositional system from the previously developed carbonate ramp is the result of marked increase in sediment supply to the basin. High sediment supply coupled with low accommodation (i.e., lowstand conditions) produced a progradational stacking pattern with offshore mudstone being replaced by lower-shoreface sandstone over time. It is noteworthy that outcropped localities in the west show a significant proportion of offshore mudstone, whereas the cored interval in the east has none (compare Figs. 6 and 7B). This supports the regional proximal–distal trend from east (core) to west (outcrops), important for the interpretation of the trace-fossil associations delineating the Intra-Valanginian omission surface. The trace-fossil suite preserved in the storm beds is dominated by dwelling traces of suspension feeders, and it illustrates the *Skolithos* Ichnofacies, recording opportunistic colonization immediately after the depositional event. In contrast, the suite present in the muddy sandstone is dominated by feeding traces of deposit feeders, and it reflects the activity of the fair-weather community, representing the *Cruziana* Ichnofacies.

6. Discussion

6.1. Conceptual model for discontinuity generation

The generation of the Intra-Valanginian Discontinuity and the immediately underlying and overlying beds in the study area are the results of several processes acting during three main phases (Fig. 11): i) final stage of outer-ramp sedimentation, ii) production and modification of the discontinuity, and iii) renewed sedimentation in shallower conditions.

6.1.1. Final stage of outer-ramp sedimentation

Prior to the onset of the relative sea-level fall (i.e., during highstand conditions), the study area represented a relatively large, lower-energy outer-ramp setting well below the fair-weather wave base (Fig. 11). Here, lime-rich muds, together with subordinated proportions of fine-grained siliciclastics, were deposited. Importantly, facies belts are typically subparallel to the coast in ramp settings, and thus any change in relative sea level would produce belt migration in a similar fashion (Wright and Burchette, 1996).

6.1.2. Production and modification of the discontinuity

The sea-level change experienced by the Neuquén Basin during the Valanginian was estimated to be approximately −100 m in some regions (Schwarz and Howell, 2005). This dramatic sea-level fall produced a regional lowering of the wave base and a concomitant basinward shift of the facies belts. During this process, the study area eventually was placed above the fair-weather wave base (i.e., it became part of an inner-ramp setting), and high-energy wave- and storm-related currents triggered submarine erosion and winnowing of the sea floor (Fig. 11). The significant volume of sand- and gravel-size carbonate intraclasts present above the discontinuity points out to relatively long-lived erosion. As this process continued, partially dewatered lime-rich muds (marls) were exhumed across the study area favoring the development of firmgrounds, likely as in the case of fine-grained siliciclastics (MacEachern et al., 1992, 2007; Pemberton et al., 2001). Comparable substrate conditions developed onto both pelagic and lagoonal arbonates have been similarly attributed to long-lived winnowing (e.g., Clari et al., 1995; Hillgärtner, 1998; Christ et al., 2012).

However, the low accumulation rates resulting from bypassing might also have contributed to partial consolidation through early cementation (Hillgärtner, 1998). The continuous sweeping of the bottom under high hydrodynamic conditions could have triggered circulation of carbonate-rich fluids and early cementation (Fig. 11). This process was likely more important in the sea floor of proximal regions, which was placed earlier above the fair-weather wave base. Early cementation produced a progressive hardening of the substrate (at least at the water–sediment interface) until true hardgrounds were developed. Downward penetration of cementation (only a few centimeters in the case of the study area) was probably limited by the low permeability of the host sediments (Shinn, 1969; Christ et al., 2012). Typical features associated with emersion and subaerial exposure, such as root horizons, karstic surfaces, paleosols, bauxitic horizons, and/or meteoric/vadose cementation (e.g., Clari et al., 1995; Hillgärtner, 1998; Wilson et al., 1998; Sattler et al., 2005) have not been found associated with the Intra-Valanginian Discontinuity. Thus, an entirely subaqueous origin for the lithification is favored in this case.

Firmgrounds and hardgrounds associated with this major marine omission surface were colonized by burrowers and borers, respectively, producing its extensive biogenic modification (Fig. 11). *Thalassinoides*-forming crustaceans (resulting in the suite attributable to the *Glossifungites* Ichnofacies) could have colonized firmgrounds of proximal and distal regions of the study area simultaneously when sea-level fall and negative accommodation ceased and sea-level started to rise (Wilson et al., 1998; Buatois and Mángano, 2011). However, if that was the case, it follows that the lithification achieved in proximal regions, and the subsequent assemblage representing the *Trypanites* Ichnofacies, would have been produced during transgression as well. Interestingly, the high density of bioturbation and bioerosion structures that characterize this surface indicates more continuous colonization windows, which is typical of transgressive scenarios (Buatois and Mángano, 2011). This is in sharp contrast with surfaces formed during falling sea level, which are characterized by rather narrow colonization windows, due to a short hiatus followed by rapid sedimentation.

