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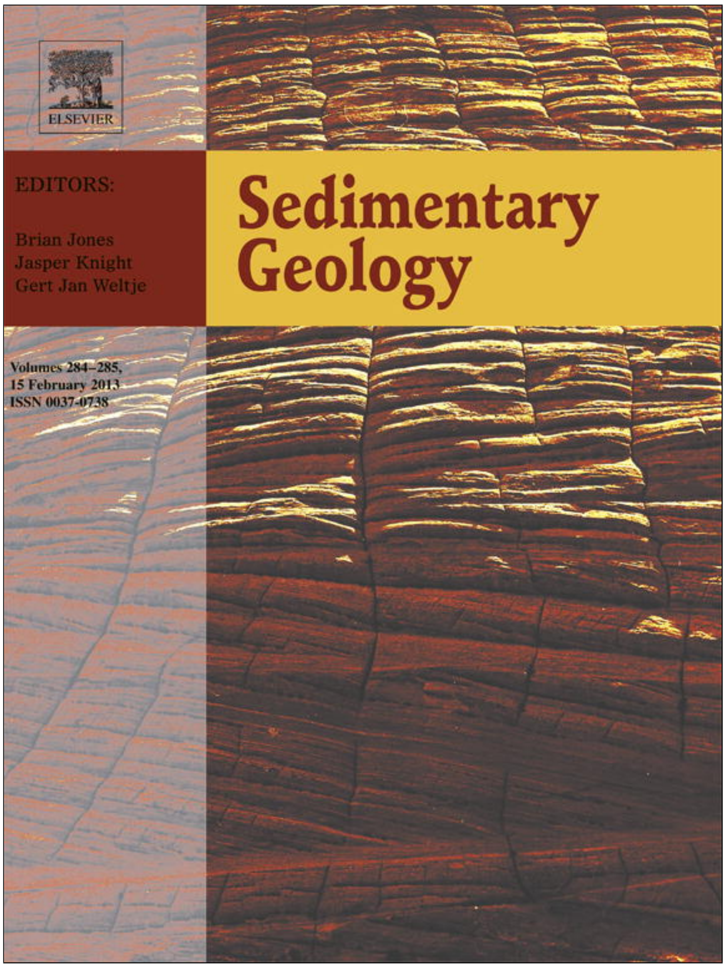

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Sedimentology and paleoenvironments of the Las Chacritas carbonate paleolake, Cañadón Asfalto Formation (Jurassic), Patagonia, Argentina

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ABSTRACT

The Las Chacritas Member is the lower part of the Cañadón Asfalto Formation (Jurassic). The unit is a completely continental limestone succession with volcanic contributions that were deposited during the development of the Cañadón Asfalto Rift Basin (Chubut province, Patagonia, Argentina). A detailed sedimentological analysis was performed in the Fossati depocenter to determine the paleoenvironments that developed in the context of this rift. The Las Chacritas Member represents a carbonate paleolake system with ramp-shaped margins associated with wetlands that were eventually affected by subaerial exposure and pedogenesis. This process is represented by three main subenvironments: a) a lacustrine setting sensu stricto (lacustrine limestone facies association), represented by *Mudstones/Wackestones containing porifera spicules* (F1), *Intraclastic packstones* (F6) and *Tabular stromatolites* (F10) in which deposition and diagenesis were entirely subaqueous; b) a palustrine setting (palustrine limestone facies association) containing *Microbial Mudstones* (F2), *Intraclastic sandy packstone with ostracode remains* (F3), *Oncolitic packstone* (F5), *Brecciated limestone* (F7) and *Nodular-Mottled limestone* (F8) representing shallow marginal areas affected by groundwater fluctuations and minor subaerial exposure; and c) a pedogenic paleoenvironment (pedogenic limestone facies association) including *Intraclastic limestone* (F4) and *Packstones containing Microcodium* (F9) facies displaying the major features of subaerial exposure, pedogenic diagenesis and the development of paleosols. The fluvial–palustrine–lacustrine succession shows a general shallow upward trend in which contraction–expansion cycles are represented (delimited by exposure and surface erosion). The variations in the successive formations reflect the responses to fluctuations in a combination of two major controls, the tectonic and local climatic variables. The predominance of the palustrine facies associations was determined by its accommodation space as well as the local climate conditions. The variations in the lacustrine limestone facies associations reflect differential patterns of subsidence within the sub-basin. The diagnostic features of the palustrine limestone facies associations (organic matter (OM) content, microinvertebrate fauna, abundant mud cracks, brecciation, presence of evaporitic minerals) frame the sub-basin in a climatic context intermediate between arid and subhumid conditions.

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1. Introduction

Africa and South America separated from each other during the Early Jurassic period due to the dismemberment of Gondwana. This separation produced structural changes resulting from tensional strains deep in the basement faults and the transtentional reactivation of old structural systems related to the widespread extension (Kay et al., 1989). These processes originated rift basins in West Gondwana (Figari and Courtade, 1993; Cortiñas, 1996; Ramos et al., 2010) such as the Cañadón Asfalto Basin. This basin resulted from extensional forces that caused individual asymmetric graben sub-basins (Silva Nieto et al., 2002b) and is located in the center of Chubut province, Patagonia Extrandina, Argentina (Silva Nieto et al., 2002a) (Fig. 1).

