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Microbialitic deposits of the Yacoraite Formation, NW Argentina: distribution, environments, paleoecology, and economic implications

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Abstract

The Yacoraite Formation (NW Argentina) displays important microbialitic deposits of varied features throughout its six sub-basins. With the discovery of important microbialitic hydrocarbon reservoirs and the interest in lacustrine systems due to recent hydrocarbon finds in the pre-salt Cretaceous series of the South Atlantic, the importance of these organo-sedimentary structures has increased considerably. Because of this, in the past decade, numerous works in Yacoraite Formation have focused on its microbialites. In this study, we provide an updated summary of the existing background and state of knowledge of the microbialites in the Yacoraite Formation, which occupy different stratigraphic positions in diverse sub-basins separated by several kilometers. Due to this, these structures have developed under diverse conditions, giving rise to a great variety of structures and morphologies, useful as reliable and high-resolution proxies for paleoenvironmental studies and to discuss important ecological paradigms. In addition, microbialites of Yacoraite Formation show promising petrophysical conditions to be evaluated as reservoir rocks. Based on the large number of deposits mentioned throughout this work, and the morphological and structural variety of their microbialites, we can highlight Yacoraite Formation as one of the most important microbialite-bearing units in Argentina and South America.

KEYWORDS: microbialites; Maastrichtian; Danian; reservoir rock; NW Argentina.

INTRODUCTION

The Yacoraite Formation (Maastrichtian-Danian) (Turner 1959) is one of the units of the Salta Group rift basin (Marquillas and Salfity 1989, Salfity and Marquillas 1994) (Fig. 1). Due to its extension and mixed carbonate/siliciclastic nature, this formation is considered the most characteristic of the Balbuena Subgroup (Moreno 1970), the middle unit of the Salta Group.

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Besides, the Yacoraite Formation exhibits a remarkable economic interest for the region, due to its role as a hydrocarbon source rock and reservoir in Northwest Argentina (e.g., Boll and Hernández 1985; Boll 1991, Cesaretti *et al.* 2000, Grosso *et al.* 2013).

The type section of this formation is located at the Yacoraite ravine, south of the Uquía station, which is the western tributary of the Grande River in the Humahuaca ravine. The name Yacoraite was used by Groeber (1952) to describe the set of sediments under the designation of Calcareous-Dolomitic Horizon, a name given by Bonarelli (1913) to the Vitiacua limestones (Mather 1922) and later erroneously extended to the whole area of Salta and Jujuy (Leanza 1969).

The paleontological record of the Yacoraite Formation is diverse and made up of body and trace fossils. Regarding the corporeous fossils, ostracods, gastropods, bivalves, foraminifera, and vertebrates, such as fishes and crocodiles, have been found (Cónsole-Gonella *et al.* 2012, and references therein). Among the trace fossils, the vertebrate tracks are one of the most well-known worldwide since 1970s (e.g., Alonso 1980, Alonso and Marquillas 1986, Díaz-Martínez *et al.* 2016, 2018, Cónsole-Gonella *et al.* 2017, 2021, de Valais and Cónsole-Gonella 2019). In addition, the unit exhibits an interesting and diverse record of microbialites (Marquillas *et al.* 2005, Cónsole-Gonella *et al.* 2009, 2012, 2017, de Valais and Cónsole-Gonella 2019, and references therein).

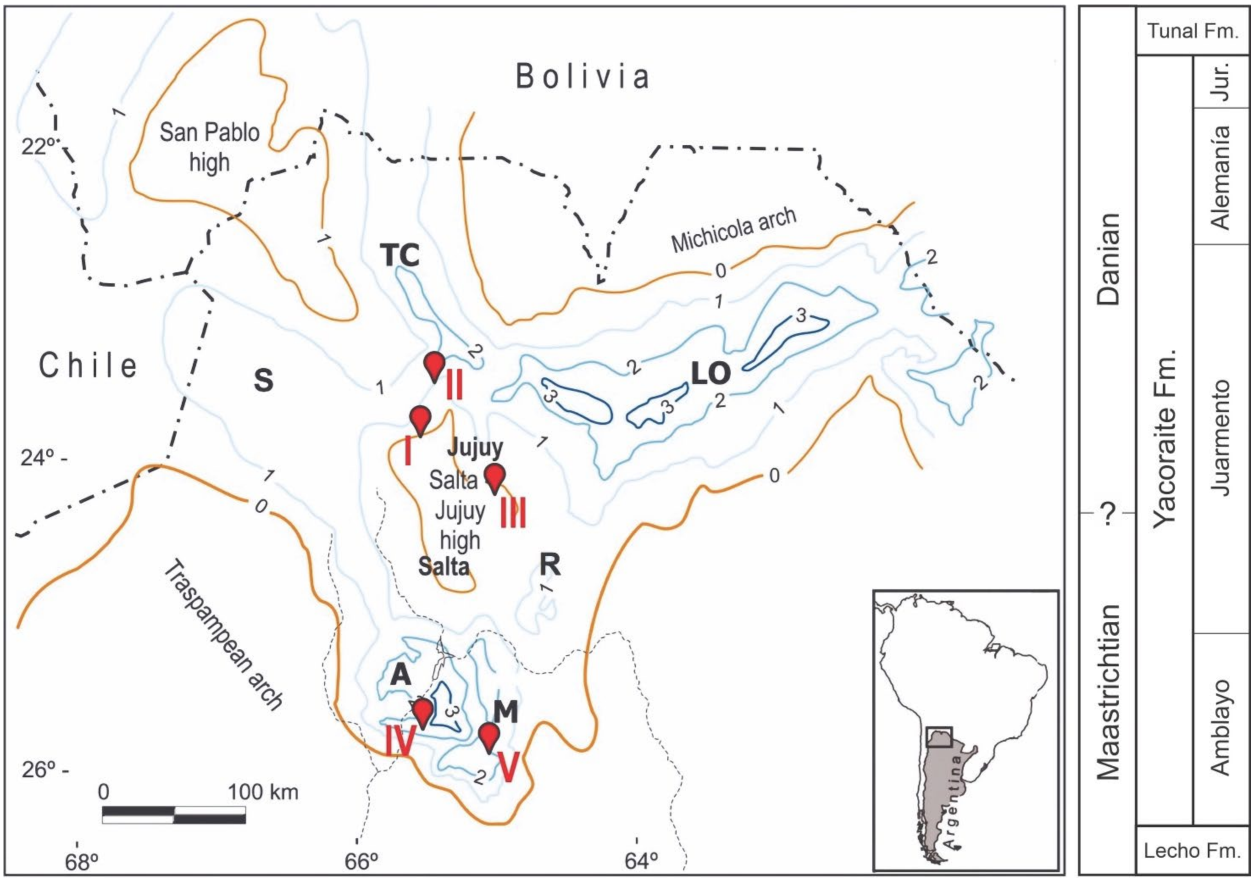


Figure 1. Location of the main sub-basins: TC (Tres Cruces), LO (Lomas de Olmedo), A (Alemanía), M (Metán), R (Rey), and S (Sey), and the isopach map of the Yacoraite Formation. Thicknesses are shown in hundreds of meters. The numbers correspond to different localities in which the authors mentioned the presence of microbialitic beds: I: Maimará, ll: Juella, lll: Alfarcito, IV: Cabra Corral, V: Amblayo. The references showing the microbialite descriptions and interpretations are summarized in Table 1. Modified from Marquillas *et al.* (2005) and Díaz-Martínez *et al.* (2018). In addition, a general column with the (litho)stratigraphy of the Yacoraite Formation and its divisions into members is shown.

Microbialites are the result of the interaction between benthic and detrital microbial communities and/or chemical sediments, constituting an excellent example of organo-sedimentary structures in marine, coastal, or freshwater environments (e.g., Burne and Moore 1987, Riding 2008). Based on their internal structure, they can be grouped into five categories:

- stromatolites, when microbialites show a laminated internal structure and grow attached to the substrate;
- oncolites, when microbialites show a laminated internal structure developing concentrically around a core;
- thrombolites, when there is no internal laminated pattern and instead agglomerations or thrombi are formed;
- dendrolites, when microbialites show an internal structure with a dendritic or branched growth pattern;
- leiolites, whose internal structure is composed of fine grains, lacking textural arrangement (e.g., Burne and Moore 1987, Riding 2011).

The knowledge about the microbialites of the Yacoraite Formation dates back to XVIII century, long before this unit was defined by Turner (1959). D'Orbigny (1842) reported in the Miraflores syncline area (Potosí, Bolivia) the existence of a marine calcareous supposedly to be Mesozoic in age, later defined as Triassic due to its lithostratigraphic similarity with the European Muschelkalk (central and western Europe). In this unit, a type of stromatolitic structure originally named *calcaire ondullé* was described, which would become one of the most distinctive elements for correlation in this formation.

Brackebusch (1883, 1891) investigated the correlation of these Argentinian Mesozoic beds, which are included in a sequence mainly made of red sandstones, calcareous sandstones, and limestones; furthermore, based on comparisons with homologous fauna of the Bahia Group in Brazil, this author proposed a Cretaceous age for them. These strata were designated as "Petroliferous Formation" and later as "Salta System." This proposal was supported by Steinmann *et al.* (1904), Steinmann (1906), and Keidel (1910), who named the Bolivian post-Paleozoic series "Arenisca de Puca" or "Areniscas Rojas" (Pucasandstein) and was considered correlative with the "Petrolifera Formation" in northwestern Argentina. These authors mentioned the domic stromatolites, named as *Pucalithus* (red rock in Quechua language), and considered equivalent to the *calcaire ondulée* of D'Orbigny, standing out for their abundance, intense red color and their "mamelonar" surface (for further details, *see* Cónsole-Gonella *et al.* 2012).

Later, Bonarelli (1913) suggested an alternative hypothesis and proposed the names "Lower Sandstones" and "Dolomitic Calcareous" for these units. Bonarelli (1921) and Cossman (1925) suggested that the "Lower Sandstones" would correspond to the Permo-Triassic and the "Dolomitic Calcareous" to the Triassic. Despite not coinciding stratigraphically, Bonarelli (1927) accepted the presence of *Pucalithus* and called them as "peculiar" and "problematic fossils."

Between 1980 and early 2000s, the presence of microbialites in the Yacoraite Formation was discussed in several contributions, doctoral theses, and conference papers (e.g., Palma 1984, Marquillas 1984, 1985, Marquillas and Salfity 1989, 1994, Marquillas *et al.* 2003, 2005, 2007, Cónsole-Gonella 2011, Cónsole-Gonella *et al.* 2009, 2012, 2017). However, those were mostly limited to brief mentions or descriptions within a regional paleoenvironmental and sedimentological context (see Cónsole-Gonella *et al.* 2012, Roemers-Oliveira *et al.* 2015).

In recent years, with the discovery of important hydrocarbon reservoirs in microbialitic levels, the study of these organo-sedimentary structures has gained great importance (e.g., Grotzinger and Al-Rawahi 2014, Muniz and Bosence 2015). A good example of these systems is the Brazilian pre-salt, with important reservoirs in mostly or partially (according to different interpretations) microbialitic and bioclastic carbonate facies, deposited in lacustrine to shallow marine environments during the Sag phase (e.g., Rangel and Carminatti 2000, Thompson *et al.* 2015, Abelha and Petersohn 2018). However, due to the limited subsurface data, reservoir distribution, and heterogeneities, the study of these systems must be complemented by analogues.

Because of its deposition during the sag phase of the Salta rift, microbialites and carbonatic facies of Yacoraite Formation attracted geoscientists attention as an important tool for the study of Brazilian pre-salt. However, the great variety in the organo-sedimentary facies of this formation limits generalization at different scales of work (Rangel and Carminatti 2000, Durieux and Brown 2007, Romero-Sarmiento *et al.* 2019, Gomes *et al.* 2020, Ruiz-Monroy 2021). Numerous works were focused on the study and understanding of microbialitic systems of Yacoraite Formation from a stratigraphic, sedimentary, paleoenvironmental, paleobiological/paleontological, and petrophysical point of view (e.g., Hamon *et al.* 2012, Cónsole-Gonella and Marquillas 2014, Villafañe 2016, Bunevich *et al.* 2017, Cónsole-Gonella *et al.* 2017, Ruiz *et al.* 2018, de Valais and Cónsole-Gonella 2019, Deschamps *et al.* 2020, Gomes *et al.* 2020, Villafañe *et al.* 2021, Granier and Lapointe 2022, Tomás *et al.* 2022).

The aim of this study was to provide an updated summary of the current background and state of knowledge of the microbialites in the Yacoraite Formation, northwestern Argentina, published during the past decades.

GEOLOGICAL SETTING

The Salta Group records the sedimentary accumulation of a continental rift basin developed from Early Cretaceous to Eocene time (e.g., Viramonte *et al.* 1984, Salfity and Marquillas 1994, Marquillas *et al.* 2005). Its origin and evolution are linked to a regional extensional context in northwestern Argentina (Marquillas *et al.* 2011). The deposits of this group are accumulated in six sub-basins, which surround the Salta-Jujuy high, namely, Tres Cruces, Lomas de Olmedo, Metán, Alemanía (Reyes 1972, Salfity 1982), El Rey (Salfity 1980), and Sey (Schwab 1984) (Fig. 1).

From bottom to top, the Salta Group is subdivided into three subgroups:

- Pirgua Subgroup (Upper Barremian-Upper Campanian) corresponding to the syn-rift stage (Valencio *et al.* 1977);
- Balbuena Subgroup (Upper Cretaceous-Lower Paleocene) corresponding to the early post-rift stage (Moreno 1970);
- Santa Bárbara Subgroup (Paleocene-middle Eocene) corresponding to the late post-rift stage (Del Papa *et al.* 2010).

