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[EA]Paleoenviromental Interpretation of the Lajas Formation (Middle Jurassic, Neuquen Basin, Argentina) in Subsurface: Fluvio-Dominated-Delta*

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Abstract

The Middle Jurassic Lajas Formation of the Neuquén Basin (Argentina) records marginal marine sediments, mainly as deltaic systems. However, there is still controversy regarding its dominant process. The Lajas Formation has been interpreted as a tide-dominated delta, fluvio-dominated delta with hyperpycnal discharges, fluvio-dominated with tidal modulation delta, and a delta that show mixed energy signatures (fluvial, tidal, and wave action). These contrasting interpretations lead to different paleoenvironmental frameworks based on the interpretation of body forms and architectures, facies associations, and sedimentary structures (both organic and inorganic) characterization. The observation, description, and analysis of outcrop data (Bajada de Los Molles, Arroyo Covunco, Sierra de la Vaca Muerta, and Arroyo Carreri outcrops), allowed the elaboration of a regional schematic paleoenvironmental model, later integrated with subsurface data (Sierra Barrosa, Aguada Toledo, and Sierra Barrosa Norte core samples and well logs). The observations made in the Sierra Barrosa/Aguada Toledo Field suggest that most of the column corresponds to a fluvial-dominated delta with hyperpycnal discharges, which subordinately develops wave-dominated deltas, with tidal effect being the least influential. This is supported by the fact that no organic or inorganic sedimentary structures typical of tidal processes were recognized.

Introduction

Deltas are landforms built by rivers where they feed into a standing body of water (Bhattacharya, 2006). The overall morphology of deltas is the result of the interplay of fluvial, tidal, and wave processes that rework the sediment carried by the river, and the dominance of one over the others (Galloway, 1975; Olariu and Bhattacharya, 2006; Bhattacharya, 2010), and the relative sea-level changes (Boyd et al., 1992; Ainsworth et al., 2011). However, the overall dominance of one process over the others does not imply the total absence of structures typical of secondary processes, and the dominant process can change also laterally and in time (Boyd et al., 1992; Orton and Reading, 1993; Bhattacharya, 2006; Rodríguez et al., 2019). The Lajas Formation has been interpreted as a transitional marine environment, mainly deltaic system. The dominant process of these deltas has been the subject of controversy, with different interpretations: river dominance and tidal influence (Gulisano and Hinterwimer, 1986; Zavala, 1996a-b; Gugliotta et al., 2015, 2016a-b; Kurcinka et al., 2018), tidal dominance (McIlroy et al., 1999, 2005; McIlroy, 2007; Spalleti et al., 2010), river dominance with hyperpycnal discharge (Ponce et al., 2012; Canale y Ponce, 2011; Montagna, et al., 2012, 2017; Canale et al., 2015, 2016), and mixed participation of river, tidal, and wave processes (Rossi and Steel, 2016). In this paper we interpret the deltaic sections of the Lajas Formation in the subsurface for the Sierra Barrosa area as fluvio-dominated, comparing it with selected outcrops that reflect similar conditions.

Geological Settings

The Neuquén Basin is located in west-central Argentina and in central Chile. Deposits accumulated in three main stages, rift, post-rift, and foreland (Howell et al., 2005), leading to a continuous, circa 7,000 m thick, stratigraphic record of marine and continental strata, spanning from the Late Triassic to the Paleocene (Arregui et al., 2011a) The Sinemurian-middle Callovian Cuyo Group represents the first major marine depositional episode that covered the Neuquén Basin (Arregui et al., 2011b) (Figure 1). The Los Molles Formation is the lowermost unit of this group and gradually passes into the Lajas Formation (Zavala, 1996a-b). This unit forms classic oil and tight-sand gas reservoir (Giusiano et al., 2011). The Cuyo Group culminates with the Challacó Formation to the south; to the northeast, Punta Rosada Formation in the subsurface and evaporitic deposits of the Tábanos Formation in the central to north areas of the basin (Arregui et al., 2011b and references therein). The 200-900 m thick Lajas Formation is regarded as Bajocian-Bathonian in age based in ammonoid zonations (Riccardi, 2008). The Lajas Formation is composed of sandstone and, to a lesser extent, dark and greenish mudstone and conglomerate with abundant carbonaceous material (Weaver, 1931; Uliana y Legarreta, 1993; Leanza et al., 2001; Zavala, 1996a-b, among others).

Materials and Methods

This work is the result of studies carried in seven wells using sedimentologic, ichnologic, core samples, well logs, and well images techniques. These results were compared to five outcrop sections previously studied by Ponce et al., (2012); Canale (2016), Canale et al., (2015, 2016) (Figure 2). The ideas that support a fluvio-dominated deltaic system are listed below.