Alternatively, the firmground suite recorded in proximal regions could have been developed when relative sea level was still falling, and progressive hardening could have been achieved sometime between maximum regression (lowstand) and early transgression. It is noteworthy that a recent study in carbonate ramp deposits has suggested that key surfaces associated with firmgrounds and hardgrounds were produced during maximum regression instead of transgression (Christ et al., 2012). In any case, the resulting discontinuity is thought to reflect a marine sequence boundary remodeled during initial transgression, that is to say, it represents the co-existence of a sequence boundary and a transgressive surface (SB/TS). This situation has been extensively reported both in siliciclastic and carbonate systems (see reviews in Pemberton et al., 2004; Buatois and Mángano, 2011).

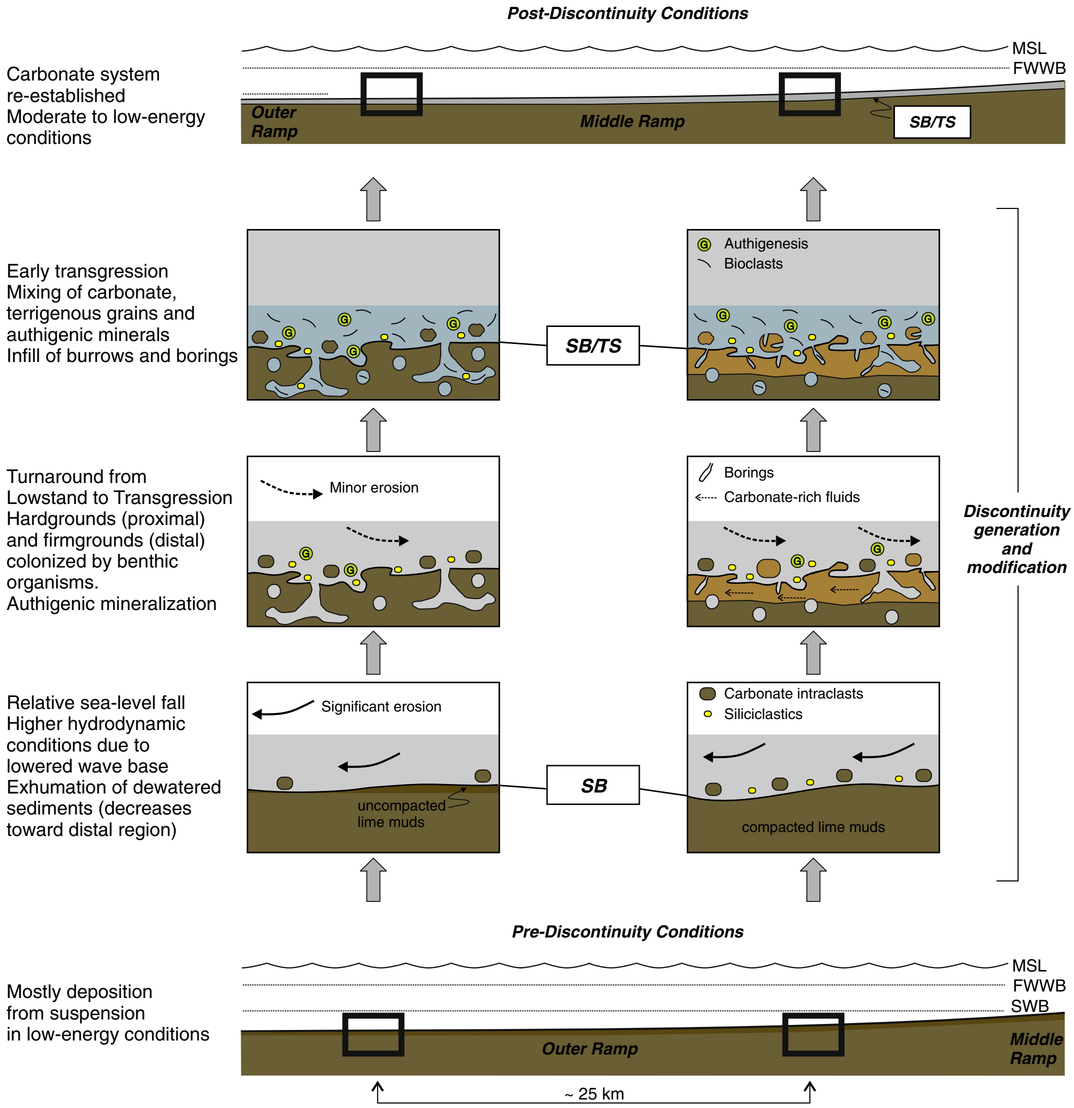

Fig. 11. Conceptual model illustrating pre-, syn- and post-discontinuity conditions across the investigated area, which represents different conditions of a carbonate ramp through time. MSL: main sea level; FWWB: fair-weather wave base; SWB: storm wave base; SB: sequence boundary; and TS: transgressive surface.