The Cañadón Asfalto Basin possesses the most complete sedimentary transtensional tectonic sequences of the slip-strike or pull-apart variety (Silva Nieto et al., 2002a) or *prerift–synrif–postrift* deposits (Figari et al., 1996; Figari, 2005) and paleontologic record in the continental Jurassic in South America. This basin provides opportunities for studies of the evolution of the complete rifting in the western margin of Gondwana. In addition, this basin includes the thickest known sequences containing a record of the changes in the lacustrine and fluvial systems over time (Cabaleri and Armella, 1999; Cabaleri et al., 2005, 2010a) in a seasonal climate with a dry–wet regime (Rees et al., 2000; Volkheimer et al., 2011). Moreover, outcroppings are widely distributed throughout

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the basin, covering an area of 30,000 km^2, which allows for interpretation of coeval deposits in different sub-basins and provides the opportunity to establish regional correlations and perform paleogeographic reconstructions.

The stratigraphy of the unit was defined by Stipanicic et al. (1968). The paleontologic records of the Cañadón Asfalto Formation are numerous and include those of vertebrates (Bonaparte, 1986; López-Arbarello et al., 2002; López Arbarello, 2004; Rauhut, 2006) and invertebrates (Tasch and Volkheimer, 1970; Vallatti, 1986; Musacchio, 1989; Musacchio et al., 1990; Musacchio, 1995; Gallego et al., 2010, 2011), in addition to paleobotanic (Escapa et al., 2008) and palynologic (Volkheimer et al., 2008) records. Despite this, there are few sedimentologic reports, and these are focused on the Río Chubut Medio area (Cerro Condor sub-basin, Chubut province) (Cabaleri and Armella, 1999, 2005; Cabaleri et al., 2005, 2010a). Therefore, it is necessary to provide a detailed sedimentologic study of the unit in each sub-basin to establish the evolution of the continental sedimentary systems in each depositional setting.

The focus of this study is the carbonate succession at the Estancia Fossati locality (42°48′56″S and 68º24′58.28″W) situated northwest of the village of El Escorial (Fig.), which is part of the Fossati sub-basin. The aims of this investigation were to reconstruct the initial paleoenvironmental evolution of the carbonate lacustrine system of the Las Chacritas Member of the Cañadón Asfalto Formation at the Estancia Fossati locality (Fossati depocenter) and to determine the expansion and contraction sequences of the system to unravel the role of tectonism and climate in the development of the thick sedimentary sequences.

2. Geologic setting

The Cañadón Asfalto Rift Basin is formed by north-westerly oriented strike half-grabens that delineate three depocenters, namely the Fossati (south-west of Pampa de Gan Gan), Portezuelo–Llanquetrus (south-west of Pampa de Gastre), and Cerro Cóndor (Cerro Cóndor village) depocenters (Figari and Courtade, 1993; Figari et al., 1996). Homovc et al. (1991), Figari and García (1992), Figari et al. (1992, 1996), and Figari and Courtade (1993) determined the tectosedimentary evolution of the Cañadón Asfalto Basin and distinguished four megasequences for the different stages of the half-graben.

The Permian–Triassic (249.7 ± 5.3 Ma, radiometric K/Ar) (López de Luchi and Rapalini, 2002) basement in the Fossati sub-basin is represented by the Mamil Choique Formation (Ravazzoli and Sesana, 1997) (Fig. 2). This unit is unconformably covered by the Las Leoneras Formation (Hettangian–Toarcian) (Nakayama, 1973). The Las Leoneras Formation is covered by the Middle Jurassic volcanic rocks of the Lonco Trapial Formation (Lesta and Ferello, 1972) (K/Ar 173.1 ± 9.4 Ma; Silva Nieto, 2005). A regional unconformity separates the Lonco Trapial Formation from the volcano-sedimentary Cañadón Asfalto Formation (*synrift* stage). The Cañadón Asfalto Formation is unconformably overlaid with the continental deposits of the Los Adobes Formation and the Cerro Barcino Formation (Barremian–Santonian) of the Chubut Group (Lesta, 1968; Codignotto et al., 1979). The Chubut Group sequences developed during a stage of tectonic stability or thermal subsidence (*sag* stage) (Ranalli et al., 2011). In the eastern area (Ea. La Sin Rumbo, Fig. 1), the Cañadón Asfalto Formation is covered by the Paso del Sapo Formation (Campanian/Maastrichtian) (Lesta and Ferello, 1972) and the Lefipán Formation (Lesta and Ferello, 1972). The Paleogene period is represented by the Salamanca Formation and the Eocene–Miocene by basalts (Fig. 2).