The basin was developed entirely on Precambrian and Paleozoic basement, and the different formations of Salta Group rest either on Pampean rocks or on the Lower Paleozoic formations of northern Argentina (Aceñolaza and Toselli 1981).

The Yacoraite Formation belongs to the Balbuena Subgroup (Upper Cretaceous-lower Paleocene) and was deposited during the initial stage of thermal subsidence of the Salta Group (Marquillas *et al.* 2005). It is a succession widely exposed in the provinces of Salta, Jujuy, and northern Tucumán (Marquillas *et al.* 2005) (Fig. 2). It is composed of dominantly calcareous deposits (partly dolomitic) organized in tabular strata, with intercalations of pelites and sandstones, as well as tuffs and vulcanites (Marquillas and Salfity 1994). Since Yacoraite Formation has a Maastrichtian-Danian age (Marquillas 1985), the Cretaceous-Paleogene boundary occurred during its accumulation (Marquillas *et al.* 2005).

Yacoraite Basin has been defined as a restricted, shallow, and extensive carbonate intracontinental basin (epicontinental sea), far from the direct and permanent influences of the open sea (Marquillas 1985). Sedimentary facies indicate shallow shoreface conditions alternating with sublittoral deposits. Dominance of wave structures, both fair and stormy weather, suggests a wave-dominated regime with subordinate tidal influence (Marquillas 1985, Marquillas *et al.* 2005, 2007).

Stratigraphy of Yacoraite Formation

Based on sequence stratigraphy data, the Balbuena Supersequence contains the Lecho and Yacoraite Formations and records sedimentation spanning from the end of the Cretaceous to the beginning of the Paleogene (Hernández *et al.* 1999). The deposits belonging to the Balbuena Supersequence can be subdivided into four sequences of third order, from bottom to top: Balbuena I, Balbuena II, Balbuena III, and Balbuena IV (Hernández *et al.* 1999).

The Balbuena I Sequence is predominantly composed of siliciclastic facies deposited in an eolian system (Hernández *et al.* 1999). The Balbuena II Sequence is divided into two sections: the basal one is made up of calcareous deposits interbedded with tractive clastics and pelites, deposited in a lacustrine environment; and the upper one is made up of predominate clastic fluvial deposits (Hernández *et al.* 1999). The Balbuena III Sequence displays pelites interbedded with very fine sandstones in the central part of the basin and fluvial conglomerates in the border zones (Hernández *et al.* 1999). Lastly, the Balbuena IV Sequence is composed of microbialites, marls,

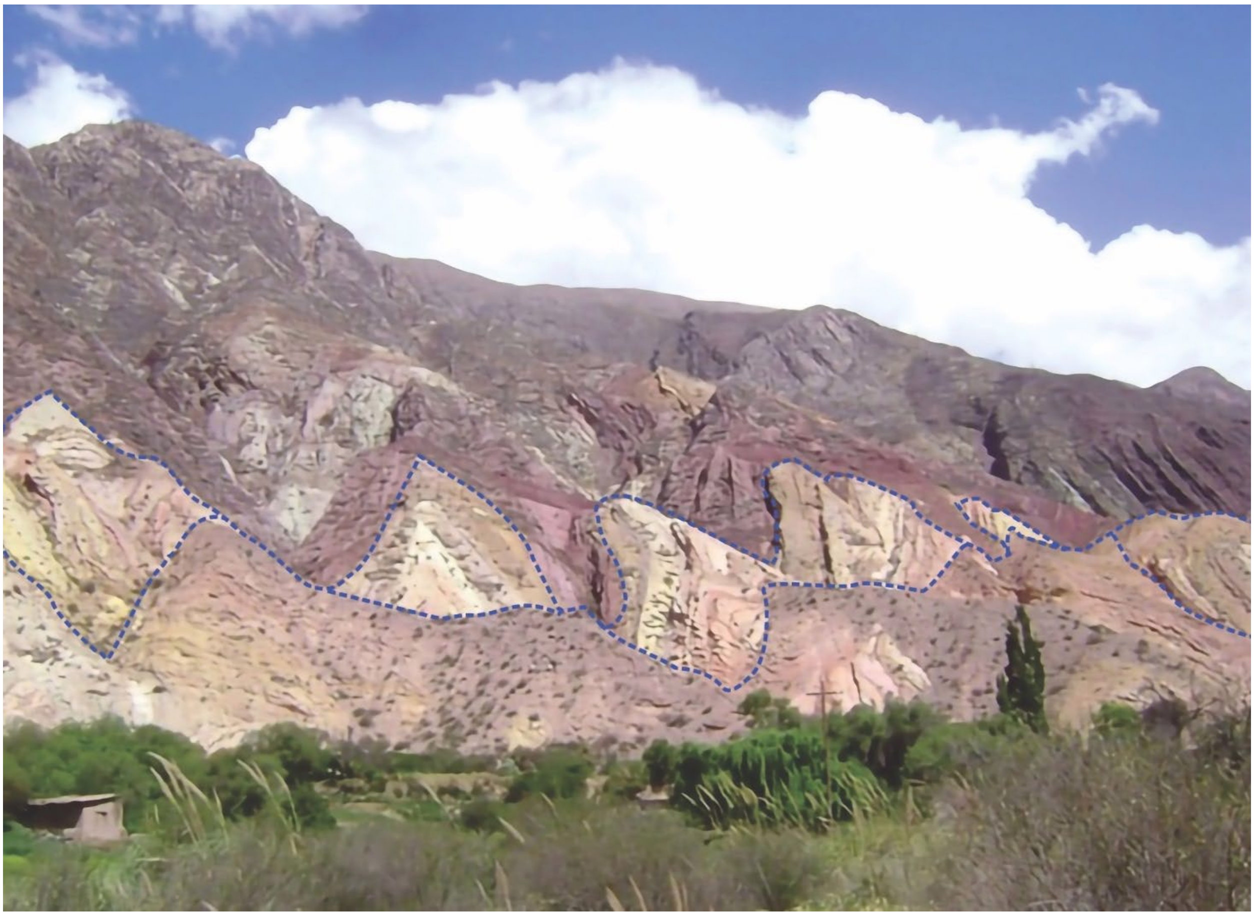


Figure 2. NW-SE outcrop view of the Yacoraite Formation (marked with a blue dotted line), yellow to whitish dominated levels, in the locality of Maimará, Jujuy (Tres Cruces sub-basin).

siltstones, argillites, arkosic, and carbonate quartzite sandstones in the central part of the basin, whereas in the marginal regions, quartz-feldspathic sandstones, arkosic, and conglomerate sandstones crop out (Hernández *et al.* 1999, Bunevich *et al.* 2017).

From a genetic and lithostratigraphic point of view, the Yacoraite Formation, according to changes in the depositional environment, has been subdivided into four members (Marquillas 1986, Marquillas and Salfity 1989, Marquillas *et al.* 2003, 2005, 2007), from base to top:

- Caliza Amblayo Member: It is the basal member of Yacoraite Formation, with an average thickness of 100 m. It displays a calcareous-dolomitic composition, formed by oolitic and intraclastic grainstones, oointraclastic packstones, fine calcareous sandstones, and stromatolitic beds. It suggests a deposition dominated by significant energy changes. Intertidal activity under stable weather conditions and subordinate stormy weather are recorded in addition to shoals or shoreface sands (Marquillas *et al.* 2005, 2007, Moreno and Marquillas 2009);
- Güemes Member: It is about 20 m thick and shows bioturbation surfaces. It is composed of bioclastic wackestones, mudstones, siltstones, and graywackes. Flows of different energy and density are suggested to their deposition, indicating water mixing, storm action, and perhaps some continental influence (Marquillas *et al.* 2005, 2007);
- Alemanía Member: It represents a large part of the upper section of the formation, approximately 70 m thick. It is composed of a thin heterolithic succession of green and black shale, micritic, intraclastic and oolitic limestones, sandy marls, and siltstones, with oolitic grainstones strata and/or stromatolitic boundstones in the upper part. Deposition may have been controlled by the alternation of traction and sedimentation processes in an environment mainly regulated by fairweather waves, where the observed stratigraphic cyclicity seems to respond to climatic variations (Marquillas *et al.* 2005, Cónsole-Gonella and Marquillas 2014);
- Juramento Member: This member is only a few meters thick, recognized in the upper part of the succession. It is mainly composed of domic stromatolites, black and gray shales, marls, oolitic limestones, bioclastic limestones, and sporadic traces of gypsum and anhydrite. It suggests mainly a high intertidal environment and a locally extended tidal flat, alternating with low-energy shallow subtidal sectors. In addition, Juramento member shows an important control by fairweather waves (Marquillas *et al.* 2005, 2007, Cónsole-Gonella and Marquillas 2014).

REGIONAL DISTRIBUTION OF MICROBIALITIC DEPOSITS

The microbialites of Yacoraite Formation have a wide regional distribution, linked to different sub-basins and sedimentary settings in different stratigraphic positions along the unit. However, not all sub-basins exhibit the same degree of knowledge on microbialitic records. Microbialites were largely described from the Tres Cruces and Metán sub-basins, while reports are limited to other sub-basins, such as Sey or Lomas de Olmedo (Gómez-Omil 1982) (Table 1, Fig. 1).

Along the northern area of the Yacoraite Basin, mainly at the Tres Cruces sub-basin, there are several microbialitic deposits. As stated before, Steinmann *et al*. (1904) correlated the Cretaceous strata in Tres Cruces area with the analogous Puca Group in Bolivia, based on the domal stromatolite *Pucalithus*. More than a century later, Cónsole-Gonella and Aceñolaza (2009) and Cónsole-Gonella *et al*. (2009) described domal stromatolites in Maimará and Juella localities of the Jujuy Province. Also, Cónsole-Gonella *et al*. (2012) presented a synthesis of the paleontological knowledge from the Yacoraite Formation (Maastrichtian-Danian) in these localities.

Villafañe (2016) proposed the usefulness of microbialites from the Yacoraite Formation in the Maimará section as a tool for high-resolution paleoenvironmental studies. Later, Cónsole-Gonella *et al*. (2017) presented a complete paleoenvironmental reconstruction, showing the ichnofacies implications describing the presence of five stromatolitic facies, some of them showing a remarkable degree of preservation. On the contrary, Villafañe *et al*. (2021) studied this series and determined the relationship between hydrodynamic energy and these organo-sedimentary structures, defining seven stromatolitic beds in this locality. Finally, at the same locality, Frías-Saba *et al*. (2021) described the influence of bacterial communities, sediment input, and CO_3 saturation of waters on the development of stromatolite microfabrics from Yacoraite Formation (for a detailed stratigraphic column with the position of microbialites, see Villafañe *et al*. 2021).

Regarding the K-Pg boundary, Sial *et al*. (2001) identified it in Maimará locality, although unfortunately its position was not clearly indicated in the stratigraphic section. On the contrary, the overlying Tunal Formation was dated as Danian based on palynomorphs (Quattrocchio *et al*. 2000). Thus, the stromatolitic beds in the Yacoraite Formation are interpreted as Maastrichtian in age and probably stratigraphically close to the K-Pg boundary.

Similar to the latter sub-basin, the Metán sub-basin shows important microbialitic deposits within its stratigraphic record. Although this sub-basin is considered a single one with the Alemanía sub-basin (Metán-Alemanía sub-basin) by some authors (Pedrinha *et al*. 2015), most of the reports correspond to the Cabra Corral dam area, Coronel Moldes District (Salta Province, Argentina), which indeed belongs to the Metán sub-basin (Table 1, Fig. 1).

Gabaglia *et al*. (2011) presented a cyclo-stratigraphic and paleoclimatic study of the Balbuena Supersequence in the Cabra Corral dam area, highlighting the occurrence of several microbialitic intervals varying from centimetric to metric in thickness. Subsequently, one of the first studies focused solely on these organo-sedimentary structures in this area is presented by Cónsole-Gonella and Marquillas (2014), who reported several microbialitic beds in the Amblayo, Alemanía, and Juramento members, in the Bahía Viñuales section. However, the authors focused on the stromatolites of the Juramento member and their interaction with metazoans.

Surrounding Cabra Corral dam, Roemers-Oliveira *et al*. (2015) studied several outcrops belonging to the Balbuena III Sequence (Maastrichtian/Danian), displaying two or more stromatolitic levels giving rise to a detailed paleoenvironmental reconstruction. Subsequently, in the same region, Bunevich *et al*. (2017) defined seven organo-sedimentary facies based on their intrabioarchitecture from the Balbuena IV sequence (Danian).

Gomes *et al*. (2020) carried out a paleoenvironmental study of the lacustrine deposits belonging to the upper part of the Yacoraite Formation in different sectors of the Metán and Alemanía sub-basins, defining four microbialitic facies based on mega-, macro-, meso-, and microstructural characteristics. Quiroga (2021) described and interpreted the presence of stromatolitic structures belonging to the Amblayo Limestone member (Alemanía sub-basin), cropping out near the Amblayo town (San Carlos, Salta).

On the contrary, some authors have focused their work on different sub-basins, looking for a correlation among them (Table 1). In Sey, Metán, and Tres Cruces sub-basins, Marquillas *et al*. (2007) mentioned the presence of stromatolites related to carbonate facies, which they used for isotopic studies (C and O isotopes) at a regional level. In addition, Marquillas *et al*. (2005) described stromatolitic boundstones associated with shales, mudstones, and grainstones in the upper part of the Yacoraite Formation within Metán and Alemanía sub-basins. Terra *et al*. (2015) studied the Yacoraite Formation in the Lomas de Olmedo, Metán-Alemanía, and Tres Cruces sub-basins as an analog for Phanerozoic lacustrine microbialitic reservoirs, as well as described the presence of microbialitic levels positioned in the upper part of the Balbuena Supersequence. Furthermore, in Lomas de Olmedo sub-basin, stromatolitic levels with vertically stacked hemispheroids (SH) and laterally linked hemispheroids (LLH) mesostructures (*sensu* Logan *et al*. 1964) were reported in association with shales and mudstones by Gómez-Omil (1982). Ruiz *et al*. (2018) study biomarkers to differentiate carbonate formation between marine, lacustrine, and terrestrial depositional environments. In this work, the presence of microbialitic levels in the Tres Cruces, Metán, and Alemanía sub-basins is mentioned. Finally, Deschamps *et al*. (2020) studied the dynamics of lacustrine sedimentary systems in the four sequences of the Yacoraite Formation, in the sub-basins of Metán, Alemanía, and El Rey. Throughout their work, they highlighted the presence of diverse microbialitic levels, mainly of the stromatolitic type, associated with diverse depositional systems.