6.1.3. Renewed sedimentation in shallower-water conditions

When accumulation re-initiated in the study area, open burrows and borings were filled with a mixture of sediments which attest not only to the previous erosional phase, but also to sediment starvation and condensation during the early stages of rising sea level. At this stage, sand-size terrigenous grains exported from the source areas during lowstand mixed with skeletal fragments of shallow-water biota, which suffered high abrasion and fragmentation in the existing high-energy ramp setting (Fig. 11). Authigenic minerals (glauconite, phosphates) probably formed at this time, due to a long residence on the sea floor and low siliciclastic supply. Additionally, carbonate intraclasts produced during earlier stages were subjected to extensive boring and mineralization. Therefore, the infill of the burrows and borings can be regarded as a transgressive lag.

Eventually, net sedimentation of shallow-marine carbonates resumed in the study area, with textures and macrofossil assemblages of resulting limestones suggesting little physical reworking and well-oxygenated bottom waters in middle-ramp settings (Fig. 11). Significantly, terrigenous supply was totally arrested. In turn, continuous rising of relative sea level eventually produced a backstepping of facies belts and accumulation of outer-ramp sediments (Mulichinco marls) in the distal (outcrop) sector of the study area, and transitional mid-outer ramp facies in the proximal (subsurface) region. The carbonate ramp eventually evolved into a siliciclastic marine system due to high sediment supply from adjacent hinterland areas.

6.2. Implications for high-resolution sequence stratigraphy

Firmgrounds and hardgrounds formed in subaqueous carbonate environments have been typically associated with maximum flooding surfaces or transgressive (ravinement) surfaces (Rodríguez Tovar et al., 2007; Buatois and Mángano, 2011). Less commonly, however, substrate-controlled ichnofacies have been associated with sequence boundaries both in siliciclastic environments (Pemberton et al., 2004 and references therein) and carbonate settings (Clari et al., 1995; Christ et al., 2012).

This study documents a case in which a discontinuity surface was generated in a marine environment during a major sea-level drop (sequence boundary), and then was modified during a subsequent transgression, which eventually originated a deepening-upward trend of overlying carbonate sediments (Fig. 12). The interpretation of this composite surface (marine sequence boundary and subsequent transgressive surface) could have been totally overlooked if detailed information, either from outcrop and subsurface, was not available. This is because key information to reconstruct the history associated with the Intra-Valanginian Discontinuity, namely the substrate-controlled