The Cañadón Asfalto Formation (Stipanicic et al., 1968) is a thick sedimentary sequence that represents lacustrine and fluvial systems with olivine basalt flows and pyroclastic intercalations at its base (Stipanicic et al., 1968; Nullo, 1983; Turner, 1983; Cabaleri et al., 2010a). The complete volcano-sedimentary unit developed in the Toarcian–Aalenian to Tithonian ages (Salani, 2007; Cabaleri et al., 2010b). The Formation is composed of two members, the Las Chacritas (lower) and the Puesto Almada (upper) Members (Silva Nieto et al., 2003; Cabaleri et al., 2010a; Gallego et al., 2011). The radiometric age (K/Ar) obtained for the Las Chacritas Member at the Cerro Cóndor depocenter is 170 ± 4.4 Ma (Salani, 2007). Similar ages were obtained from radiometric dating (Ur/Pb) (Cabaleri et al., 2010a,b) and palynologic studies (Bajocian–Early Bathonian) (Volkheimer et al., 2008). Cabaleri et al. (2008, 2010b) described the stratigraphy of the Cañadón Asfalto Formation. Cabaleri and Armella (1999, 2005), Cabaleri et al. (2005, 2006, 2008) and Silva Nieto et al. (2007) presented a detailed study of the unit and its sub-basins, paleoenvironments and paleoclimates.

The type locality of the Las Chacritas Member is the Cerro Cóndor locality in the Cerro Cóndor sub-basin. There, the Member is represented by sedimentary rocks interbedded with pyroclastic deposits and basalt flows (Cabaleri and Armella, 1999). The lacustrine facies are brownish-gray homogeneous silicified limestone with chert nodules, planar stromatolites, algal boundstones, intraformational conglomerates and bituminous black shale. At the top of the Member, limestone with mud cracks and symmetric ripples are interbedded with shale containing conchostracans and bivalves. In addition, limestone containing ostracodes, coal remains and Brecciated limestone with evaporitic associations are often present. In some areas, fine-grained sandstone beds with planar cross-stratification and bioturbation features are interbedded with tuffite sandstone and yellowish-gray to white, very fine and massive siliciclastic tuffs. These tuffs are associated with fluvial channel deposits, angular limestone and chert intraclasts and tuff, tuffite, andesite and olivine basalt extraclasts. The olivine basalts correspond to flows and sills up to 20 m in thickness as well as dykes (Cabaleri et al., 2010a). In the upper section of the Las Chacritas Member, there are hyperconcentrated flows deposits containing vertebrate remains (Cabaleri and Armella, 1999).

3. Materials and methods

The study is based on detailed logs of two sections of the Las Chacritas Member of the Cañadón Asfalto Formation at the Estancia Fossati locality. The outcrops cover a belt 2700 m long and 300 m thick that has a stratigraphic thickness of 79 m. The field descriptions include the morphology, size, color, lithology, and relevant characteristics of the beds in vertical succession and lateral variations when there were changes in the sedimentation. A control profile was developed according to Flügel (2004), taking 74 samples on a cm scale. Then, 12 additional samples from each of the previously defined microfacies were taken. Polished slabs and standard thin sections (7.5 cm^2) were prepared from the samples at the Taller de Cortes y Secciones Delgadas, Instituto de Geocronología y Geología Isotópica (INGEIS). The polished slabs were observed using a low-magnification binocular microscope (Leica S8 APO, Switzerland). The thin sections were stained with Alizarin S Red to differentiate calcite from dolomite and were observed and photographed using a petrographic microscope (ZEISS Axioskop 40, Germany). The microfacies were designated F plus a correlative number.

4. Sedimentology of the Las Chacritas Member

The Las Chacritas Member is represented by different main categories of carbonate and associated siliciclastic and volcano-clastic facies (Table 1). Erosive surfaces are common in the carbonate sequence (Fig. 3). The main facies (Table 1) are described below.

4.1. Facies

Mudstones/Wackestones with porifera spicules (F1) (Fig. 4A). This facies occurs as strata overlying the Lonco Trapial Formation (volcanic breccia). The beds are nearly 0.50 m thick and 15 m wide. Thin sections reveal that they are composed of homogeneous micrite and microsparite