TYPES OF MICROBIALITES AND DEPOSITIONAL ENVIRONMENTS

Microbialites are the sedimentary products of the dynamic interaction between intrinsic (producing microorganisms) and extrinsic factors (environmental parameters) of the environment throughout their growth (Grotzinger and Knoll 1999,

Table 1. Microbialitic deposits of the Yacoraite Formation grouped with respect to the sub-basin, locality/region, and stratigraphic position*.

Main microbialite papers in the Yacoraite Formation				
Sub-basin	**Region/ locality**	**Stratigraphic position/age**	**Paleoenvironment**	**Authors**
Tres Cruces	Maimará (I)	Maastrichtian, in a stratigraphic position close to the K-Pg boundary.	Paleoenvironment that varied from lower intertidal to shallow subtidal, close to the coastline, partially restricted and affected by hydrodynamic action.	Cónsole-Gonella and Aceñolaza (2009) Cónsole-Gonella (2011) Cónsole-Gonella *et al.* (2012) Villafañe (2016) Cónsole-Gonella *et al.* (2017) Villafañe *et al.* (2021) Frías-Saba *et al.* (2021)
	Juella (II)	Upper Maastrichtian.	Shallow and brackish marine environment, near the coast or sporadically emerged areas.	Cónsole-Gonella *et al.* (2009) Cónsole-Gonella *et al.* (2012)
	Alfarcito (III)	Not specified.	Stromatolitic facies correspond to an intertidal environment, formed in the photic zone, less than 10 m deep.	Cónsole-Gonella (2011)
	Not specified	Not specified.	Marine environment with higher clastic input, especially at the marginal areas.	Marquillas *et al.* (2007)
	Not specified	Upper part of Balbuena Supersequence.	Not specified	Terra *et al.* (2015)
	Not specified	Not specified.	Shallow marine environment.	Ruiz *et al.* (2018)
Metán	Cabra Corral dam (IV)	Balbuena Supersequence.	Lacustrine environment, whose base level is influenced by relative changes in sea level.	Gabaglia *et al.* (2011)
		Balbuena III sequence.	Closed lacustrine environment.	Roemers-Oliveira *et al.* (2015)
		Balbuena IV sequence.	Lacustrine with fluctuating climatic conditions and increasing aridity.	Bunevich *et al.* (2017)
		Upper Yacoraite Formation.	Lacustrine, in shore line positions.	Gomes *et al.* (2020)
		Juramento Member.	Shallow, stressed marine environment with high salinity, represented by intertidal and tidal flat deposits.	Cónsole-Gonella and Marquillas (2014)
	Not specified	Not specified.	Marine conditions with periods of subaerial exposure.	Marquillas *et al.* (2007)
	Not specified	Not specified.	Shallow marine environment.	Ruiz *et al.* (2018)
Metán-Alemanía	Not specified	Upper part of Balbuena Supersequence.	Lacustrine environment with high siliciclastic supply in humid periods.	Terra *et al.* (2015)
	Not specified	Balbuena Supersequence	High-energy littoral to supralittoral environments.	Deschamps *et al.* (2020)
	Not specified	Upper Yacoraite Formation	Shallow carbonated marine environment.	Marquillas *et al.* (2005)
Alemanía	Different localities	Upper Yacoraite Formation	Lacustrine, in shore line positions.	Gomes *et al.* (2020)
	Amblayo (V)	Caliza Amblayo Member	Shallow intertidal paleoenvironment with alkaline pH, temperatures between 20º C and 40°C, good light and high salinity.	Quiroga (2021)
	Not specified	Not specified	Shallow marine environment.	Ruiz *et al.* (2018)
Sey	Not specified	Not specified	Marine environment with higher clastic input, especially at the marginal areas.	Marquillas *et al.* (2007)
Lomas de Olmedo	Not specified	Upper part of Balbuena Supersequence	Lacustrine environment with marine influence.	Terra *et al.* (2015)
	Not specified	Not specified	Lacustrine environment with low contribution of siliciclastic sediment and important carbonate participation.	Gómez-Omil (1982)
El Rey	Not specified	Balbuena Supersequence	Not specified	Deschamps *et al.* (2020)

*The numbers (I–V) correspond to the different localities in Fig. 1 where the authors mentioned above found microbialitic deposits.

Riding 2008, Dupraz *et al.* 2011). If during their development the intrinsic or extrinsic factors vary, changes in their internal structure occur, providing an excellent tool for environmental interpretations (Dupraz *et al.* 2006, Mercedes-Martín *et al.* 2014, Suosaari *et al.* 2016).

As mentioned before, sediments belonging to the Yacoraite Formation were deposited in an epicontinental sea after the Early Cretaceous rifting and represent the last marine input during that period (Marquillas *et al.* 2005). However, given the size of the basin, the distance between the studied localities, and the diverse stratigraphic positions in which the microbialites occur, it is likely that the environmental conditions would not have been homogeneous, resulting in a great variety of organo-sedimentary structures.

In general terms, Hamon *et al.* (2012) suggested that microbialites of Yacoraite Formation can be classified according to their internal structure (mesostructure), coupled with the particular environmental conditions, into six types:

- oncoidal rudstone, observed on the most proximal part of the sedimentary system and interpreted as tidal flat deposits;
- planar-laminated stromatolites, related to proximal tidal flats and in restricted lagoon;
- "mustach-like" stromatolites formed by wavy internal laminations, in tidal flat environments;
- isolated nodular stromatolitic domes, interpreted as lagoon to tidal flat deposits;
- coalescent nodular to bulbous stromatolites, interpreted as lagoon to restricted flat deposits;
- branching or tubular stromatolites, interpreted as high-energy environment deposits (shoal related).

Hamon *et al.* (2012) provided an important background on the relationship between microbialites of the Yacoraite Formation and their growth environment. However, in the past 10 years, new deposits have been reported and used as a high-resolution proxy for paleoenvironmental reconstructions. These authors seek to characterize in detail the dynamic interaction between microbialites and environmental parameters in specific localities, mainly from the Tres Cruces and Metán-Alemanía sub-basin, as detailed below.

Microbialites in Tres Cruces sub-basin

Throughout the sedimentary succession of the Tres Cruces sub-basin (Maastrichtian), several microbialitic levels have been reported. All of them are Maastrichtian in age.

As mentioned before, Cónsole-Gonella *et al.* (2012) reported *Pucalithus*-type domic stromatolites, both in Maimará and Juella localities, characterized by reddish color and "mamelonar" external structure (Fig. 3A). Although the authors have not studied their internal structure, they suggested that these domes developed in a epicontinental environment, under hydrodynamic stress and with important salinity fluctuations.

Based on a more focused study on these organo-sedimentary structures in the Maimará locality, Cónsole-Gonella *et al.* (2017) described a sedimentary section with five microbialitic levels (from bottom to top):

- Stromatolites with a mat-like structure extending over large areas, and less frequently hemispheroidal domes with an average height of 17 cm, variably spaced (types LLH-S and LLH-C, *sensu* Logan *et al.* 1964);
- Stromatolitic domes with an LLH-S structure (*sensu* Logan *et al.* 1964), better developed than in the first level, with an average height of 40 cm;
- Mat-like stromatolites with a laminated and homogeneous internal structure and height from 5 to 35 cm;
- Oblate to semicircular stromatolites, with an SS-I structure (*sensu* Logan *et al.* 1964) and a maximum thickness of 43 cm. In a transverse section view, some stromatolites show lamination in two directions around a micritic nucleus;
- Semicircular to semi-oval stromatolites with an LLH-C structure (*sensu* Logan *et al.* 1964).

The set forms a "stromatolite reef" very similar to the one observed by Logan (1961). Cónsole-Gonella *et al.* (2017) suggested that these levels were in association with a carbonate lagoon shoreline deposit, in a subtidal-lower intertidal zone of moderate/high energy under wave and tide action. Each level represents an environmental stage where the hydrodynamic conditions and the accommodation space (depth) have conditioned the growth of these organo-sedimentary structures.

In the same section, Villafañe *et al.* (2021) made a high-resolution paleonvironmental study, focusing on one three-dimensionally exposed stromatolitic level (Fig. 3B). These authors described domic structures organized in clusters (Fig. 4A) with a laminated columnar internal structure proposing a classification for the various erosional structures scouring observed at the outcrop. Clusters are limited by the first-order channels, usually developed perpendicular to the coastline with a clear hydraulic tendency, suggesting the transport of tidal water and/or stream water through them (Figs. 4B and 4C). On the contrary, water dissipation after runoff occurs in the second-order channels, located inside the clusters (Fig. 4C). Finally, the hydrodynamic energy also influenced the internal structure of the stromatolites, where the third-order channels, separating the columns from each other, are the result of differential erosive effects during runoff of water truncating the microbial mats *in vivo* (Fig. 4C). Based on the characterization of hydrodynamic and bathymetric parameters, they suggested that these stromatolites developed in a lower intertidal (ca. 40 cm depth) to shallow subtidal (> 70 cm depth) paleoenvironment, close to the coastline, partially restricted and affected by hydrodynamic action.

In the lower part of the same section, Frías-Saba *et al.* (2021) described a new microbialitic level composed of domical shapes up to 25 cm. The internal morphology of these domes shows a basal sector with columnar structures alternating with laminated structures and an upper sector with well-developed columns separated by the third-order channels, similar to those described by Villafañe *et al.* (2021). The authors suggested that these microbialites developed in a subtidal/intertidal environment with moderate to high hydrodynamic energy were controlled by a shallowing upward process.