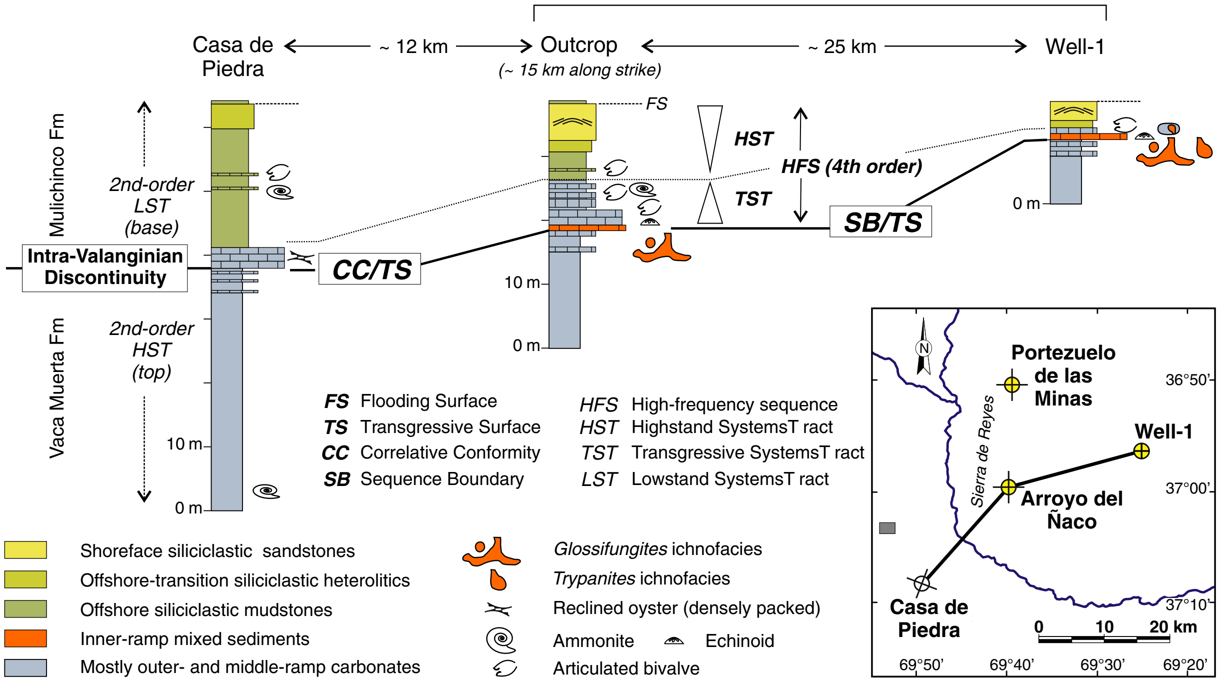

Fig. 12. Simplified sections of the study area showing main depositional environments and key stratigraphic surfaces that exemplify a high-frequency sequence within the basal Mulichinco Formation deposits. The figure incorporates a section located further downdip (Casa de Piedra Section, simplified from Schwarz et al., 2006, their Fig. 13), showing how the findings of the study area can help to clarify the timing of carbonate accumulation, as well as the non-erosive character of the marine sequence boundary, in that direction.

suites of trace fossils and their associated sediments, is preserved in a <20-cm-thick succession and there is low facies contrast between pre- and post-discontinuity facies (Fig. 12). Without this key information, a gradual (non-interrupted) transition from basinal sediments passing to outer-ramp deposits in turn grading into mid-outer settings during a long-term regressive event would have been more plausible to suggest. In fact, this interpretation was put forward in previous studies of more regional scope (Legarreta and Kozlowski, 1981; Mitchum and Uliana, 1985).

This study also clarifies the sequence-stratigraphic framework of the post-discontinuity deposits (i.e., basal Mulichinco Formation strata) across larger regions of the marine realm (Fig. 12). The outer- and middle-ramp carbonate deposits reported in this contribution were evidently formed during transgressive conditions, when clastic flux from hinterland areas was null to very low. Further to the west, Schwarz et al. (2006) reported an abrupt vertical facies change from fine-grained carbonates into oyster-dominated bioaccumulations, in turn passing into siliciclastic mudstones and heterolithics (Fig. 12). Neither physical erosion nor substrate-controlled ichnofacies were recorded at the contacts between each interval, and the correct location of the marine sequence boundary was problematic (Schwarz et al., 2006, their Fig. 13). Based on the findings of this contribution, and considering that oyster bioaccumulations in the Neuquén Basin are favored by low net sedimentations rates (Schwarz and Howell, 2005; Lazo, 2007), these oyster aggregations can be confidently correlated as time-equivalent of the transgressive carbonate deposits described above the discontinuity in the study area. Interestingly, due to the non-erosive nature of the basal bounding surface of the oyster bioaccumulations, the Intra-Valanginian Discontinuity in this basinward locality should be considered as the correlative conformity of the sequence boundary merged with the transgressive surface (Fig. 12).

Collectively, the skeletal carbonate deposits immediately overlying the SB/TS represent the transgressive systems tract of a high-frequency sequence (fourth order?), within the long-term lowstand conditions (Fig. 12). In turn, the coarsening-upward offshore to shoreface siliciclastics that gradually grade from the carbonates are interpreted to represent the highstand systems tract. This high-frequency sequence, up to 20 m thick, can be confidently identified across an ~40 km-wide region (Fig. 12).

6.3. Controls on regional variations across major discontinuities

The regional extension of major discontinuities in carbonate systems seems to be controlled by several factors, such as the physiography of the basin, the depth of the basin during its generation, and the magnitude of relative sea-level changes (Clari et al., 1995; Hillgärtner, 1998; Christ et al., 2012). However, regionally extensive discontinuities demarcated by substrate-controlled ichnofacies and representing sequence boundaries (or composite surfaces, SB/TS) have not been widely reported in carbonate successions (see review in Buatois and Mángano, 2011).

In shallow-marine carbonate systems characterized by platform morphology, some studies concluded that multiple, but likely local, discontinuities would be more likely to develop rather than single, regional discontinuities, for times of both overall sea-level fall and rise (Hillgärtner, 1998). More recently, however, detailed studies in Jurassic ramp carbonate systems suggested that discontinuities generated during maximum regression (i.e., sequence boundaries) in high-energy settings could be of regional extent (Christ et al., 2012), but the relative small area covered by that investigation (<2 km) precluded a reasonable test of that hypothesis.