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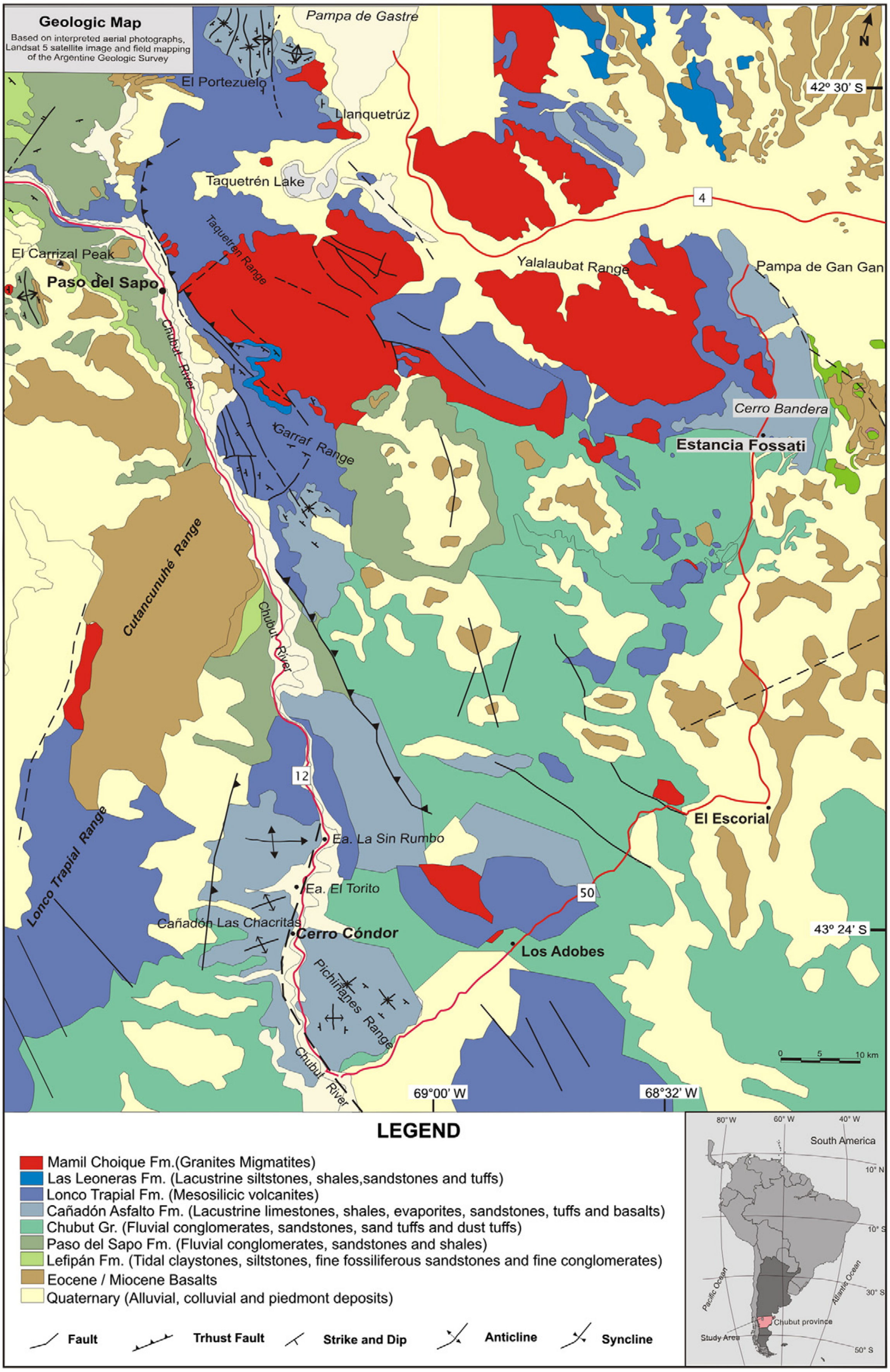

Fig. 1. Location and geologic map of the Estancia Fossati locality. The following main sub-basins are shown: Cerro Cóndor, Fossati and El Portezuelo–Llanquetrus in the Cañadón Asfalto Basin (Jurassic) in the north-central region of Chubut Province, Argentina.

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cement. Microspar constitutes 3–5% of the sample, infilling the pores and associated with micropeloidal micrite. The bioclasts are sponge spicules, horizontally disposed ostracodes represented by articulated valves 100 μm long and 50 μm wide that were recrystallized with spar, and 60 μm fish scales. Horizontally disposed carbonaceous remains approximately 80 μm wide were also observed in the matrix. There are a few siliciclastic grains, represented by quartz, feldspar and fragments of volcanic rock ranging in size from 250 to 600 μm. Elongated horizontal structures up to 300 μm recrystallized with spar and microcrystalline silica disrupt the fabric.

Interpretation: Sponges identified as *Palaeospongilla chubutensis* (Ott and Volkheimer, 1972) are the predominant fauna in this facies, indicating subaqueous deposition with no evidence of subaerial exposure. The structures disrupting the fabric are interpreted as signs of bioturbations of fine-grained sediments that occur in well-oxygenated, low-energy, permanently subaqueous zones of a lacustrine system (Buatois and Mángano, 1995, 1998; Bromley, 1996).