Grain Size and Delta Processes

Orton and Reading (1993) state that “the amount, mode of transport, and grain size of the sediment load delivered to a delta front have a considerable effect on the facies, formative physical processes, related depositional environments, and morphology of the deltaic depositional system”. In that sense, they expand the classification made by Galloway (1975), adding grain size to the ternary diagram of dominant processes (Figure 3). In that diagram, the fluvio- and wave-dominated deltas are more prone to developed coarse grain deposits. The Lajas Formation deposits are mainly composed by fine to coarse sandstones and conglomerates, and to a lesser extent, heterolithic and mudstone deposits

(Arregui et al., 2011; Zavala, 1996a-b; McIlroy et al., 1999). Based on the main grain size of the Lajas Formation, in Orton and Reading (1993) classification, Lajas Formation is more likely to lie near the fluvio- or wave-dominated section, rather than in the tide dominated section.

Geometry and Architecture of the Geoforms

The geometry and architecture of the main components of a delta, in particular, delta plain and delta front are determined by the main processes that rework the sediment deposited by the river (Olariu and Bhattacharya, 2006; Bhattacharya, 2010; Rossi et al., 2016) (Figure 4). If the river is the dominant process and there is not enough energy from tide and/or wave action to rework the sand delivered to the delta front, the latter will be formed by an amalgamation of sand bar complexes. In the delta plain, the channels of a fluvio-dominated delta will exhibit a dendritic pattern, with a high number of distributary channels and a high avulsion rate, and with lateral cannibalization of channels. This situation is clearly observable in outcrop (for more detail see Canale, 2016; Canale et al., 2015, 2016) (Figure 5). Although this situation in core is more difficult to see, it has been interpreted to be similar to the outcrops (Arregui et al., 2019).

Dispersion of Paleocurrents

Another feature that rises from the geometry and architecture description (see previous section) is the fact that in a fluvio-dominated delta the channels will be way more numerous than in a tide or wave dominated delta, and they will display a dendritic pattern (Olariu and Bhattacharya, 2006). This pattern will result in a large dispersion of paleocurrents. In outcrop, a large dispersion of the paleocurrents has been observed (Canale et al., 2016; Llanos et al., 2019). In the Sierra Barrosa area, a paleocurrent study was made using well images. The division of lower, middle, and upper division of Lajas Formation (Freguglia et al., 2009; Licitra et al., 2011) is use here. This division has been made with seismic data, but has been contrasted with core samples studies, and for the lower section it mainly represents delta front environments, and mainly delta plain environments for the middle and the upper section (Montagna et al.2012; Arregui and Rodríguez, 2018 a, b). The result of this study is resumed in Figure 6. The paleocurrents show a high degree of dispersion in the Sierra Barrosa/Aguada Toledo Field.

Phytodetritus

Previous interpretations of Lajas Formation tide- dominated nature, has been based on some structures that has been pointed as “mud drapes” and “tidal bundles“ (McIlroy, 2007; McIlroy et al., 2005), indicating the alternation of bidirectional currents and slack-water suspension deposition, typical of tidal processes. But in more recent studies, the nature of this structure has been reviewed, and what was previously described as mud, is in fact plant debris (phytodetritus) (Canale and Ponce, 2012; Ponce et al., 2012; Canale et al., 2015, 2016; Gugliotta et al., 2015, 2016; Kurcinka et al., 2018., Arregui et al., 2019). Ponce and Carmona (2011) and Canale et al., (2016) interpreted phytodetritus as being deposited as tractive load from a hyperpycnal flow. This is reinforced with recent work showing that layers containing plant debris in shelfal sand bodies may have resulted from hyperpycnal flows (Steel et al., 2018; Zavala et al., 2012) These structures observed on outcrop and on core samples may resemble tidal structures, like mud drapes, tidal bundles, and flaser stratification (Figure 7). But a more detailed observation shows that they do not have their typical characteristics, such as continuous mud drapes, rhythmic cyclicity, mud couplets, well defined sand bundles, as described in Visser, 1980 (Figure 5 therein), see also discussion in Canale et al., 2015.

Bidirectional Structures

One of the sedimentary structures that are related to tidal action are bidirectional cross-strata. This structure (also known as herringbone) is not common because it requires near equal flood and ebb tidal currents conditions, and this situation is atypical (Davis, 2012). Also, sometimes structures that resemble bidirectional cross-strata are only apparent inclinations of a trough cross bedding structure (Figure 8).

Ichnology

River-dominated deltas are the most stressful deltaic environments for the marine biota (MacEachern et al., 2005; Buatois et al., 2011). Canale et al., (2016) described trace fossils that shows low diversity and abundance, as well as simple tiering structures (impoverished *Cruziana* ichnofacies in prodelta, and *Skolithos* ichnofacies in delta front). Similar observations were made in core sample by Arregui et al., (2019) (impoverished *Cruziana/Skolithos* in delta front, and *Scoyenia* ichnofacies in delta plain). The low diversity, low abundance, and simple tiering trace fossil associations are due to short time colonization windows that reflect brief suitable environmental conditions for development of the benthos. In facies that evidence is more direct fluvial and hyperpycnal conditions, trace fossils are almost absent. The environmental parameters that control the benthos are salinity, turbidity, and hydrodynamic energy. Also, *Glossifungites* ichnofacies were recognized in outcrop (Canale et al., 2015) and in core samples, interpreted as exhumation surfaces made by channel or lobes avulsion (autogenic control). All these ichnological data (Figure 9; Figure 10) are compatible with fluvio-dominated delta ichnological models (MacEachern et al. 2015; Buatois and Mángano, 2011).