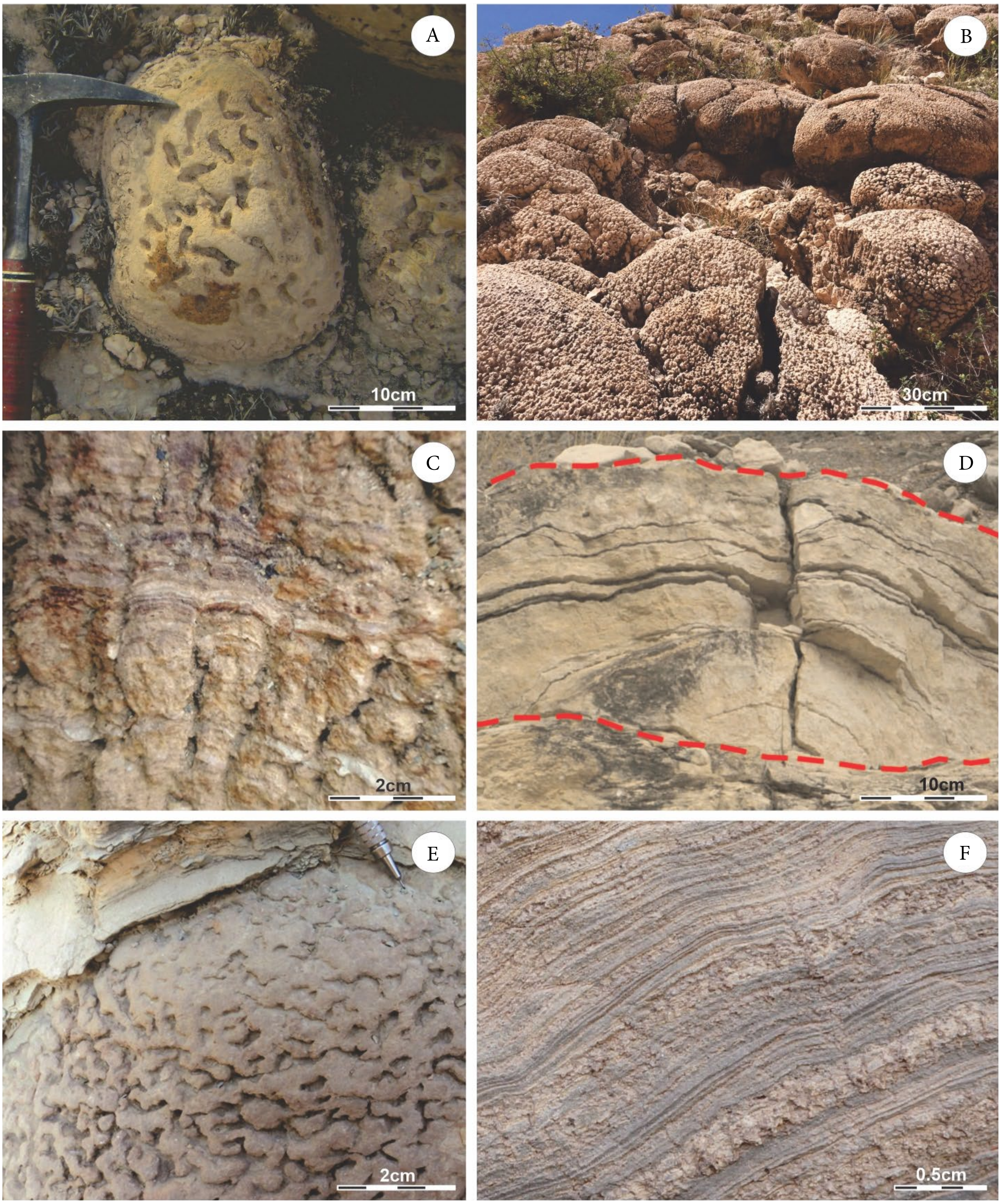
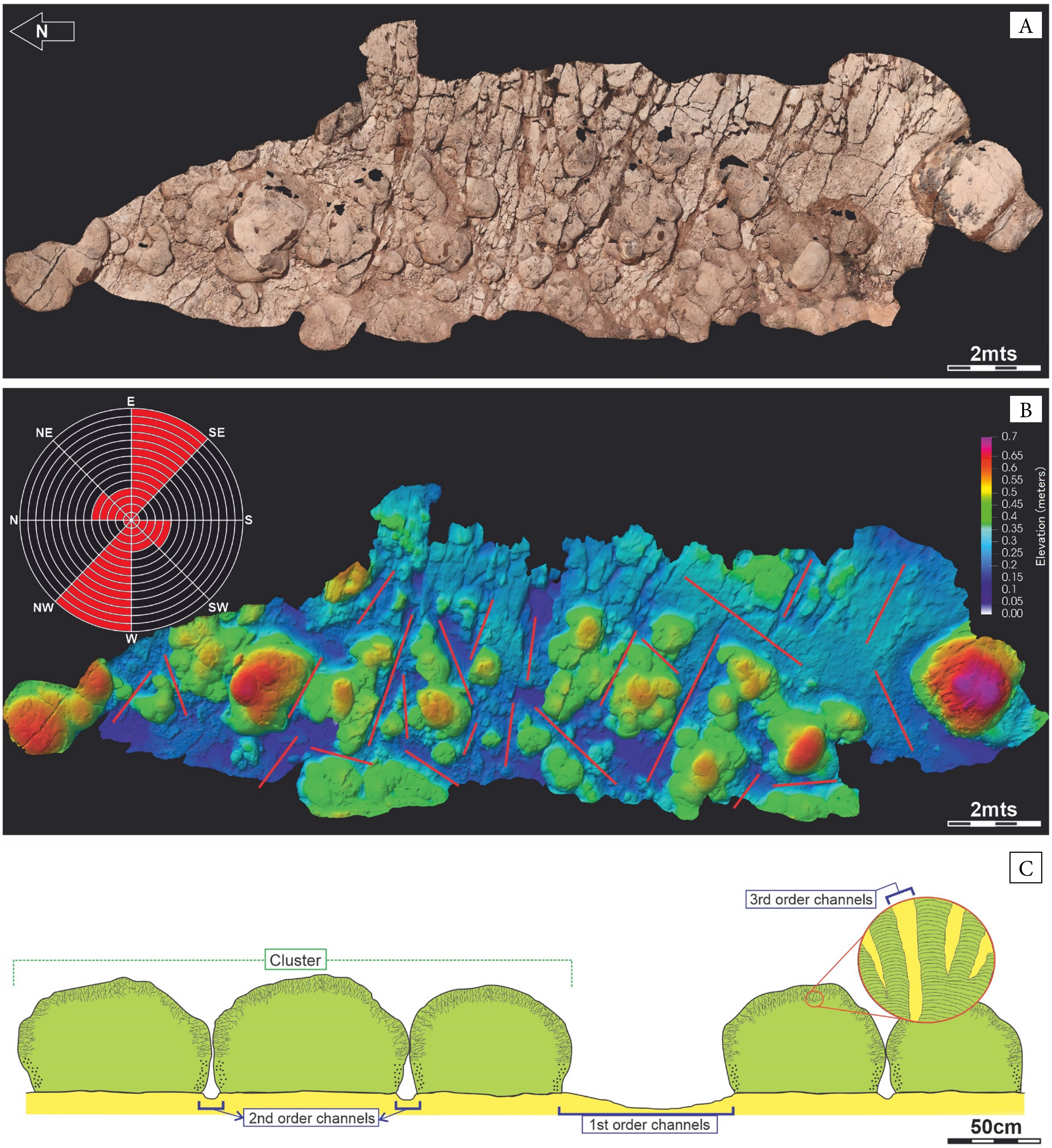


Figure 3. Microbialites of different morphologies observed throughout the geological record of the Yacoraite Formation. (A) Pucalithus domic stromatolites reported by Cónsole-Gonella *et al.* (2012) in Maimará, Jujuy (Tres Cruces sub-basin). (B) Cerebroid stromatolitic levels, preserved in three dimensions, reported by Villafañe *et al.* (2021) in Maimará, Jujuy (Tres Cruces sub-basin). (C) Stromatolites with columnar internal structure (SH) reported by Roemers-Oliveira *et al.* (2015) at Vapumas outcrop (Balbuena III Sequence), Salta (Metán sub-basin). (D) Domic stromatolites reported by Bunevich *et al.* (2017) in Cabra Corral dam (Sequência Balbuena IV), Salta (Metán sub-basin). (E) Cerebroid stromatolitic levels (plan view) reported by Roemers-Oliveira *et al.* (2015) at Vapumas outcrop (Balbuena III Sequence), Salta (Metán sub-basin). (F) Coarse-grained agglutinating microlumpy type stromatolites, Bunevich *et al.* (2017) in Cabra Corral dam (Sequência Balbuena IV), Salta (Metán sub-basin).

Microbialites in Metán-Alemanía sub-basin

In the Metán sub-basin, most of the works focused on the description and interpretation of microbialites were carried out in the Cabra Corral dam area and its surroundings. Microbialites have different stratigraphic positions, spanning in Maastrichtian-Danian time.

Initially, Gabaglia *et al.* (2011) conducted a comprehensive cyclostratigraphic and climatic study of the Balbuena Supersequence, in which they report microbialitic intervals



Source: modified from Villafañe *et al.* (2021).

Figure 4. Stromatolitic level MNE5 described in the locality of Maimará (Tres Cruces sub-basin). (A) Orthomosaic of the best-preserved group of clusters in the stromatolitic level MNE5. (B) Wind rose plot of the first-order channels. This figure shows a clear hydraulic tendency of the first-order channels in the E/SE-W/NW direction. Wind rose normalized to the horizontal. (C) Channel classification by order and relative dimensions at section view of clusters based on the macro-, meso-, and microstructural description of the stromatolitic level MNE5.

centimetric to metric in thickness. Although they do not perform detailed work on these microbialitic intervals, they suggested that these organo-sedimentary levels developed in a lacustrine environment, but possibly under a subordinate influence of relative open sea-level changes affecting the lacustrine base level.

Roemers-Oliveira *et al.* (2015) identified at least two intervals of stromatolitic levels, ranging from 20 to 50 cm in thickness, in several outcrops of the Balbuena III Sequence (Maastrichtian/Danian) in the Metán sub-basin. The lower stratum is characterized by tabular stromatolites of the LLH type (*sensu* Logan *et al.* 1964), while in the upper stratum the stromatolites are domic of the SH type (*sensu* Logan *et al.* 1964) (Fig. 3C). Both levels have a columnar internal structure and a cerebroid aspect. The authors suggested a closed lacustrine environment, with negative water balance (evaporation > precipitation) and limited sediment input, where these organo-sedimentary structures would have developed in coastal areas in the lacustrine environment under shallow waters (photic zone).

On the contrary, Bunevich *et al.* (2017) worked in the same region but in the Balbuena IV Sequence (Danian) and described three main types of microbiological morphologies, namely, domical (Fig. 3D), tabular, and planar. Based on their intrabioarchitecture, they defined seven types of organo-sedimentary structures:

- coarse-grained agglutinant microbialite;
- banded fasciculate/fine-grained agglutinant microbialite;
- pseudo-microcolumnar micrite-binding microbialite;
- "arbustiforme" fine-grained agglutinant microbialite;
- fine-grained agglutinating dendriform microbialite;
- fine-grained banded microbialite with spherulites;
- coarse-grained agglutinating stromatolite.

These structures are associated with a lacustrine environment with fluctuating climatic conditions and increasing aridity. The climatic variations affected the base level of the lake, as well as the input of siliciclastic sediments, biotic, and geochemical processes, influencing the final morphology of these microbialitic systems.

In the upper part of Yacoraite Formation (Juramento member), Metán Sub-basin, Cónsole-Gonella and Marquillas (2014) described hemispherical dome stromatolites with internal lamination and heights ranging from 90 to 100 cm. The authors suggested that these structures developed in an intertidal or high intertidal environment, with high hydrodynamic energy, episodes of sub-aerial exposure and high salinity.

From this sub-basin, even from an upper position of the Early Paleocene Yacoraite Formation, Gomes *et al.* (2020) reported the presence of two types of organo-sedimentary structures:

- laminated domes (micrite and agglutinated material) with thicknesses ranging from 20 to 110 cm;
- microbialites with tabular geometry and millimeter-thick microbialitic layers interbedded with fangolites and grainstones.

Both levels respond to a lacustrine environment in shoreline positions, subjected to transgressive and regressive variations. Laminated domes are related to periods of relatively high lacustrine level, while microbialites with tabular geometry and millimeter-thick microbialitic layers are related to a reducing environment with high organic matter content.

Finally, near the town of Amblayo (Alemanía sub-basin), Quiroga (2021) described stromatolitic domes of up to 17 cm diameter and 12 cm high. Internally, these domes present two zones of laminated columns developed around a core, giving rise to an internal structure of the SS-I type (*sensu* Logan *et al.* 1964). The author suggests that these organo-sedimentary structures are formed in a shallow intertidal environment under the important hydrodynamic influence, with a marked storm episode that caused the rotation of the structure.

METAZOA-MICROBIALITES INTERACTION

Currently, the role that grazing and burrowing metazoans had in disrupting the Phanerozoic microbial mats that formed microbialites is a major topic of discussion (Rishworth *et al.* 2019). One of the most important structures to understand the interaction between organisms and biogenic substrates is bioclaustrations (*see* Tapanila 2005).

Bioclaustrations have been reported in Cenozoic microbialitic deposits from Wyoming, USA (Eocene) (Lamond and Tapanila 2003); Lodward, Kenya (Pleistocene-Holocene) (Lamond and Tapanila 2003); and Eastern Cape coast, South Africa (Holocene) (Rishworth *et al.* 2019). The study of these structures provides further evidence for the refugia hypothesis, where metazoans are not necessarily restrictive of microbialite integrity under certain conditions (Rishworth *et al.* 2019). However, much remains to be discussed regarding the metazoa–microbialites interaction, and few Phanerozoic records have been studied.

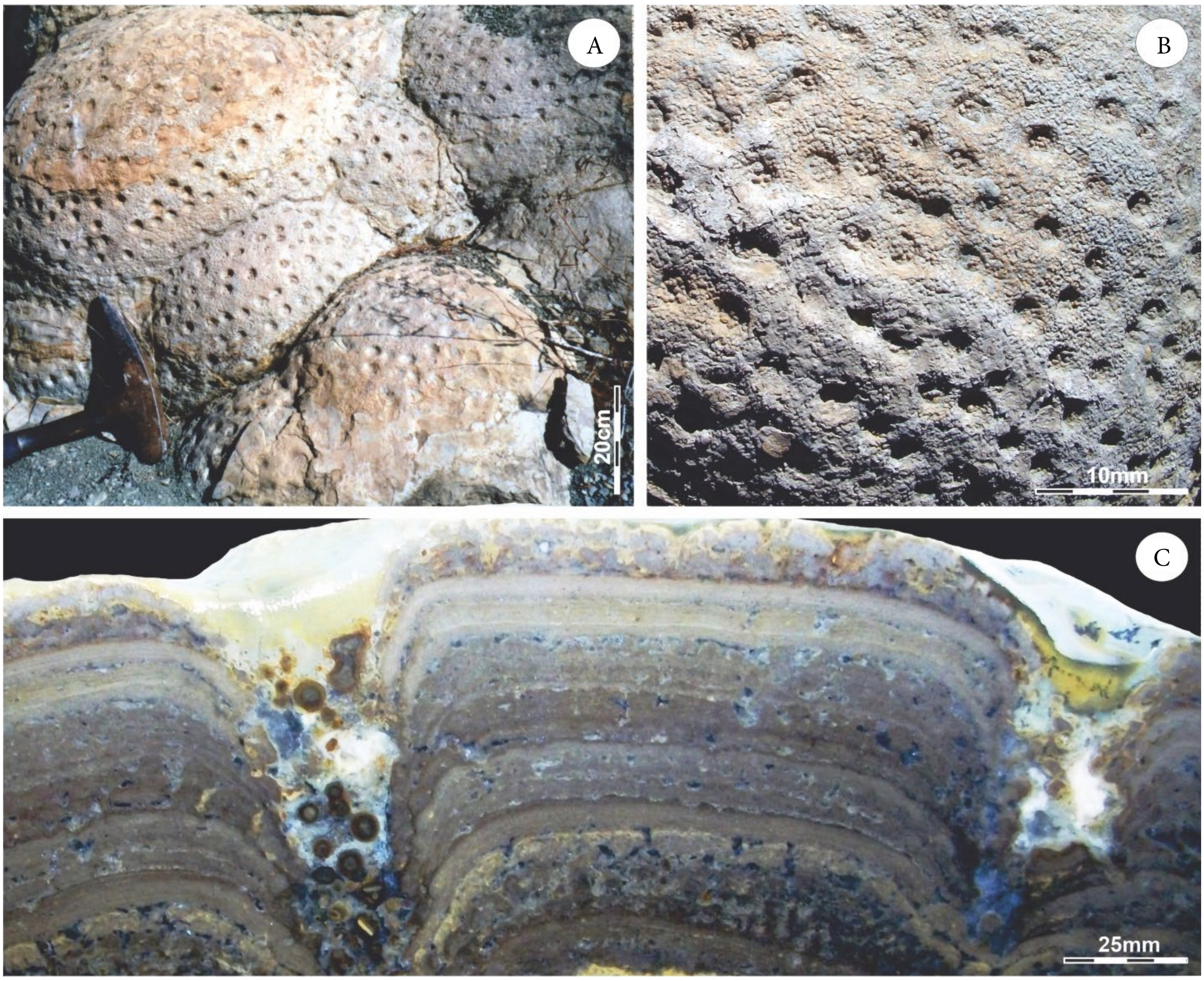
Initially, through a study of gastropods associated with trace fossils in the Yacoraite Formation, Cónsole-Gonella *et al.* (2009) described clavate borings in stromatolites from the Juella locality (Tres Cruces sub-basin). The construction in the opening section of borings immediately distinguishes it from *Trypanites*, and typical *Gatrochaenolites* varies in size in diameter from 2 to 45 mm and length from 3 to 100 mm. This study allowed defining a shallow depositional environment, characteristic of a marine context under high-energy conditions.