Microbial Mudstones (F2) (Fig. 4B, C). This facies occurs in two tabular laminated beds that are 0.30 m thick. The laminar sets are composed of alternating dark and light laminae. The dark laminae are crenulated and 50 mm thick. These laminae are composed of poorly preserved dark micritic filaments (7 μm long) that appear within clotted micrite and are associated with organic matter. The light laminae (1 cm thick) are composed of microspar with a fenestral fabric consisting of vugs filled with granular calcite and microgranular silica. Coated grains with an irregular cortex and spar nuclei represent the organic matter in the outer margins and dispersed within the matrix. The bioclasts are phytoclasts, charophytes, ostracodes and pelecypod valves. The phytoclasts are aligned and concentrated in and around the dark micrite laminae. The scarce intraclasts (8%) are subangular to rounded and composed of clotted micrite, microcrystalline silica and calcite. The angular siliciclastic (1%) grains are quartz, orthoclase and lithic volcanic particles that are observed only within dark laminae orientated with their major axis parallel to the surface stratification. The microfabric is intensively disrupted by horizontal and vertical structures associated with the coated grains and organic matter.

Interpretation: The laminated morphology of microbialites indicates formation in non-turbulent environments in the marginal areas of a lake system. The particular orientation of the siliciclastic grains suggests the influence of sporadic water movement (turbulence) that transported the intraclasts from the palustrine areas and the angular siliclasts from beach deposits. The latter originated as fluvial detritus concentrated along shorelines (Abbado et al., 2005). Few of the angular siliciclasts were carried by wind. The presence of charophytes indicates a shallow environment. According to Cohen and Thouin (1987), the charophytes indicate bodies of water no deeper than 10 m. Phytoclasts belonging to hygrophyte plants likely developed within shallower areas of the lake, as has been reported by Arenas et al. (2007). The disrupting structures and the coated grains are interpreted as due to rhizobrecciation (Freytet and Plaziat, 1982).

Intraclastic sandy packstones containing ostracode remains (F3) (Fig. 4D). The facies consists of 2-m-thick lenticular limestone layers with cross-bedded trough stratification. The stratum constitutes the top of a repetitive tripartite succession up to 10 m thick that occurs repetitively (Fig. 3). The base of the succession is shale that gradually gives way to reddish-brown laminated, brecciated mudstones. The mudstones are finely laminated; the laminae are 1 mm thick, forming sets that are 1 cm thick. Vertical mud cracks up to 3.5 cm in depth intensively disrupt the lamination in these mudstones. The mudstones contain angular to subrounded clasts of various sizes that are moderately to poorly sorted. The siliciclastic grains (20%) are represented by quartz and feldspar crystals and lithic fragments of basalts, andesite, and metamorphic rocks. The intraclasts (8%) are composed of micrite containing iron oxides and organic matter. The bioclasts (1%) are fragmented and reworked ostracode shells. Pseudospar is commonly found.

Interpretation: The mud cracks observed in the laminated mudstones indicate that desiccation occurred (Arp, 1995). The presence of organic matter (cutans) associated with some fabric-disrupting structures is attributed to rhizobrecciation and the early development of pedogenic processes (Freytet and Plaziat, 1982). Therefore, these sediments are interpreted as having been deposited in a mudflat setting related to a lacustrine system (Smoot and Lowenstein, 1991). The trough cross-stratification of the limestone indicates the effect of fluvial systems. The compositional immaturity of the sediments (quartz, feldspar and lithic fragments) and their angularity suggests their provenance from a proximal area (Jain et al., 2005). The bioclasts originated in shallow lacustrine environments. The fragmentation of the ostracode shells indicates that there were episodes of high energy in the system.

Intraclastic limestones (F4) (Fig. 4E, F). This facies/microfacies type occurs in the lower and upper sections of the log (Fig. 3) and forms tabular beds 0.70 to 1.5 m thick and with 15 m of lateral extent, with ripple cross stratification at the top. Siliciclasts are quartz, feldspar and pyroclastic material (shards). The grain sizes of intraclasts (25%) are very fine to fine sand. They can be chert, microcrystalline silica and calcite in composition, and the major axis is parallel to the stratification plane. Their shape is prolate and angular to subangular. They are moderately well to very well sorted. There are also homogeneous micrite intraclasts (10%), well-rounded, prolate and equidimensional in shape. Bioclasts are small conchostracans (Euestheriidae) (Gallego et al., 2010). Phytoclasts are carbonaceous remains. Calcite individual prisms that are 400 μm in longitudinal section with a central canal preserved as a dark axis are observed. These prisms and phytoclasts are rare (less than 5%). The matrix is micrite with iron oxides. Scarce (2%), concentric circular structures and spheroids approximately 450 μm in diameter with irregular surfaces are found. Also abundant vertically and horizontally oriented structures 8 μm wide and 160 μm long that had been replaced by spar are observed disrupting the microfabric. These structures are associated with cutans.

Interpretation: The calcite prisms with a clear dark central canal strongly resemble *Microcodium*. Kappla (1978) originally considered these structures to be calcified mycorrhizae and later, Freytet and Plaziat (1982) described them to be calcified algae of the rhizosphere. Currently, they are considered to be calcified root cells (Košir, 2004). Calcified roots are common in areas affected by pedogenic processes and also in calcrete profiles, as was observed by Alonso-Zarza and Wright (2010). The structures disrupting the microfabric are interpreted as root bioturbations (rhizobrecciation of Freytet and Plaziat, 1982). Therefore, this facies was deposited in a palustrine setting. The silicification resulted from circulation of silica-rich fluids through the limestone probably during early burial stages. As has been highlighted by Bustillo (2010) these processes are common in palustrine limestones. The frequent presence of well-rounded micrite intraclasts indicates reworking of the intraclasts in the early lithified mud of primary carbonates related to pedogenic processes (Alonso-Zarza et al., 2012).