The results of this study aid in validating such a hypothesis. The Intra-Valanginian Discontinuity reported here represents a single, regionally-extensive discontinuity surface developed in a ramp-type carbonate setting, correlated across tens of kilometers along strike and dip (Fig. 12). Thus, it seems reasonable to consider that a sea-level change of a given magnitude would lead to a coeval environmental response over larger areas in low-angle, ramp-type carbonate settings than in more irregular carbonate platforms. Nonetheless, the extension of the Intra-Valanginian unconformity might also have been affected by two additional factors: the magnitude of the sea-level change and the hydrodynamic conditions (and depth) of the pre-omission succession.

It is noteworthy that the high-amplitude sea-level change associated with the discontinuity (in the order of several tens of meters) probably produced a dramatic basinward shift of facies belts and erosion across large areas of the previous ramp setting, likely contributing to enlarging the extension of the discontinuity. As for the second controlling factor, some studies have demonstrated that if the pre-discontinuity conditions are very shallow (e.g., tidal flats, inner platforms), the lateral variability of the discontinuity in terms of substrate-controlled suites and morphology could be so high that it would be difficult to recognize the same discontinuity across a vast region (Gingras et al., 2001; Sattler et al., 2005). On the contrary, if the pre-omission succession accumulated in distal, open-marine settings with sediments and hydrodynamic conditions changing only very little across vast regions (as in the case of the present study), the spatial and temporal distribution of firmgrounds and hardgrounds during the lowstand and subsequent transgression would be more plausible to organize in a predictable fashion. Indeed, within the reported example, total lithification of substrates and suites attributed to the *Trypanites* Ichnofacies were only developed in proximal regions upon earlier firmgrounds, whereas in distal regions lithification was never achieved, and the *Glossifungites* Ichnofacies demarcates the discontinuity (Fig. 12).

In summary, it is postulated that the generation (and recognition) of the Intra-Valanginian Discontinuity in the distal sectors of the Neuquén Basin is thought to be the result not only of a ramp (vs. platform) setting, but also of the combination of a high-amplitude sea-level fall and the relatively deep-marine setting prior to the formation of the discontinuity.

7. Conclusions

1. By integrating sedimentologic, ichnologic and sequence-stratigraphic data from outcrops and cores, this study has allowed documentation of the marine distal expression of a single, regional-extensive discontinuity surface, termed the Intra-Valanginian Discontinuity, across ~1600 km^2.
2. This discontinuity was excavated within marly sediments deposited in a carbonate-dominated, outer-ramp setting. Well-defined and robust *Thalassinoides* filled with overlying sediments demarcate the omission surface all across the study area. They are interpreted to represent the *Glossifungites* Ichnofacies.
3. A trace-fossil suite composed of *Gastrochaenolites turbinatus*, *G. lapidicus*, *G. torpedo*, as well as other unidentified borings, is superimposed onto the firmground suite in the proximal region, and is attributed to the *Trypanites* Ichnofacies.
4. Firmgrounds and hardgrounds associated with the Intra-Valanginian Discontinuity are interpreted to be the result of erosion and exhumation of previous sediments, together, at least in proximal regions, with early cementation.
5. The post-discontinuity bed contains carbonate intraclasts, marine bioclasts (bivalves, echinoids, etc.), siliciclastics grains, and minor glauconite and apatite. This suggests a phase of siliciclastic starvation and authigenic mineralization in a marine setting. Subaerial-exposure-related features are not present.
6. The Intra-Valanginian Discontinuity represents a significant omission surface that was created during a major sea-level fall, and subsequently was remodeled during an early transgression. Therefore represents a composite marine sequence boundary/transgressive surface.
7. During the transgression, a middle to outer-ramp system was established in the study area, and was subsequently replaced by a progradational siliciclastic system, collectively forming a high-frequency sequence.
8. The elaborated high-resolution sequence-stratigraphic framework for the study area may serve as template for nearby regions and for similar geological settings worldwide. Basinward of the study area, oyster bioaccumulations are interpreted to represent transgressive deposits, developed on a non-erosional omission surface (correlative conformity/transgressive surface).
9. The generation and preservation of the features associated with the Intra-Valanginian Discontinuity (demarcated by different substrate-controlled trace fossils in time and space) are thought to result from the combination of a ramp-type pre-existing morphology, coupled with a high-amplitude sea-level fall and a relatively deep marine setting prior to the formation of the omission surface.

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