In Metan sub-basin, domal stromatolitic boundstones in the shallow carbonate facies at the top of the Yacoraite Formation (Upper Cretaceous-Lower Paleocene) present peculiar cavities interpreted as bioclaustrations (Cónsole-Gonella and Marquillas 2014). This is the oldest reported record of bioclaustrations in stromatolites and the first in shallow marine environments. Bioclaustrations in stromatolites from the Yacoraite Formation have circular cavities that reach 12 mm in diameter (Figs. 5A and 5B). In transversal section, conical morphologies without lateral connection developed parallel to the growth axis of the domes were observed (Fig. 5C). These morphologies provide clear evidence of "*incrustante*"-microbialite symbiosis (Tapanila and Ekdale 2007, Tapanila 2008).

The interpretation of the stromatolitic facies and their stratigraphical/sedimentological context suggests an environmentally stressed shallow high salinity marine setting, represented by an intertidal setting within an extensive tidal flat. From the standpoint of chronostratigraphy, the time at which endobionts colonized the stromatolitic mat coincides with the end of the deposition of the Yacoraite Formation (Cónsole-Gonella and Marquillas 2014).

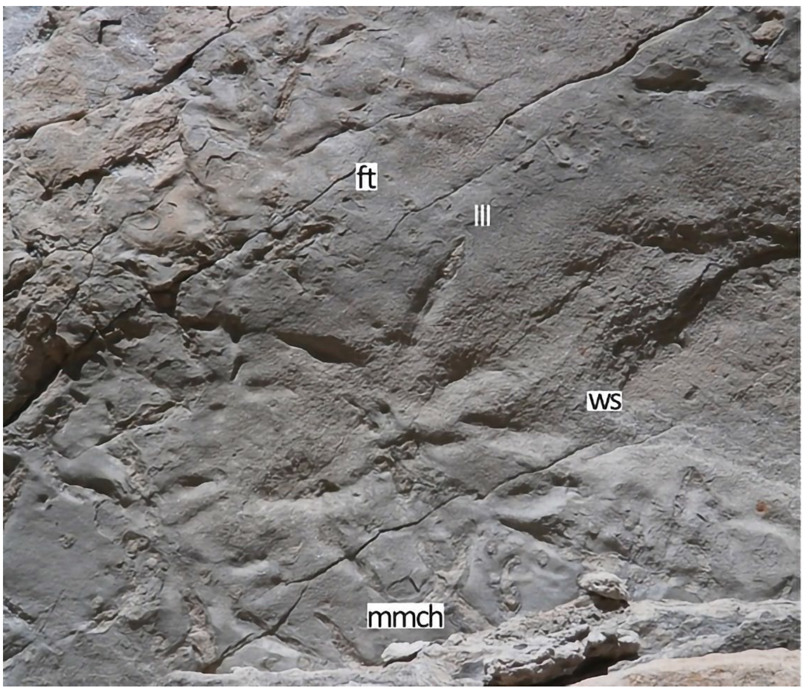
Cónsole-Gonella and Marquillas (2014) demonstrated how the study of bioclaustrations in microbialites can provide important tools for fine-tuning paleoenvironmental and paleobiological reconstructions. They also suggested that deeper neoichnological studies regarding relationship between biofilms and metazoans would probably allow further specification of the possible range of bioclaustration producers on microbialitic substrates.

Paleobiological interaction among avian track-makers, worm-like burrowers, and biofilms have been discussed from Maimará and Quebrada del Tapón ichnosites (de Valais and Cónsole-Gonella 2019) (Fig. 6). The ichnological evidence and the presence of MISS (microbially induced sedimentary structures) seem to support a putative trophic network, composing of at least three levels:



Source: modified from Cónsole-Gonella and Marquillas (2014).

Figure 5. Yacoraite Formation stromatolites and bioclaustrations. (A) Bedding-plane view of stromatolite domes riddled with bioclaustrations cavities. (B) Surface view of stromatolite with bioclaustrations. The cavities are filled with clayey shale and ooids. (C) View of two bioclaustrations structures in cross section.



mmch: microbial mat chips; ws: wrinkle structures; ft: feeding traces; III: digit III impression.

Figure 6. Evidence of paleobiological interaction. Several avian tracks (Gruipeda avis = "Yacoraitichnus avis") from Valle del Tonco, Salta Province, Yacoraite Formation.

- the mats and biofilms as the producers of the paleocommunity, represented by the cyanobacteria, algae, archaea, and unicellular eukaryotes, such as diatoms;
- the herbivores or first-order consumer, represented by invertebrates, and probably some birds, feeding on the microbial mats;
- the second-order consumers or carnivores, performed by others birds eating the invertebrates (de Valais and Cónsole-Gonella 2019).

These feeding strategies resemble those of modern wading birds (Kushlan 1978, Lockley *et al.* 1994). Neoichnological studies have reinforced this concept, showing that low energy stages in such environments allow, first, the establishment of microbial mats, and second, its colonization by the invertebrates, probably food of the wading birds (e.g., Swennen and Van der Baan 1959, Cadée 1990). This type of association seems to be recurrent since the Mesozoic, as suggested by Lockley *et al.* (1994) and Doyle *et al.* (2000).

ECONOMIC INTEREST OF MICROBIALITE LEVELS IN THE YACORAITE FORMATION

Actually, more than 60% of the petroleum in the world and 40% of the gas had been found in carbonate-type reservoirs (Schlumberger 2007). In this type of reservoirs, microbialites play an important role. Some well-known examples are, for instance, the Cretaceous Brazilian pre-salt, the Smackover microbial reservoir (Jurassic) in the Little Cedar Creek of Alabama (United States), the microbial carbonates of the Xiaoerbulak Formation (Lower Cambrian) in the Tarim basin (China), or microbialite boundstone in the Cameia Field of Kwanza Basin (Angola) (e.g., Al Haddad and Mancini 2013, Cazier *et al.* 2014, Jinmin *et al.* 2014, Abelha and Petersohn 2018).

The Yacoraite Formation (Maastrichtian-Danian), in northwestern Argentina, is a deposit of similar features and potential economic interest (e.g., Masaferro *et al.* 2004, Starck 2011). This unit has the particularity of including, among its facies, interbedded with parent (shales) and reservoir rocks (carbonate rocks) (Grosso *et al.* 2013). Yacoraite Formation has been studied for exploratory purposes (e.g., Boll and Hernández 1985, Gómez-Omil *et al.* 1989, Boll 1991, Gómez-Omil and Boll 2005, Hernández *et al.* 2008), supported by state agencies through exploration projects for conventional and nonconventional systems of Argentine oil basins made by YPF, S.A. Likewise, it has been included in the Strategic Production Plan (2011–2020) of the Jujuy Province, which highlights a historical productivity of 9,887,000 m^3 for the Caimancito well (Calilegua, Jujuy) and also emphasizes the need to invest in its exploration (Benetti *et al.* 2011).

Another point that arouses interest in the microbialitic facies of the Yacoraite Formation is their potential as an analog for the Brazilian pre-salt. In the past decade, no other country has discovered hydrocarbon volumes similar to those of the Brazilian pre-salt, positioning this country as one of the most important when it comes to satisfying world energy demand (Abelha and Petersohn 2018). This oil province is characterized by large prospects for excellent quality light oil, accumulated in mostly or only partially (depending on dominant interpretation theories on their genesis) microbialitic and bioclastic carbonate facies, and deposited between the Barremian and Aptian (e.g. Rangel and Carminatti 2000, Muniz and Bosence 2015, Thompson *et al.* 2015).

In general terms, the facies assigned to microbialites in the Brazilian pre-salt were developed in lacustrine shallow marine depositional environment during the Sag phase, which suggests that microbial organisms played important roles in sediment production and accumulation (e.g. Borsato *et al.* 2012, Dorobek *et al.* 2012, Lima and De Ros 2019). In Yacoraite Formation, a carbonate-dominated succession has been also deposited during a sag phase in the Salta rift system (Roemers-Oliveira *et al.* 2015). Because of this, numerous works have suggested the microbialites of the Yacoraite Formation as an excellent analog for Brazilian pre-salt microbialites (e.g. Hamon *et al.* 2012, Bunevich *et al.* 2017, Adelinet *et al.* 2018, Deschamps *et al.* 2020, Gomes *et al.* 2020). Using these analogous deposits to increase the knowledge of lacustrine microbialites may be of great importance to make predictions regarding the construction of facies models that may suggest the location of large, stratigraphically significant, lacustrine microbialite reservoirs in the subsurface (Awramik and Buchheim 2012). However, the great variety in the organo-sedimentary facies of this formation limits extrapolations at different scales of work (Rangel and Carminatti 2000, Durieux and Brown 2007, Romero-Sarmiento *et al.* 2019, Gomes *et al.* 2020, Ruiz-Monroy 2021).

From a technical point of view, one of the most important aspects related to microbialitic reservoir extraction is its inherent complexity. This complexity is linked to the variety of processes that influence the pore genesis, which in turn generates variations in the quality and efficiency of these deposits and that can lead to technical risks (e.g. Humbolt 2008, Tonietto *et al.* 2012, Machado *et al.* 2015, Rezende and Pope 2015). Understanding pore genesis and how it relates to microfabric is crucial in the sub-surface mapping, for evaluation of the petrophysical flow units within organo-sedimentary deposits (Ahr *et al.* 2005).

Along Tres Cruces sub-basin, the microstructure of microbialitic levels in Yacoraite Formation is mainly controlled by *in situ* biologically induced carbonatic precipitation and to a lesser extent by "trapping and binding" (Cónsole-Gonella *et al.* 2017, Frías-Saba *et al.* 2021, Villafañe *et al.* 2021). In addition, the microstructure is directly influenced by the hydrodynamic conditions of the environment (Frías-Saba *et al.* 2021, Villafañe *et al.* 2021). Some authors suggest that after the microbial growth, diagenetic processes such as fluid circulation and recrystallization may affect the petrophysical features of these structures, giving rise to a variety of pores (*see* Frías-Saba *et al.* 2021, Villafañe *et al.* 2021).

Villafañe and Cónsole-Gonella (2019) and Villafañe *et al.* (2021) defined different types of pores in one microbialitic level of Maimará section (MNE5): intraparticle, vug, cavern, fenestral, intercrystalline, interparticle (Fig. 7). These have a good interconnectivity and reached a porosity of 29.7%. Different types of fenestral porosity (irregular voids and bubble-like vugs) described in this level support the importance

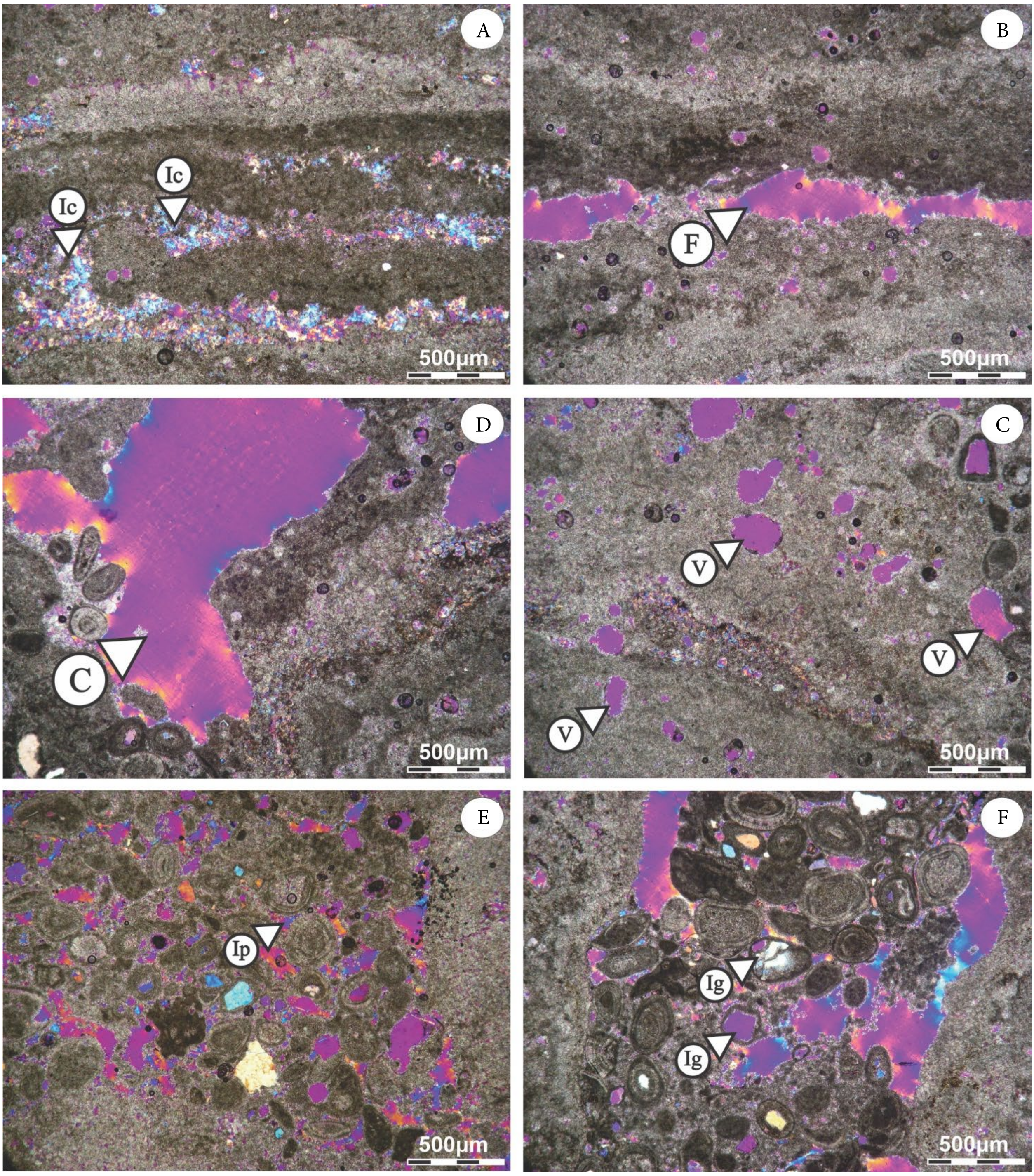


Figure 7. Different types of porosities observed in the stromatolites of the MNE5 level, Maimará, Jujuy (Tres Cruces sub-basin). (A) Intercrystalline porosity (Ic). (B) Fenestral porosity (F), parallel to the lamination. (C and D) Nonselective factory porosity of cavern (c) and vug type (v). (E and F) Cavities filled by clastic material where interparticle (Ig) and intraparticle (Ip) porosity are observed. Modified from Villafañe and Cónsole-Gonella (2019).

of understanding the role of biological activity for better evaluating the petrophysical characteristics of these systems (*see* Villafañe *et al.* 2021). In addition, the same succession shows diagenetic processes, such as dolomitization, that can also affect the pore genesis and the porosity percentages (Villafañe and Cónsole-Gonella 2019, Frías-Saba *et al.* 2021) (Fig. 8).