In tide-dominated environments were erosion leaves no record of rhythmic sedimentation, rhythmic tidalites are preserved in the passive infill of trace fossils, like *Ophiomorpha* (Wetzel et al., 2014; Gingras et al., 2015; Rodriguez-Tovar et al., 2019). All *Ophiomorpha* and *Thalassinoides* structures recognized for the Lajas Formation (outcrops and core samples) have passive infill that shows no sign of tidal sedimentation.

Conclusions

Lajas Formation environment in subsurface in Aguada Toledo/Sierra Barrosa is interpreted as a fluvio- dominated delta. The evidence for that interpretation is:

- The overall coarse grain size of the Lajas Formation.
- The geometry and architecture of the geoforms.
- The large dispersion of paleocurrents.
- The presence of phytodetritus.
- The absence of tidal sedimentary structures (tidal ripples, mud couplets, mud drapes, tidal bundles, bidirectional cross strata, tubular tidalites).
- The ichnological model.

All these evidences leads to the conclusion that deltas in the Lajas Formation are for the most part fluvio-dominated deltas.

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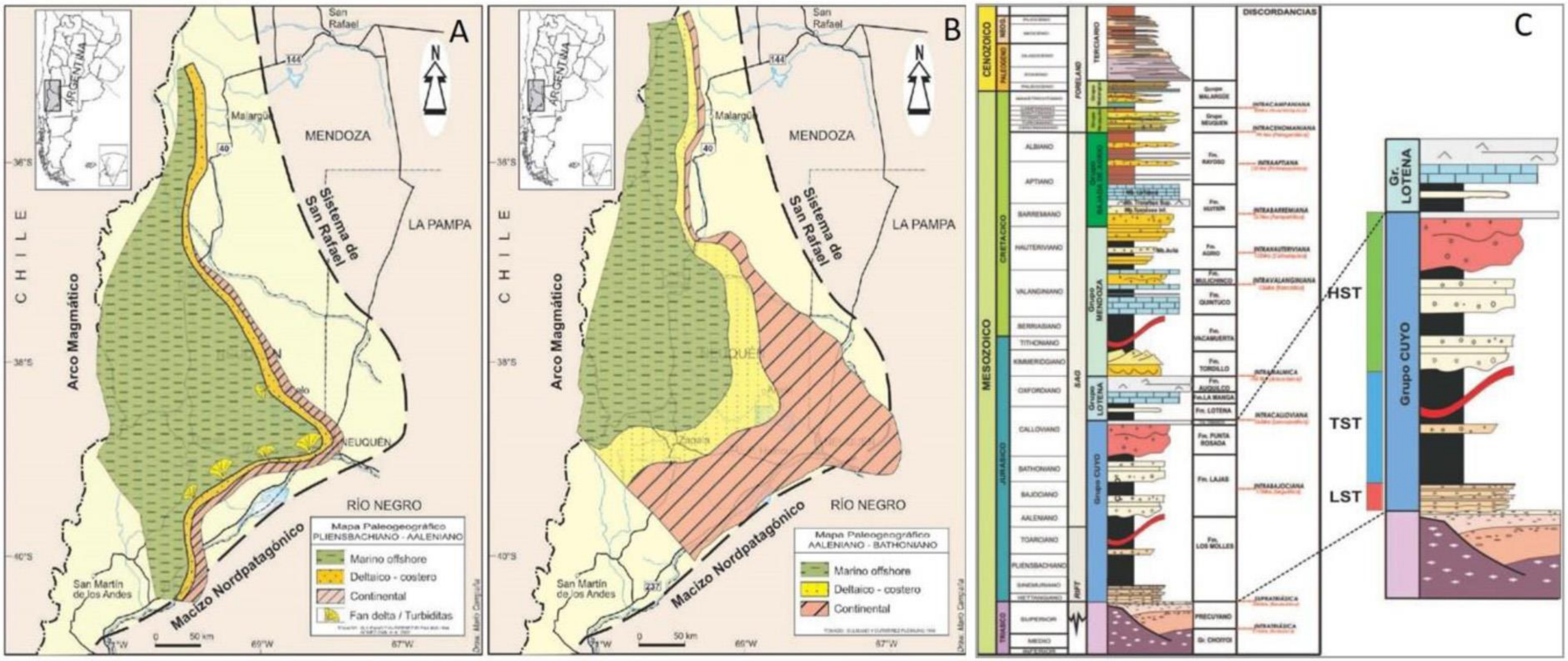

Figure 1. A-B) Location of Neuquén Basin and paleoenvironmental evolution of the Cuyo Group (Pliens-Bath). C) Stratigraphic chart and detail of the cuyo Group (From Arregui et al., 2011).