Oncolitic packstones (F5) (Fig. 4G and H). This facies appears in two tabular beds of 0.60 m and 1.65 m thickness, respectively, both 20 m in length. Oncolites are the main components of the microfacies. Their measurements fall in a range of 280 μm to 2 mm, and they have concentric wavy to strongly crenulated laminations in the cortex with alternating dark and light laminae. The laminae may contain iron oxides. The nuclei are micritic. Radial deposits of micritic structures approximately 40 μm thick were observed in the cortices of some oncolites. The degree of sorting is very well/moderately well sorted, and the fabric is grain-supported. Some oncolites have been deformed and protrude into each other. The bioclasts (5%) are charophytes, ostracodes, gastropods and pelecypods. Carbonaceous remains are also observed dispersed in the matrix. The micritic matrix is reddish-brown, due to the presence of iron oxides and clay minerals. Mud cracks 160 μm long and 40 μm wide are very common. Additionally, vertical structures 2 cm long and 2 mm wide are observed disrupting the fabric with oncolite fragments infill and associated to cutans.

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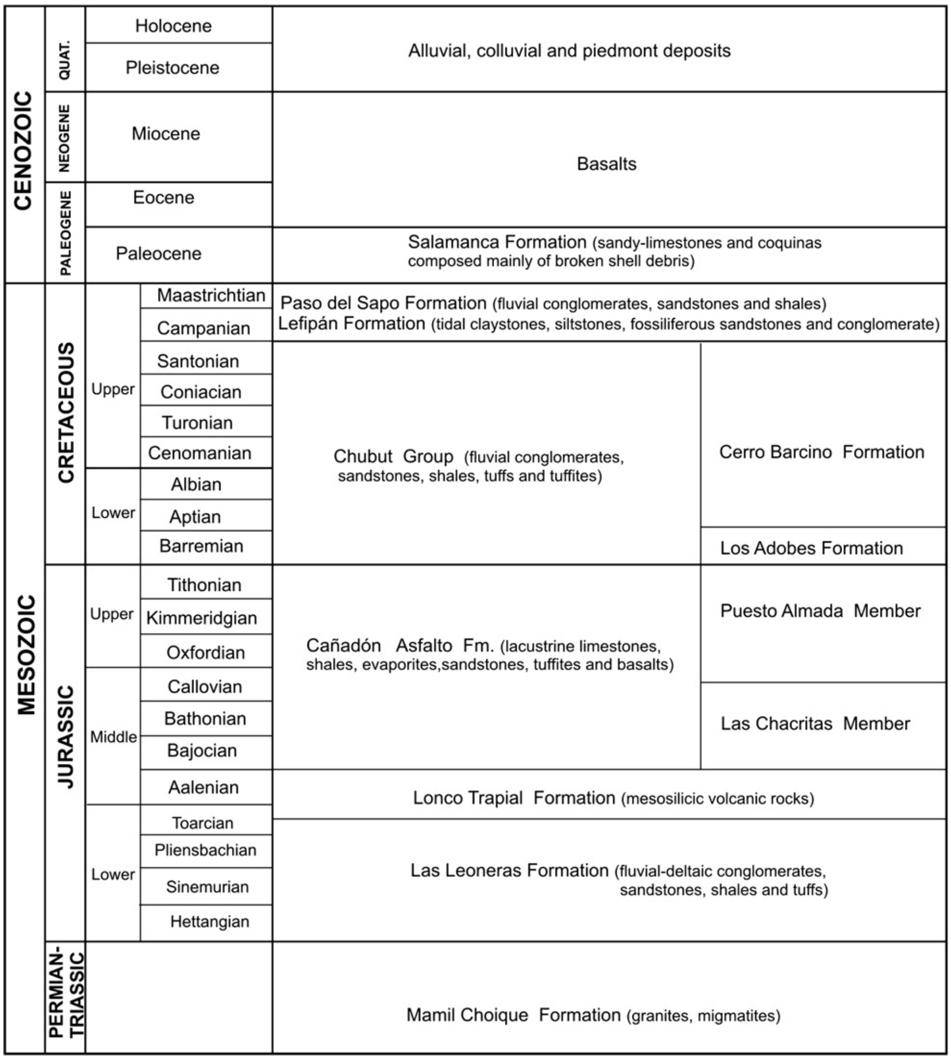

Fig. 2. General stratigraphy of the Fossati sub-basin in Chubut Province, Argentina.