The growth of the microbialitic levels described in Metán-Alemanía sub-basin is controlled both by *in situ* biologically induced carbonatic precipitation and "trapping and binding". This allows different primary porosities among which we can mention intraparticle, intercrystalline, and fenestral porosities (Roemers-Oliveira *et al.* 2015, Bunevich *et al.* 2017, Gomes *et al.* 2020). As in the Tres Cruces sub-basin, post-depositional processes increase the pore rates. Some of them are related to dissolution and dolomitization (Bunevich *et al.* 2017, Gomes *et al.* 2020), while others are biologically induced, such as bioerosion (Cónsole-Gonella and Marquillas 2014).

CONCLUDING REMARKS

Based on the number of deposits mentioned in this work, the Yacoraite Formation represents one of the most

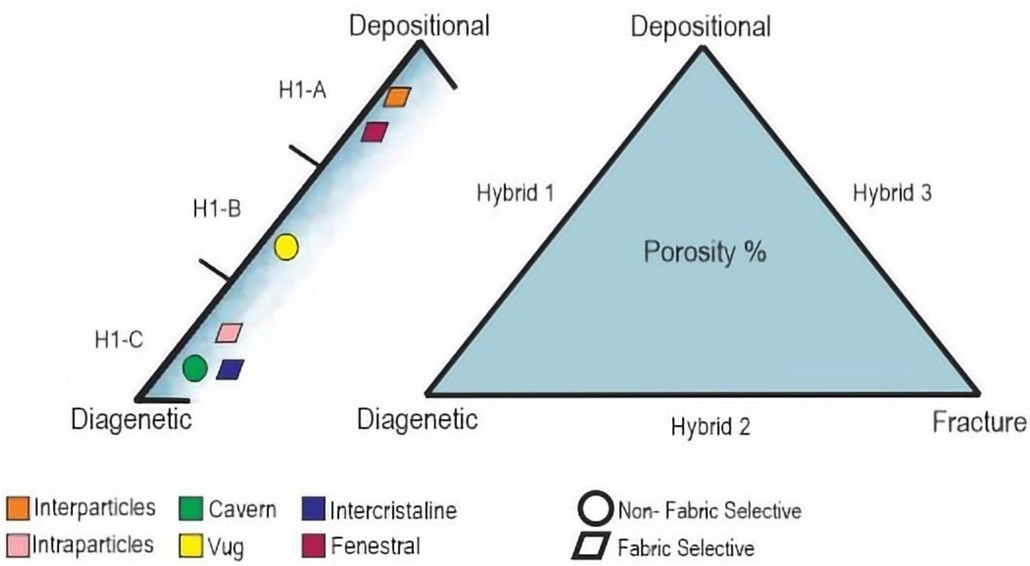


Figure 8. Different porosity types of the Yacoraite Formation described by Villafañe and Cónsole-Gonella (2019) plotted in the triangle classification of Ahr *et al.* (2005) modified by Humbolt (2008). Villafañe and Cónsole-Gonella (2019) described the whole interconnection of the pores as high, except for the vug type. Even when this type of porosity is post-depositional, the interconnection increases directly with the diagenesis (e.g., making cavern types).

important microbialitic records in Argentina and South America. Although the presence of these organo-sedimentary structures was initially limited to brief mentions or descriptions, in the past 20 years, these microbialites of Yacoraite Formation have been deeply discussed in studies that focused on the understanding of the dynamics of the systems, considerably increasing their importance for economic geology.

The microbialitic deposits occur in different sub-basins occupying different stratigraphic positions within the Yacoraite Formation. The Tres Cruces and Metán sub-basins show the highest abundance of microbialites. In the Tres Cruces sub-basin, microbialites are restricted to the Maastrichtian, while in Metán sub-basin, they range from the Maastrichtian to the Danian.

These microbialitic beds are associated with diverse paleoenvironmental conditions, resulting in a great variety of structures and morphologies, which respond mainly to hydrodynamic energy, bathymetry and the mineral saturation/sedimentary input ratio. As several authors have shown, these records represent reliable and high-resolution proxies for understanding regional environmental changes through time. In addition, some deposits provide the possibility to discuss important ecological paradigms, such as the relationship between biofilms and metazoans.

In general, microbialites of Yacoraite Formation show promising petrophysical conditions to be evaluated as reservoir rocks. However, it is important to highlight that these porosity values are directly affected by the microbial (and diagenetic) activity, being necessary to carry out new studies in order to model the porosity-microstructure relationship.

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PGV.: Term, conceptualization, methodology, investigation, writing – original draft, writing – review & editing, visualization, and supervision. RCF-S: Term, conceptualization, methodology, investigation, writing – original draft, writing – review & editing, and visualization. MD-V: Term, conceptualization, methodology, investigation, writing – original draft, writing – review & editing, and visualization. PC: Term, conceptualization, methodology, investigation, writing – original draft, writing – review & editing, and visualization. ID-M.: Term, conceptualization, methodology, investigation, writing – original draft, writing – review & editing, and visualization. SV: Term, conceptualization, methodology, investigation, writing – original draft, writing – review & editing, visualization, supervision, and funding acquisition. FGA: Visualization and supervision. RAM: Visualization and supervision. CC-G: Term, conceptualization, methodology, investigation, writing – original draft, writing – review & editing, visualization, supervision, and funding acquisition.

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REFERENCES

Abelha M., Petersohn, E. 2018. The state of the art of the Brazilian pre salt exploration. *Search and Discovery Article*, **30586**:20-23.

Aceñolaza F.G., Toselli A.J. 1981. *Geología del Noroeste Argentino*. Facultad de Ciencias Naturales e Instituto Miguel Lillo, Universidad Nacional de Tucumán, Tucumán, 212 pp.

Adelinet M., Deschamps R., Rohais S., Bemer E., Hamon Y., Labat K., Sciuma M. 2018. Facies classification in lacustrine carbonates derived from geophysical data, comparison between outcrop and core measurements. *In*: AAPG Europe Regional Conference, Global Analogues of the Atlantic Margin. Lisbon, Portugal.

Ahr W.M., Allen D., Boyd A., Bachman H.N., Smithson T., Clerke E., Gzara K., Hassall J.K., Murty C.R.K., Zubari H., Ramamoorthy R. 2005. Confronting the carbonate conundrum. *Oilfield Review*, **17**(1):18-29.

Al Haddad S., Mancini E.A. 2013. Reservoir characterization, modeling, and evaluation of Upper Jurassic Smackover microbial carbonate and associated facies in Little Cedar Creek field, southwest Alabama, eastern Gulf coastal plain of the United StatesSmackover Microbial Carbonate and Associated Facies in Little Cedar Creek Field. *AAPG Bulletin*, **97**(11):2059-2083. https://doi.org/10.1306/07081312187

Alonso R.N. 1980. Icnitas de dinosaurios (Ornithopoda, Hadrosauridae) en el Cretácico superior del Norte de Argentina. *Acta Geológica Lilloana*, **15**(2):55-63.

Alonso R.N., Marquillas R.A. 1986. Nueva localidad con huellas de dinosaurios y primer hallazgo de huellas de aves en la Formación Yacoraite (Maastrichtiano) del Norte Argentino. *In*: Congreso Argentino de Paleontología y Bioestratigrafía, 4., 1986, Mendoza. *Actas*, **2**:33-41.

Awramik S.M., Buchheim H.P. 2012. The quest for microbialite analogs to the South Atlantic Pre-Salt carbonate hydrocarbon reservoirs of Africa and South America. *Houston Geological Society Bulletin*, **55**(1):21-27.

Benetti W., Malizia L., Rosa R. 2011. Plan Estratégico Productivo de Jujuy 2011-2020. *In*: Benetti W.D. (Ed.). *Minería e Hidrocarburos: Sector Petrolero*. Jujuy: Ministerio de Producción, p. 357-361.

Boll A. 1991. Identificación y correlación de secuencias somerizantes del Miembro Las Avispas (Formación Yacoraite), Noroeste Argentino. *In*: Congreso Geológico Argentino, 10., 1991. *Actas*, **2**:153-156.

Boll A., Hernández R. 1985. Área Tres Cruces. Prov. de Jujuy: Análisis estratigráfico-estructural y evaluación como objetivo exploratorio. *Informe YPF*, in press.

Bonarelli G. 1913. Las sierras subandinas del Alto y Aguaragüe, y los yacimientos petrolíferos del distrito minero de Tartagal, departamento de Orán, provincia de Salta. *Anales del Ministerio de Agricultura, Sección Geología, Mineralogía y Minería*, **8**(4):1-50.

Bonarelli G. 1921. Tercera contribución al conocimiento geológico de las regiones petrolíferas subandinas del norte (provincias de Salta y Jujuy). *Anales del ministerio de Agricultura de la Nación*, **4**(1):1-94.

Bonarelli G. 1927. Fósiles de la Formación Petrolífera. *Boletín de la Academia Nacional de Ciencias de Córdoba*, **30**:55-115.

Borsato R., Jones W., Greenhalgh J., Martin M., Roberson R., Fontes C., Markwick P., Quallington A. 2012. South Atlantic conjugate margin: an exploration strategy. *First Break*, **30**(12):79-84. https://doi.org/10.3997/1365-2397.30.12.65620

Brackebusch L. 1883. Estudios sobre la Formación Petrolífera de Jujuy. *Boletín de la Academia Nacional de Ciencias de Córdoba*, **5**:1-50.

Brackebusch L. 1891. *Mapa Geológico de Interior de la República Argentina (1875-1888)*. Gotha: Institute Geography de Hellfarth.

Bunevich R.B., Borghi L., Gabaglia G.P., Terra G.J., Freire E.B., Lykawka R., Fragoso D.G. 2017. Microbialitos da Sequência Balbuena IV (Daniano), Bacia de Salta, Argentina: caracterização de intrabioarquiteturas e de microciclos. *Pesquisas em Geociências*, **44**(2):177-202. https://doi.org/10.22456/1807-9806.78270

Burne R.V., Moore L.S. 1987. Microbialites: organosedimentary deposits of benthic microbial communities. *Palaios*, **2**(3):241-254. https://doi.org/10.2307/3514674

Cadée G.C. 1990. Feeding traces and bioturbation by birds on a tidal flat, Dutch Wadden Sea. *Ichnos*, **1**(1):23-30. https://doi.org/10.1080/10420949009386328

Cazier E.C., Bargas C., Buambua L., Cardoso S., Ferreira H., Inman K., Shinol J. 2014. Petroleum geology of Cameia field, deepwater pre-salt Kwanza basin, Angola, West Africa. *In*: AAPG International Conference and Exhibition, Istanbul, Turkey. *Actas*, **4**:14-176.

Cesaretti N.N., Parnell J., Dominguez E.A. 2000. Pore fluid evolution within a hydrocarbon reservoir: Yacoraite formation (upper Cretaceous), northwest basin, Argentina. *Journal of Petroleum Geology*, **23**(4):375-398. https://doi.org/10.1111/j.1747-5457.2000.tb00493.x

Cónsole-Gonella C.A. 2011. *Bioestratigrafía y Paleoambientes del Subgrupo Balbuena, Cuenca Cretácico-Terciaria del Noroeste Argentino (Grupo Salta), en la Subcuenca de Tres Cruces, Provincia de Jujuy*. PhD Thesis, Universidad Nacional de Tucumán, Tucumán, 263 p.

Cónsole-Gonella C.A., Aceñolaza F.G. 2009. Icnología de la Formación Yacoraite (Mastrichtiano-Daniano) al sur de la localidad de Maimará, Cordillera Oriental de Jujuy. Argentina. *Acta Geológica Lilloana*, **21**(2):100-110.

Cónsole-Gonella C.A., Díaz-Martínez I., Citton P., Valais S. 2021. New record of Late Cretaceous vertebrate tracks from the Yacoraite Formation (Juella, Quebrada de Humahuaca, northwestern Argentina): aerial drone survey, preservation and sedimentary context. *Journal of South American Earth Sciences*, **107**:103-116.