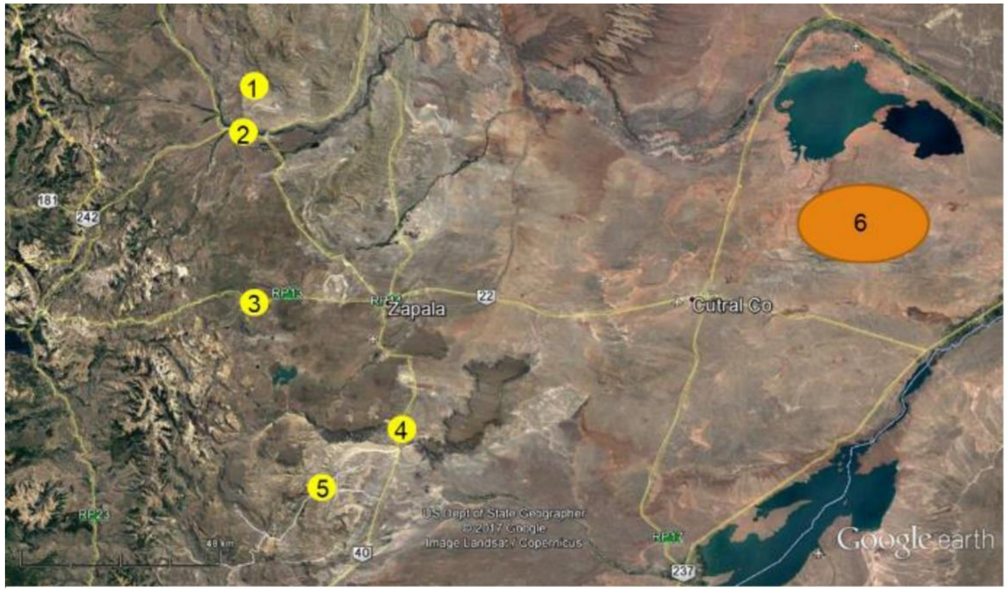

Figure 2. Location of outcrops. 1-Sa. de la Vaca Muerta, 2-Ao. Covunco, 3-Carreri, 4-Puesto Seguel, 5-Bajada de Los Molles, 6-Sierra Barrosa/Aguada Toledo (subsurface).

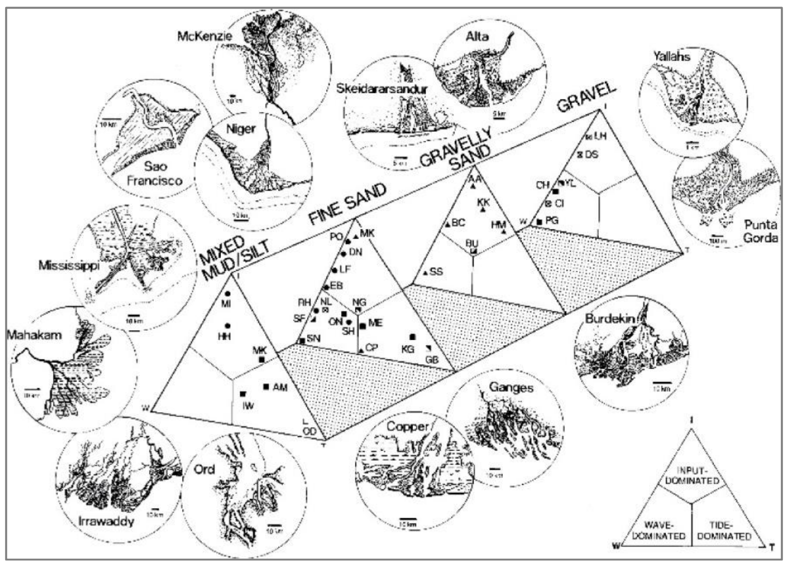

Figure 3. Grain Size and type of delta (Orton and Reading, 1993. Modified from Galloway, 1975).

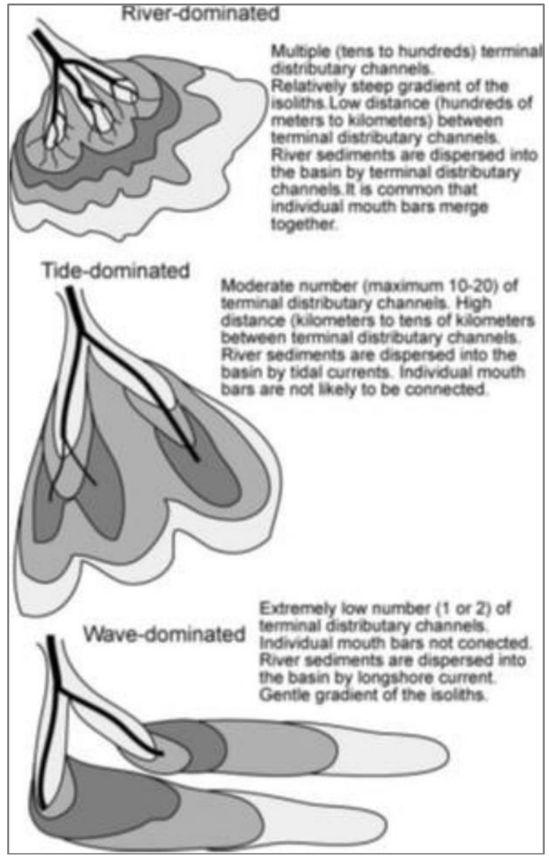

Figure 4. Geometry and architecture of deltaic systems. From Olariu and Bhattacharya, 2006.