Interpretation: The circular structures observed in the cortices of some oncolites were interpreted as thalli of charopytes that had been strongly modified by diagenesis. Therefore, the oncolites likely formed from the coating of these algae (Arenas et al., 2007; Benavente et al., 2012). The sorting and the grain-supported fabric indicate the deposition of the oncolites in marginal environments of a lake with sporadic desiccation. The carbonaceous remains were reworked and transported. The disrupting structures associated with cutans are capillary root bioturbations (Freytet and Plaziat, 1982). The presence of iron, protruding and deformed oncolites and cracks suggests the diagenetic alteration of the microfabric through compaction (Flügel, 2004). The presence of benthic invertebrates suggests that the waters were well-oxygenated (Gray, 1988) they are also indicators of the quality of the substratum, due to their limited mobility (Bhatacherjee, 2008).

Intraclastic packstones (F6) (Fig. 5A). This facies occurs in tabular beds nearly 1 m thick and approximately 15 m wide that have erosive contacts and the common rippled cross-lamination. Their main components are reworked pebbles (3%) and intraclasts (27%). The pebbles are small (0.5 to 1 mm) micritic grains with the same composition as the matrix. The intraclasts formed in the mud substratum have different compositions: micrite with a fenestral fabric, homogeneous micrite, silica and micrite originating from all the previous microfacies. The intraclasts are coated with micrite-containing rare iron oxides and clays. The bioclasts (3%) are articulated ostracode shells, charophyte algal fragments and fish scales. The oncolites (20%) are concentric, broken or complete, with nuclei of different compositions (spar crystals or shells). The siliciclastic grains (5%) are quartz, orthoclase, plagioclase, basalts, and weathered volcanic rocks. The fabric is grain-supported and poorly to very poorly sorted. The matrix is composed of clotted peloidal micrite and minor amounts of clays and has been partially recrystallized to spar.

Interpretation: The composition of the pebbles (Flügel, 2004) is micritic and is interpreted as carbonate primary mud (Alonso-Zarza and Wright, 2010). Their presence and those of the reworked intraclasts and fragmented oncolites in other microfacies and the ripple cross-stratification and sorting indicate a high-energy shore environment. The siliciclastic grains, particularly those of basalts and weathered volcanic rocks, would indicate a fluvial input. The fragmentation of some of the bioclasts indicates that they were transported into the facies from shore environments.

Brecciated limestones (F7) (Fig. 5B, C). This facies is formed by lenticular bodies that are 11 m long and 0.25–0.50 m thick with erosive bases interbedded with shale. The nodules (60%) are composed of micrite, microspar, laminated micrite with a fenestral fabric or spar, microcrystalline silica, and micrite with microcrystalline silica. They are angular to subrounded, and some are fragmented. The fabric

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Table 1
Summary of the facies associations and the sedimentological and paleoenvironmental characteristics of the lacustrine, palustrine and pedogenic limestones of the Las Chacritas Member.

Facies associations	Facies/microfacies	Fabric	Structures	Bedding	Fossil content	Interpretation	Controls
Lacustrine limestones	Mudstones Wackestones with porifera spicules (F1)	Micritic	Massive	0.50 m thick	Sponge spicules	Subaqueous low energy deposition	Climate and tectonic dominants
	Intraclastic packstone (F6)	Grain-supported, poorly to very poorly sorted	Ripple cross stratification	Tabular beds, 1 to 15 m of lateral extension	Ostracode shells, charophytes and fish scales	High energy subaqueous environment	
	Tabular stromatolites (F10)	Micritic	Flat thin (0.5–10 mm) crenulated lamination, discontinuous couplets (4 to 6 cm). Stromatoids (0.5 to 2 cm).	Tabular beds, 20 m of lateral extension,	–	Subaqueous precipitation	
Palustrine limestones	Microbial Mudstones (F2)	Micritic	Discontinuous crenulated lamination (5 cm)	Tabular beds, 0.30 m thick	Plant debris, charophytes, filamentous algae, ostracodes and pelecypod valves	Calm shallow areas associated to the lake margin	Climate dominant, low tectonic influence
	Intraclastic sandy packstones with ostracode remains (F3)	Intraclastic–bioclastic	Trough cross-bedding stratification. Mud cracks.	Lentiform beds, 2 m thick in 10 m repetitive units	Ostracodes	Mudflat associated to the lake system	
	Oncolitic packstones (F5)	Micritic	Concentric crenulated oncolites (0.2–2 mm)	Tabular beds, 0.60 m and 1.65 m thick respectively, 20 m of lateral extent	–	Environments associated to the marginal lake	
	Brecciated limestones (F7)	Disrupted, nodular and fenestral	Micritic, microsparitic, laminated micritic with fenestral fabric, sparitic and microcrystalline silica nodules	Lenticular beds, 0.25–0.50 m thick, 11 m of lateral extent, erosive bases interbedded with shales	–	Rare subaerial exposure of pond environments	
	Nodular-Mottled limestones (F8)	Mottling, Micritic	Disrupted with diffuse haloes, Nodules and microbial lamination	Tabular carbonate beds (0.5 to 1.5 m thick) interbedded with mudstones 10 m in lateral extent	Bivalves, *Microcodium*	Palustrine environment affected by groundwater fluctuations, high water table and scarce pedogenic features	
Pedogenic limestones	Intraclastic limestones (F4)	Intraclasts and siliciclasts	Scarce oncolites	Tabular beds, 0.70 to 1.5 m thick, 15 m in lateral extent	Conchostracans (Euestheriidae), phytoclasts and *Mycrocodium*	Environments adjacent to the palustrine setting with common pedogenic alteration	Climate dominant, low tectonic influence
	Packstones with Mycrocodium (F9)	Micritic, microsparitic	Disrupted	Tabular beds, 0.60 to 2 m thick, 12 m in lateral extent, interbedded with tuffite levels	*Mycrocodium*, fish scales, ostracodes	Common pedogenic influences	