Cónsole-Gonella C.A., Griffin M., Aceñolaza F.G. 2009. Gastropods associated with Trace Fossils from Yacoraite Formation (Maastrichtian-Danian), and its paleoenvironmental significance, Jujuy, Northwestern Argentina. *Acta Geologica Sinica*, **83**(5):860-867. https://doi.org/10.1111/j.1755-6724.2009.00122.x

Cónsole-Gonella C.A., Griffin M., Cione A., Gouric Cavalli S., Aceñolaza F.G. 2012. Paleontología de la Formación Yacoraite (Maastrichtiano-Daniano) en el ámbito de la Subcuenca de Tres Cruces, Cordillera Oriental de la provincia de Jujuy, Argentina. *In*: Marquillas R., Salfity J., Sánchez M.C. (eds.). *XIII Reunión Argentina de Sedimentología, Aportes Sedimentológicos a la Geología del Noroeste Argentino*. Salta: Asociación Argentina de Sedimentología, p. 45-56.

Cónsole-Gonella C.A., Marquillas R.A. 2014. Bioclaustration trace fossils in epeiric shallow marine stromatolites: the Cretaceous-Paleogene Yacoraite Formation, Northwestern Argentina. *Lethaia*, **47**(1):107-119. https://doi.org/10.1111/let.12043

Cónsole-Gonella C.A., Valais S., Marquillas R.A., Sánchez M.C. 2017. The Maastrichtian–Danian Maimará tracksite (Yacoraite Formation, Salta Group), Quebrada de Humahuaca, Argentina: environments and ichnofacies implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **468**:327-350. https://doi.org/10.1016/j.palaeo.2016.11.008

Cossman M. 1925. Description de gasteropodes mesozoiques du Nord-Ouest de Argentine. *Com. Museo N.H. Bernardino Rivadavia II, 19. Paleont. Invert.*, **10**:193-209.

Del Papa C., Kirschbaum A., Powell J., Brod A., Hongn F., Pimentel M. 2010. Sedimentological, geochemical and paleontological insights applied to continental omission surfaces: a new approach for reconstructing an Eocene foreland basin in NW Argentina. *Journal of South American Earth Sciences*, **29**(2):327-345. https://doi.org/10.1016/j.jsames.2009.06.004

Deschamps R., Rohais S., Hamon Y., Gasparrini M. 2020. Dynamic of a lacustrine sedimentary system during late rifting at the Cretaceous-Palaeocene transition: Example of the Yacoraite Formation, Salta Basin, Argentina. *The Depositional Record*, **6**(3):490-523. https://doi.org/10.1002/dep2.116

De Valais S., Cónsole-Gonella C. 2019. An updated review of the avian footprint record from the Yacoraite Formation (Maastrichtian-Danian), Northwestern Argentina. *Ichnos*, **26**(3):224-241. https://doi.org/10.1080/10420940.2018.1538982

Díaz-Martínez I., de Valais S., Cónsole-Gonella C. 2016. First evidence of Hadrosauropodus in Gondwana (Yacoraite Formation, Maastrichtian-Danian), northwestern Argentina. *Journal of African Earth Sciences*, **122**:79-87. https://doi.org/10.1016/j.jafrearsci.2016.02.012

Díaz-Martínez I., de Valais S., Console-Gonella C. 2018. New sauropod tracks from the Yacoraite Formation (Maastrichtian–Danian), Valle del Tonco tracksite, Salta, northwestern Argentina. *Journal of Iberian Geology*, **44**(1):113-127. https://doi.org/10.1007/s41513-017-0035-1

D'Orbigny A. 1842. Voyage dans l'Amérique méridionale. *Paléontologie*, **10**:188.

Dorobek S., Piccoli L., Coffey B., Adams, A. 2012. Carbonate rock-forming processes in the Pre-salt "sag" successions of Campos Basin, offshore Brazil: evidence for seasonal, dominantly abiotic carbonate precipitation, substrate controls, and broader geologic implications. *In*: AAPG Hedberg Conference "Microbial Carbonate Reservoir Characterization", Houston Texas. *Actas*, **12**:4-5.

Doyle P., Wood J.L., George G.T. 2000. The shorebird ichnofacies: an example from the Miocene of southern Spain. *Geological Magazine*, **137**(5):517-536. https://doi.org/10.1017/S0016756800004490

Dupraz C., Pattisina R., Verrecchia E. 2006. Translation of energy into morphology: simulation of stromatolite morphospace using a stochastic model. *Sedimentary Geology*, **185**(3-4):185-203. https://doi.org/10.1016/j.sedgeo.2005.12.012

Dupraz C., Reid R.P., Visscher P.T. 2011. Microbialites, Modern. *In*: Reitner J., Thiel V. (Eds.). *Encyclopedia of Earth Sciences Series*. Heildelberg: Springer, p. 617-635.

Durieux C.G., Brown A.C. 2007. Geological context, mineralization, and timing of the Juramento sediment-hosted stratiform copper–silver deposit, Salta district, northwestern Argentina. *Mineralium Deposita*, **42**(8):879-899. https://doi.org/10.1007/s00126-007-0138-2

Frías-Saba R.C., Villafañe P.G., Della-Vedova M., Cónsole-Gonella C., Citton P., Díaz-Martínez I., de Valais S. 2021. Short-term environmental changes in epeiric shallow marine stromatolite facies (YacoraiteFformation, Northwestern Argentina): influence of extrinsic factors in organo-sedimentary fabric. *In*: RAS-VIII CLS, 17., 2021, Paraná. *Actas y Resúmenes*.

Gabaglia R., Bento G.P., Freire E., Terra G., Rodrigues E., Lykawka R. 2011. Cyclostratigraphy and climatic control on microbiol influenced sedimentation (Balbuena Supersequence, Yacoraite Formation, Paleocene, Salta–Argentina. *In*: IAS Meeting of Sedimentology, 28, 2011, Zaragosa. *Resumos*. Krijgslaan: International Association of Sedimentologists, p. 51.

Gomes J.P.B., Bunevich R.B., Tonietto S.N., Alves D.B., Santos J.F., Whitaker F.F. 2020. Climatic signals in lacustrine deposits of the Upper Yacoraite Formation, Western Argentina: evidence from clay minerals, analcime, dolomite and fibrous calcite. *Sedimentology*, **67**(5):2282-2309. https://doi.org/10.1111/sed.12700

Gómez-Omil R. 1982. *Estratigrafía del Subgrupo Balbuena - Grupo Salta, en la Subcuenca de Lomas de Olmedo, Provincia de Salta y Jujuy*. PhD Thesis, Facultad de Ciencias Naturales, Universidad Nacional de Tucumán, Tucumán.

Gómez-Omil R., Boll A. 2005. Cuenca Cretácica del Noroeste Argentino. *Frontera Exploratoria de la Argentina*. p. 63-76.

Gómez-Omil R.J., Boll A., Hernández R.M. 1989. Cuenca cretácico-terciaria del Noroeste argentino (Grupo Salta). Cuencas Sedimentarias Argentinas. *Universidad Nacional de Tucumán, Serie de Correlación Geológica*, **6**:43-64.

Granier B.R.C., Lapointe P. 2022. The KALKOWSKY Project - Chapter II. Wobbly ooids in a stromatolite from the Yacoraite Formation (Argentina). *Carnets Geol.*, **22**(3):111-117. https://doi.org/10.2110/carnets.2022.2203

Groeber P. 1952. Mesozoico, Ándico. *In*: Groeber P., Stipanicic P.N., Mingramm A.R.G. (Eds.). *Geografía de la República Argentina*. Buenos Aires: Sociedad Argentina de Estudios Geográficos GCA, p. 349-54.

Grosso S., López R., Vergani G., O'leary S. 2013. Reservorios carbonáticos naturalmente fracturados en el Yacimiento Caimancito (Formación Yacoraite), cuenca cretácica del noroeste argentino. *Revista de la Asociación Geológica Argentina*, **70**(1):53-69.

Grotzinger J., Knoll A. 1999. Stromatolites in Precambrian carbonates: evolutionary mileposts or environmental dipsticks? *Annual Review of Earth and Planetary Sciences*, **27**:313-358. https://doi.org/10.1146/annurev.earth.27.1.313

Grotzinger J.P., Al-Rawahi Z. 2014. Depositional facies and platform architecture of microbialite-dominated carbonate reservoirs, Ediacaran–Cambrian Ara Group, Sultanate of Oman Microbialite Reservoirs in Oman. *AAPG Bulletin*, **98**(8):1453-1494. https://doi.org/10.1306/02271412063

Hamon Y., Rohais S., Deschamps R., Gasparrini M. 2012. Outcrop analogue of pre-salt microbial series from South Atlantic: the Yacoraite Fm, Salta rift system (NW Argentina). *In*: AAPG Hedberg Conference "Microbial Carbonate Reservoir Characterization", Houston. *Proceedings*.

Hernández R., Disalvo A., Boll A., Gómez-Omil R. 1999. Estratigrafía secuencial del Grupo Salta, com enfasis em las subcuencas de Metan-Alemania, noroeste Argentino. *In*: Congreso Geológico Argentino, 14., 1999. Salta. *Relatorio: Geologia del Noroeste Argentino*. Salta: Universidade Nacional de Salta, p. 264-284.

Hernández R., Gómez-Omil R., Boll A. 2008. Estratigrafía, tectónica y potencial petrolero del rift Cretácico en la provincia de Jujuy. *In*: Congreso Geológico Argentino, 17., 2008, Jujuy. *Actas*, p. 207-232.

Humbolt N. 2008. *Genetic pore typing as a means of characterizing reservoir flow units: San Andres, Sunflower field, Terry Country, Texas*. PhD thesis, Texas A & M University, Texas.

Jinmin S.O.N.G., Ping L.U.O., Shisheng Y.A.N.G., Di Y., Chuanmin Z., Pengwei L.I., Xiufen Z.H.A.I. 2014. Reservoirs of Lower Cambrian microbial carbonates, Tarim Basin, NW China. *Petroleum Exploration and Development*, **41**(4):449-459. https://doi.org/10.1016/S1876-3804(14)60051-3

Keidel J. 1910. Estudios geológicos en la Quebrada de Humahuaca, en la de Iruya y algunos de sus valles laterales. *In*: Memoria de la División de Minas, Geología e Hidrología, 1908. *Anales del Ministerio de Agricultura de la Nación*, **5**(11):2.

Kushlan J.A. 1978. Feeding ecology of wading birds. *In*: Ogden J.C., Winckler S. (eds.). *Wading Birds*. New York: National Audubon Society, Sprunt IV A, p. 249-296.

Lamond R., Tapanila L. 2003. Embedment cavities in lacustrine stromatolites: evidence of animal interactions from Cenozoic carbonates in U.S.A. and Kenya. *Palaios*, **18**(4-5):445-453. https://doi.org/10.1669/0883-1351(2003)018%3C0445:ECILSE%3E2.0.CO;2

Leanza A.M. 1969. Sistema de Salta. Su edad, sus peces voladores, su asincronismo con el Horizonte Calcáreo-Dolomítico y con las calizas de Miraflores y la hibridez del Sistema Subandino. *Revista de la Asociación Geológica Argentina*, **24**(4):393-407.

Lima B.E.M., De Ros L.F. 2019. Deposition, diagenetic and hydrothermal processes in the Aptian Pre-Salt lacustrine carbonate reservoirs of the northern Campos Basin, offshore Brazil. *Sedimentary Geology*, **383**:55-81. https://doi.org/10.1016/j.sedgeo.2019.01.006

Lockley M.G., Hunt A., Meyer C. 1994. Vertebrate tracks and the ichnofacies concept: implications for palaeoecology and palichnostratigraphy. *In*: Donovan S.K. (ed.). *The Paleobiology of trace fossils*. Chichester: John Wiley and Sons, p. 241-268.

Logan B.W. 1961. Cryptozoon and associate stromatolites from the recent, Shark Bay, Western Australia. *The Journal of Geology*, **69**(5):517-533.

Logan B.W., Rezak R., Ginsburg R. 1964. Classification and environmental significance of algal stromatolites. *The Journal of Geology*, **72**(1):68-83.

Machado A.S., Dal Bó P.F.F., Lima I., Borghi L., Lopes R. 2015. X-ray microtomography characterization of carbonate microbialites from a hypersaline coastal lagoon in the Rio de Janeiro State—Brazil. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **784**:574-580. https://doi.org/10.1016/j.nima.2014.12.107

Marquillas R. 1984. La Formación Yacoraite (Cretácico Superior) en el río Juramento, Salta: Estratigrafía y ciclicidad. *In*: Congreso Geológico Argentino, 9., 1984, San Carlos de Bariloche. *Actas*, p. 186-196.

Marquillas R. 1985. *Estratigrafía, sedimentología y paleoambientes de la Formación Yacoraite (Cretácico superior) en el tramo austral de la cuenca, Norte Argentino*. PhD Thesis, Universidad Nacional de Salta, Salta, 139 p.

Marquillas R.A. 1986. Ambiente de depósito de la Formación Yacoraite (Grupo Salta, Cretácico-Eocénico), Norte argentino. *In*: Simposio Proyecto 242 PICG-UNESCO, 1., 1986. *Actas*, p. 157-173.

Marquillas R.A., Del Papa C., Sabino I. 2005. Sedimentary aspects and paleoenvironmental evolution of a rift basin: Salta Group (Cretaceous-Paleogene), northwestern Argentina. *International Journal of Earth Sciences*, **94**(1):94-113. https://doi.org/10.1007/s00531-004-0443-2

Marquillas R.A., Del Papa C., Sabino I., Heredia J. 2003. Prospección del límite K/T en la cuenca del Noroeste, Argentina. *Revista de la Asociación Geológica Argentina*, **58**(2):271-274.