Figure 5. Panoramic view of high and low sinuosity large scale hyperpychnal channel-lobe deposits. Bajada de Los Molles outcrop (From Canale, 2016).

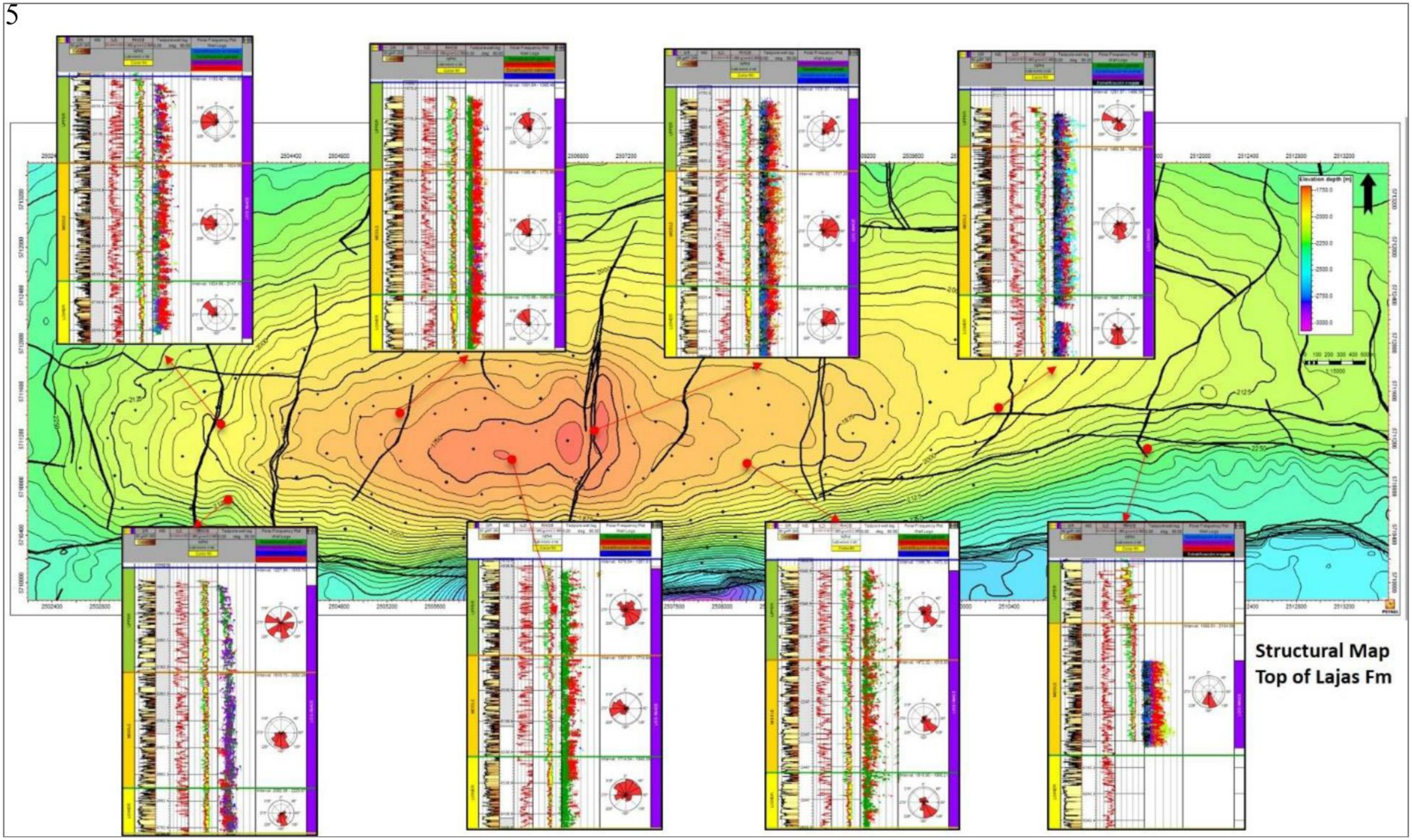

Figure 6. Paleocurrents for the Sierra Barrosa-Aguada Toledo area in subsurface. Notice the large dispersion of the paleocurrents.