Marquillas R.A., Sabino I., Nóbrega Sial A., Del Papa C., Ferreira V., Matthews S. 2007. Carbon and oxygen isotopes of Maastrichtian-Danian shallow marine carbonates: Yacoraite Formation, northwestern Argentina. *Journal of South American Earth Sciences*, **23**(4):304-320. https://doi.org/10.1016/j.jsames.2007.02.009

Marquillas R.A., Salfity J.A. 1989. Distribución regional de los embros de la Formación Yacoraite (Cretácico Superior) em el noroeste argentino. *In*: Simposio Cretácico de América Latina, International Geological Correlation Program-Project, 1989, Buenos Aires. *Actas*, p. 253-272.

Marquillas R.A., Salfity J.A. 1994. Relaciones estratigráficas regionales de la Formación Yacoraite (Cretácico Superior), norte de la Argentina. *In*: Congreso Geológico Chileno, 7., 1994. *Actas*, **1**:479-483.

Marquillas R.A., Salfity J.A., Matthews S.J., Matteini M., Dantas E. 2011. U–Pb zircon age of the Yacoraite Formation and its significance to the Cretaceous–Tertiary boundary in the Salta Basin, Argentina. *In*: Salfity J.A., Marquillas R.A. (eds.). *Cenozoic Geology of the Central Andes of Argentina.* SCS Publisher, p. 227-246.

Masaferro J.L., Bourne R., Jauffred J.C. 2004. Three-dimensional seismic volume visualization of carbonate reservoirs and structures. *Shell International EampP, Technology Applications amp Research* (SEPTAR), 11-41.

Mather K.F. 1922. Front Ranges of the Andes between Santa Cruz, Bolivia, and Embarcacion, Argentina. *Bulletin of the Geological Society of America*, **33**(4):703-764. https://doi.org/10.1130/GSAB-33-703

Mercedes-Martín R., Salas R., Arenas C. 2014. Microbial-dominated carbonate platforms during the Ladinian rifting: sequence stratigraphy and evolution of accommodation in a fault-controlled setting (Catalan Coastal Ranges, NE Spain). *Basin Research*, **26**(2):269-296. https://doi.org/10.1111/bre.12026

Moreno J.A. 1970. Estratigrafía y paleogeografía del Cretácico Superior en la cuenca del noroeste argentino, con especial mención de los Subgrupos Balbuena y Santa Bárbara. *Revista de la Asociación Geológica Argentina*, **24**:9-44.

Moreno M.J., Marquillas R.A. 2009. Estratigrafía del miembro Amblayo (Maastrichtiano) en la subcuenca de Metán del grupo Salta (Cretácico-Paleógeno). *In*: Jornadas de Comunicaciones de la Facultad de Ciencias Naturales, 4., Jornadas de Enseñanza de las Ciencias Naturales de Salta, 2., 2009, Salta. *Actas*, **4**:116.

Muniz M.C., Bosence D.W.J. 2015. Pre-salt microbialites from the Campos Basin (offshore Brazil): image log facies, facies model and cyclicity in lacustrine carbonates. *Geological Society (London), Special Publications*, **418**(1):221-242. https://doi.org/10.1144/SP418.10

Palma R. 1984. *Características sedimentológicas y estratigráficas de las Formaciones en el límite Cretácico Superior-Terciario Inferior, en la Cuenca Salteña*. PhD thesis, Universidad Nacional de Tucumán, Tucumán, 239 p.

Pedrinha S., Gabaglia G., Lykawka R., Dias-Brito D. 2015. High-resolution sequence tracking in Metán-Alemania Sub-basin (Salta Basin Maastrichtian-Argentina): detailed stratigraphic anatomy of a lacustrine system under the influence of microbial processes. *Boletim Técnico da Petrobras*, 23 p.

Quattrocchio M., Ruiz L., Volkheimer W. 2000. Palynological zonation of the Paleogene of the Colorado and Salta Group basins, Argentina. *Revista Española de Micropaleontología*, **32**(1):61-78.

Quiroga L. 2021. *Facies estromatoliticas de la Formación Yacoraite (Maastrictiano-Daniano), Amblayo, Salta: estructura, patrones de crecimiento e implicancias paleoambientales*. Degree Thesis, Universidad Nacional de Tucumán, Tucumán, 62 p.

Rangel H.D., Carminatti M. 2000. Lake Stratigraphy of the Lagoa Feia Formation, Campos Basin, Brazil. *In*: Gierlowski-Kordesch E.H., Kelts K.R. (Eds.). *AAPG Studies in Geology*. America Association of Petroleum Geologists, 46, Chapter 18. https://doi.org/10.1306/St46706C18

Reyes F.C. 1972. Correlaciones en el Cretácico de la cuenca Andina de Bolivia, Perú y Chile. *Revista Técnica YPFB*, **1**:101-144.

Rezende M.F., Pope M.C. 2015. Importance of depositional texture in pore characterization of subsalt microbialite carbonates, offshore Brazil. *Geological Society of London Special Publications*, **418**(1):193-207. https://doi.org/10.1144/SP418.2

Riding R.E. 2008. Abiogenic, microbial and hybrid authigenic carbonate crusts: components of Precambrian stromatolites. *Geologica Croatia*, **61**(2-3):73-103.

Riding R.E. 2011. The Nature of Stromatolites: 3,500 million years of history and a century of research. *In*: Reitner J., Queric N., Arp G. (eds.). *Advances in Stromatolite Geobiology*. Berlin, Heidelberg: Springer, p. 29-74.

Rishworth G.M., Edwards M.J., Cónsole-Gonella C., Perissinotto R. 2019. Modern active microbialite-metazoan relationships in peritidal systems on the Eastern Cape coast of South Africa: Ecological significance and implication for the palaeontological record. *Journal of African Earth Sciences*, **153**:1-8. https://doi.org/10.1016/j.jafrearsci.2019.02.013

Roemers-Oliveira E., Fernandes L.A., Freire E., Simões L.S.A. 2015. Filamentos microbianos em estromatólitos e laminitos da Sequência Balbuena III (Maastrichtiano/Daniano) da Formação Yacoraite na Sub-bacia Metán-Alemania, na região de Salta, Argentina, e seus significados paleoambientais. *Brazilian Journal of Geology*, **45**(3):399-413. https://doi.org/10.1590/2317-488920150030255

Romero-Sarmiento M.F., Rohais S., Littke R. 2019. Lacustrine Type I kerogen characterization at different thermal maturity levels: Application to the Late Cretaceous Yacoraite Formation in the Salta Basin–Argentina. *International Journal of Coal Geology*, **203**:15-27. https://doi.org/10.1016/j.coal.2019.01.004

Ruiz R., Ondrak R., Horsfield B., Rossello E. 2018. Depositional Environment Interpretation from Organofacies Characterization for Yacoraite Fm. outcrop samples, Cretaceous Salta Basin-Argentina. *In*: EGU General Assembly Conference. *Abstracts*, p. 8280.

Ruiz-Monroy R. 2021. *Organic geochemical characterization of the Yacoraite Formation (NW-Argentina)-paleoenvironment and petroleum potential.* PhD thesis, Universität Potsdam, Postdam, 161 p.

Salfity J.A. 1980. *Estratigrafía de la Formación Lecho (Cretácico) en la Cuenca Andina del Norte Argentino*. PhD thesis, Universidad Nacional de Salta, Salta, 91 p.

Salfity J.A. 1982. Evolución paleogeográfica del Grupo Salta (Cretácico-Eogénico), Argentina. *In*: Congreso Latinoamericano de Geología, 5., 1982, Buenos Aires. *Actas*, **1**:11-25.

Salfity J.A., Marquillas R.A. 1994. Tectonic and sedimentary evolution of the Cretaceous-Eocene Salta Group basin, Argentina. *In*: Salfity A. (Ed.). *Cretaceous tectonics of the Andes*. Wiesbaden: Springer-Verlag, p. 226-315.

Schlumberger. 2007. Carbonate reservoirs: meeting unique challenges to maximise recovery. Available at: https://www.slb.com/~/media/Files/industry_challenges/carbonates/brochures/cb_carbonate_reservoirs_07os003.pdf. Accessed on: 20 March 2022.

Schwab K. 1984. Contribución al conocimiento del sector occidental de la cuenca sedimentaria del Grupo Salta (Cretácico-Eogénico) en el noroeste argentino. *In*: Noveno Congreso Geológico Argentino, Bariloche. *Actas*, **1**:586-604.

Sial A.N., Ferreira V.P., Toselli A.J., Parada M.A., Aceñolaza F.G., Pimentel M.M., Alonso R.N. 2001. Carbon and oxygen isotope compositions of some Upper Cretaceous–Paleocene sequences in Argentina and Chile. *International Geology Review*, **43**(10):892-909. https://doi.org/10.1080/00206810109465054

Starck D. 2011. Cuenca Cretácica-Paleógena del noroeste argentino. *In*: Congreso de Exploración y Desarrollo de Hidrocarburos, 8., 2011, Mar del Plata, Argentina. Simposio Cuencas Argentinas: Visión Actual, Instituto Argentino del Petróleo y el Gas. *Actas*, **8**:407-453.

Steinmann G. 1906. Die Entsthung der Kupfererzlagerstätte von Corocoro und verwandter Vorkommnisse in Bolivia. *Festschrift zum*, **70**:335-368.

Steinmann G., Hoek H., Bistram A. 1904. Zur Geologie des Südostlichen Boliviens. Zentralblatt für Mineralogie. *Geologie und Paläontologie*, 1-4.

Suosaari E.P., Reid R.P., Playford P.E., Foster J.S., Stolz J.F., Casaburi G., Eberli G.P. 2016. New multi-scale perspectives on the stromatolites of Shark Bay, Western Australia. *Scientific Reports*, **6**:20557. https://doi.org/10.1038/srep20557

Swennen C., Van der Baan G. 1959. Tracking birds on tidal flats and beaches. *British Birds*, **12**:15-18.

Tapanila L. 2005. Palaeoecology and diversity of endosymbionts in Palaeozoic marine invertebrates: trace fossil evidence. *Lethaia*, **38**(2):89-99. https://doi.org/10.1080/00241160510013123

Tapanila L. 2008. The endolithic guild: an ecological framework for residential cavities in hard substrates. *In*: Wisshak M., Tapanila L. (eds.). *Current developments in bioerosion*. Berlin, Heidelberg: Erlangen Earth Conference Series, Springer-Verlag, p. 3-20.

Tapanila L., Ekdale A.A. 2007. Early history of symbiosis in living substrates: trace-fossil evidence from the marine record. *In*: Miller W., III (ed.). *Trace fossils:* concepts, problems, prospects. Arcata"Elsevier, p. 339-349.

Terra G.J.S., Babaglia G.P.R., Freire E.B., Lykawka R., Bunevich R.B., Hernandez R., Hernandez J. 2015. Balbuena Supersequence, Salta Basin, Argentina: a good analog for Phanerozoic lacustrine microbialite-bearing reservoirs. *In*: Carbonate plays around the World-analogues to support exploration and development. *Abstracts*. American Association of Petroleum Geologists Bulletin, Geoscience Technology Workshop. https://doi.org/10.13140/RG.2.1.4543.1442

Thompson D.L., Stilwell J.D., Hall M. 2015. Lacustrine carbonate reservoirs from Early Cretaceous rift lakes of Western Gondwana: Pre-salt coquinas of Brazil and West Africa. *Gondwana Research*, **28**(1):26-51. https://doi.org/10.1016/j.gr.2014.12.005

Tomás S., Vallati M., Galli C., Mutti M. 2022. Are stromatolite morphologies and fabrics good paleoenvironmental proxies? An example from the Salta Basin (Argentina). *In*: *Copernicus Meetings*. Vienna, Austria, N° EGU22-11997.

Tonietto S.N., Shane E.K., Ahr W.M., Pope, M.C. 2012. Pore type characterization and petrophysical properties on microbial carbonate reservoirs. *In*: AAPG Hedberg Conference. Houston, Texas. Microbial Carbonate Reservoir Charaterization. *Procedures*.

Turner J.C.M. 1959. Estratigrafía del cordón de Escaya y de la sierra de Rinconada (Jujuy). *Revista de la Asociación Geológica Argentina*, **13**(1-2):15-41.

Valencio D.A., Mendía J.E., Giudici A., Gascon J.O. 1977. Palaeomagnetism of the Cretaceous Pirgua Subgroup (Argentina) and the age of the opening of the South Atlantic. *Geophysical Journal International*, **51**(1):47-58. https://doi.org/10.1111/j.1365-246X.1977.tb04189.x

Villafañe P.G. 2016. *Facies estromatolíticas de la formación yacoraite (maastrictiano-daniano) maimará, provincia de jujuy. Significado geológico e implicancias paleoambientales*. Degree Thesis, Universidad Nacional de Tucumán, Tucumán, 105 p.

Villafañe P.G., Cónsole-Gonella C. 2019. Microfabric analysis and poral characterization of microbialites: Yacoraite Formation, Maimará, Jujuy, Argentina. *In*: YES Network Congress, 5., 2019, Berlín, Germany. *Procedures*.

Villafañe P.G., Cónsole-Gonella C., Citton P., Díaz-Martínez I., de Valais S. 2021. Three-dimensional stromatolites from Yacoraite Formation (Maastrichtian-Danian, Argentina): Modeling and assessing hydrodynamic controls on growth patterns. *Geological Magazine*, **158**(10):1756-1772. https://doi.org/10.1017/S0016756821000315

Viramonte J., Alonso R.N., Gutierrez R., Argañaraz R. 1984. Génesis del litio en los salares de la Puna Argentina. *In*: Congreso Geológico Argentino, 9., 1984, San Carlos de Bariloche. *Actas*, **3**:471-481.