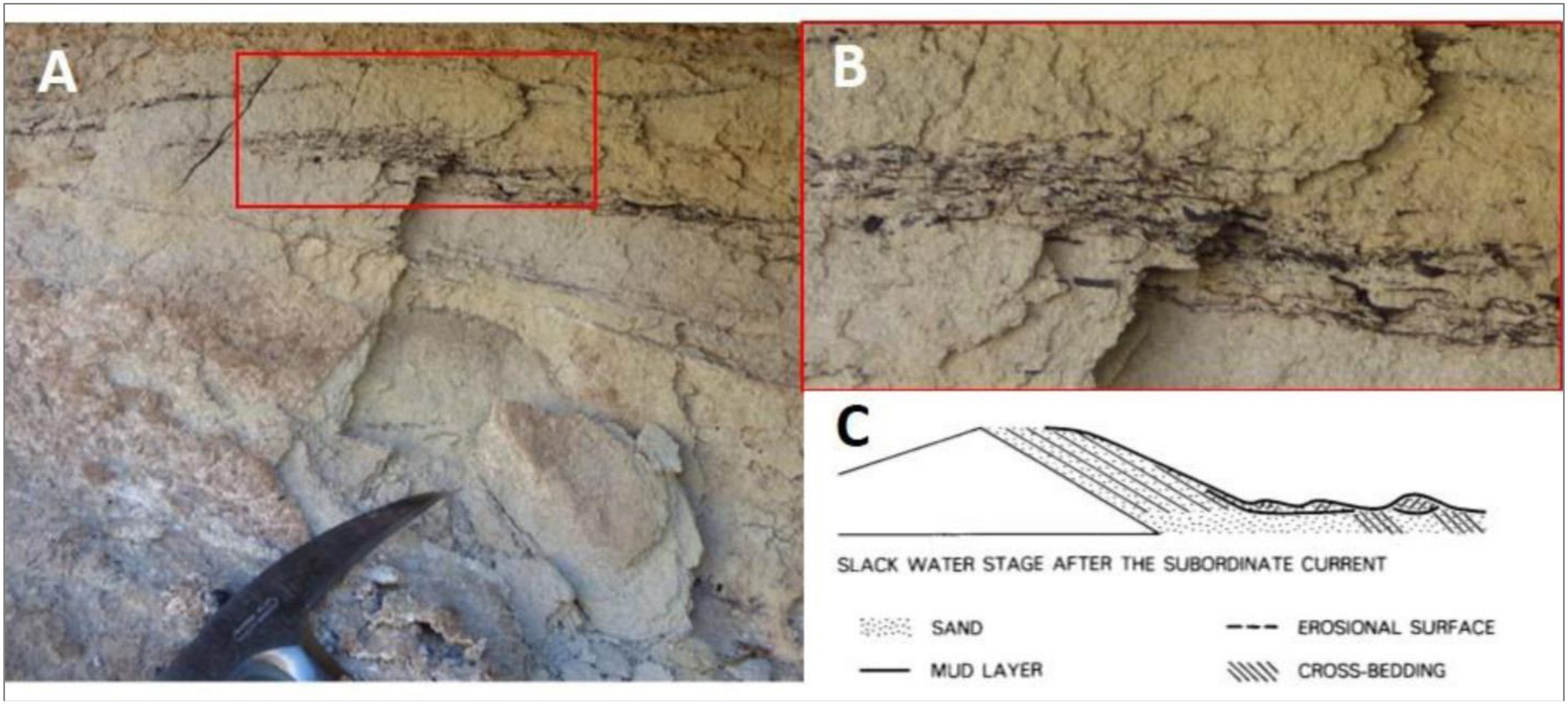

Figure 7. A-B) Level and detail of the phytodetritus. Bajada de Los Molles outcrop. C) Tidal ripple structure with all its components (Modified from Visser, 1980).

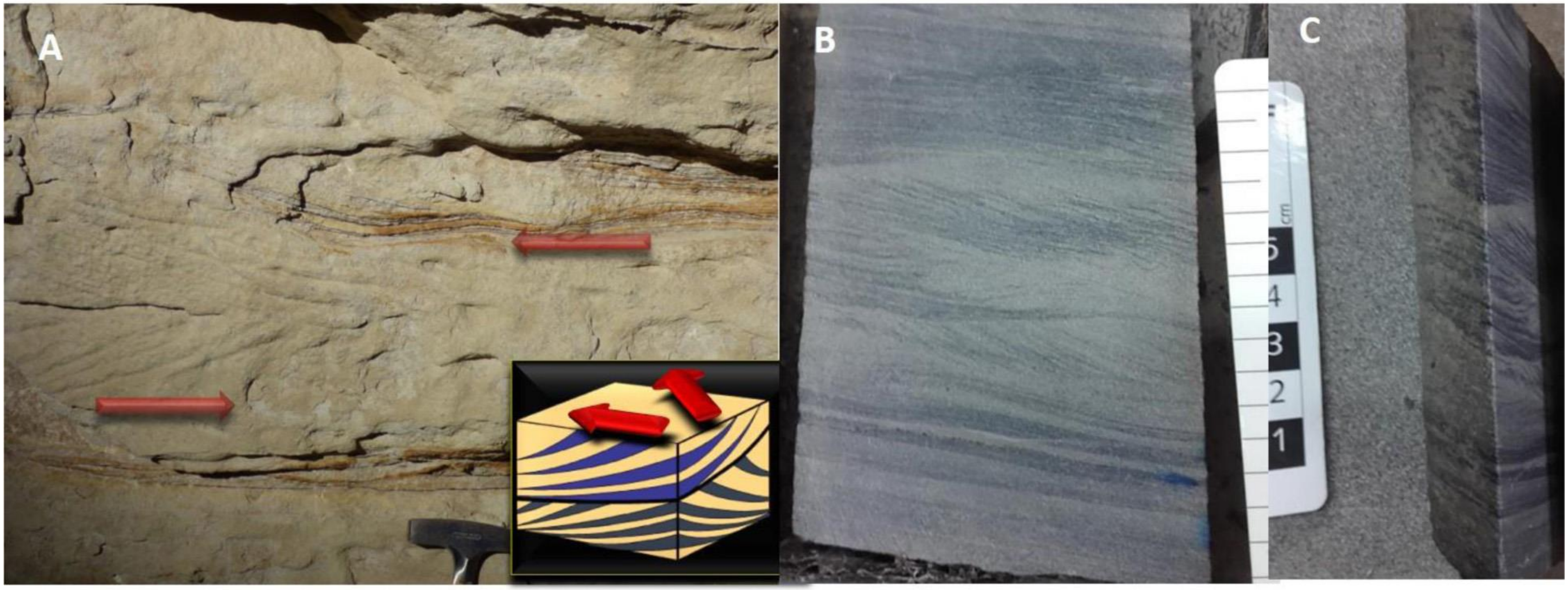

Figure 8. Cross-trough bedding showing apparent bidirectional cross strata. A) In outcrop, Bajada Los Molles. B-C) in core sample. Sierra Barrosa Area.

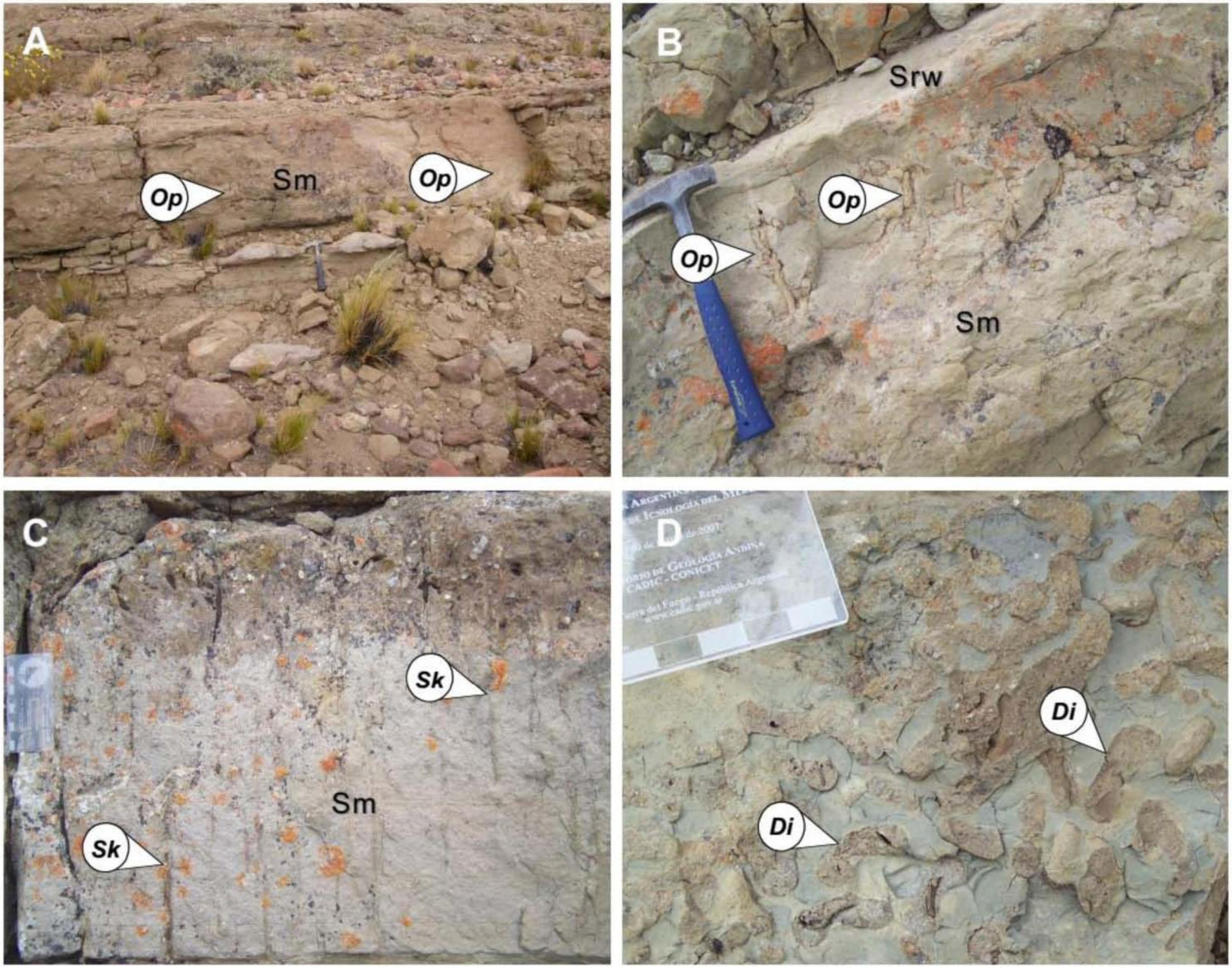

Figure 9. Trace fossils in Arroyo Covunco outcrops. A) Massive sandstones bioturbated by *Ophiomorpha*. B) Massive sandstones with wave evidence on top. C) Massive sandstones with *Skolithos* isp. Colonization. D) *Glossifungites* ichnofacies in an autogenic surface. Sm: massive sandstone; Op: *Ophiomorpha*; *Sk*: *Skolithos*; *Di*: *Diplocraterion* (From Canale et al., 2015).

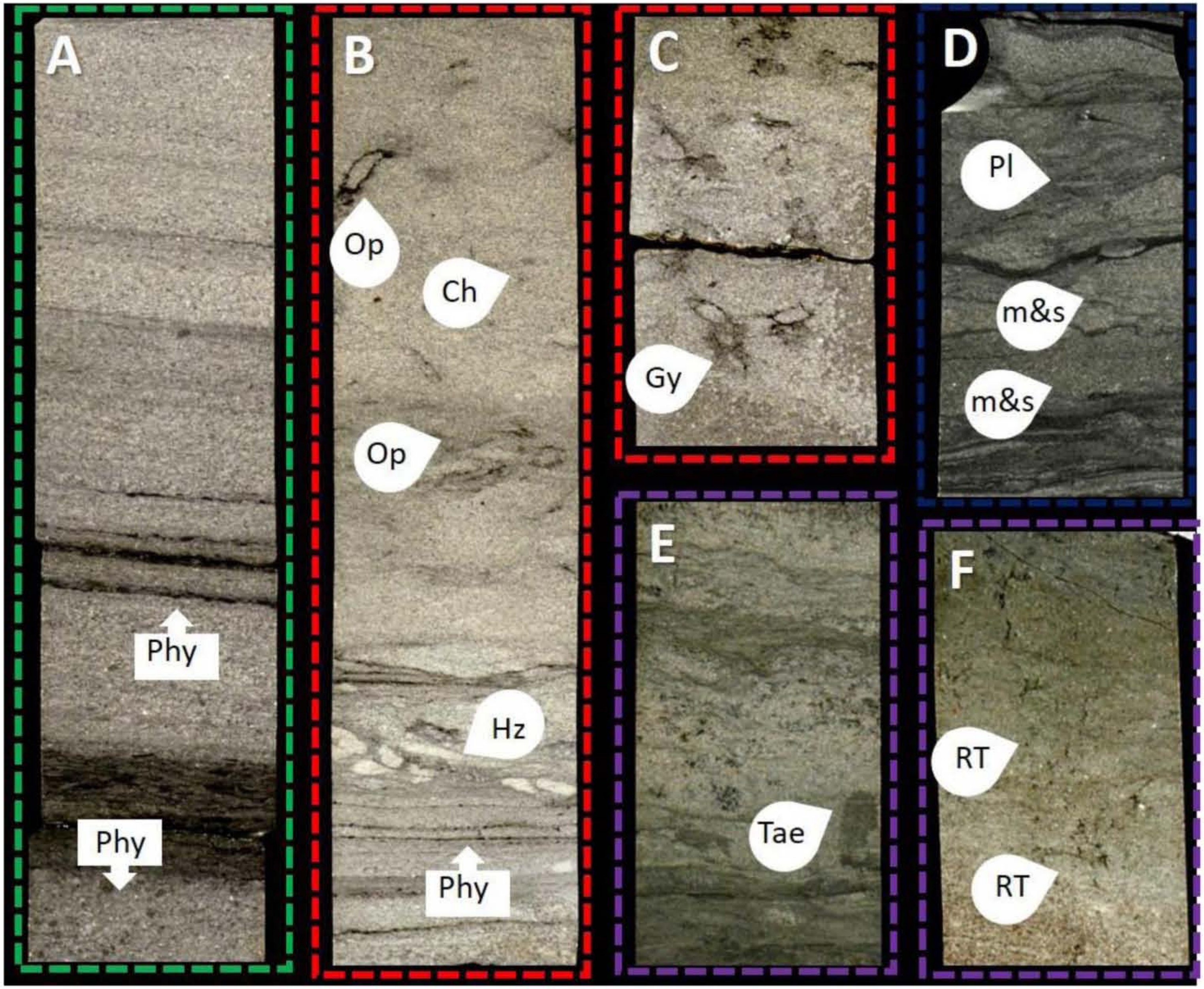

Figure 10. Core samples. Sierra Barrosa/Aguada Toledo Field. A) Unbioturbated delta front sand bars, with phytodetritus levels. B-C) Highly bioturbated delta front sand bars. D) Interbar deposits. E, F) Delta plain deposits. Phy: Phytodetritus; *Op: Ophiomorpha, Ch: Chondrites, Hz: Haentzchelinia, Gy: Gyrolithes, Pl: Planolites, Tae: Taenidium,* M& S: Mantle & Swirl structures RT: Root traces. Modified from Arregui, et al; 2019.