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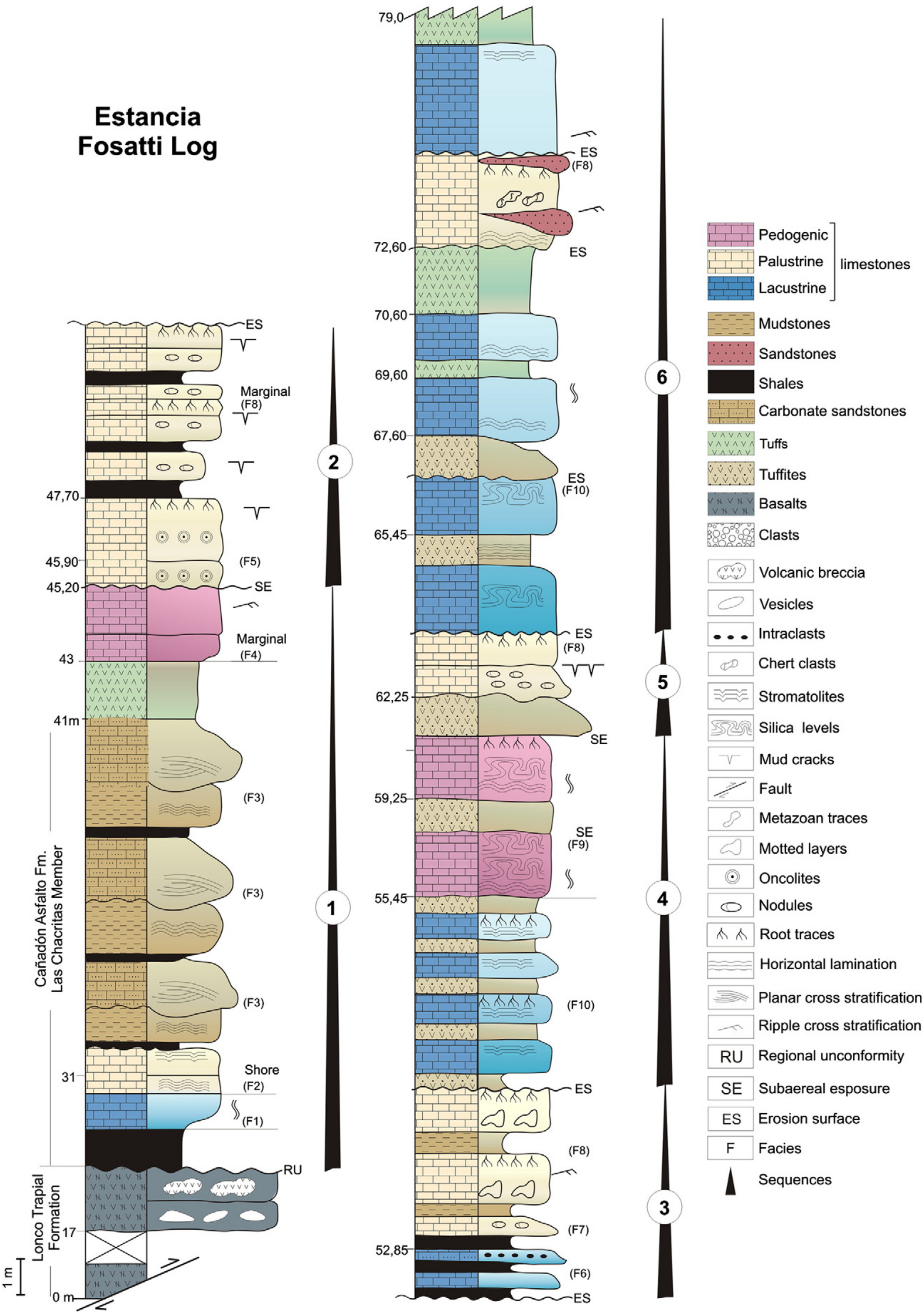

Fig. 3. Field log with lithology, sedimentary structures, paleoenvironments and stratigraphic sequences of the lacustrine system of the Las Chacritas Member (Cañadón Asfalto Formation) at the Estancia Fossati locality.

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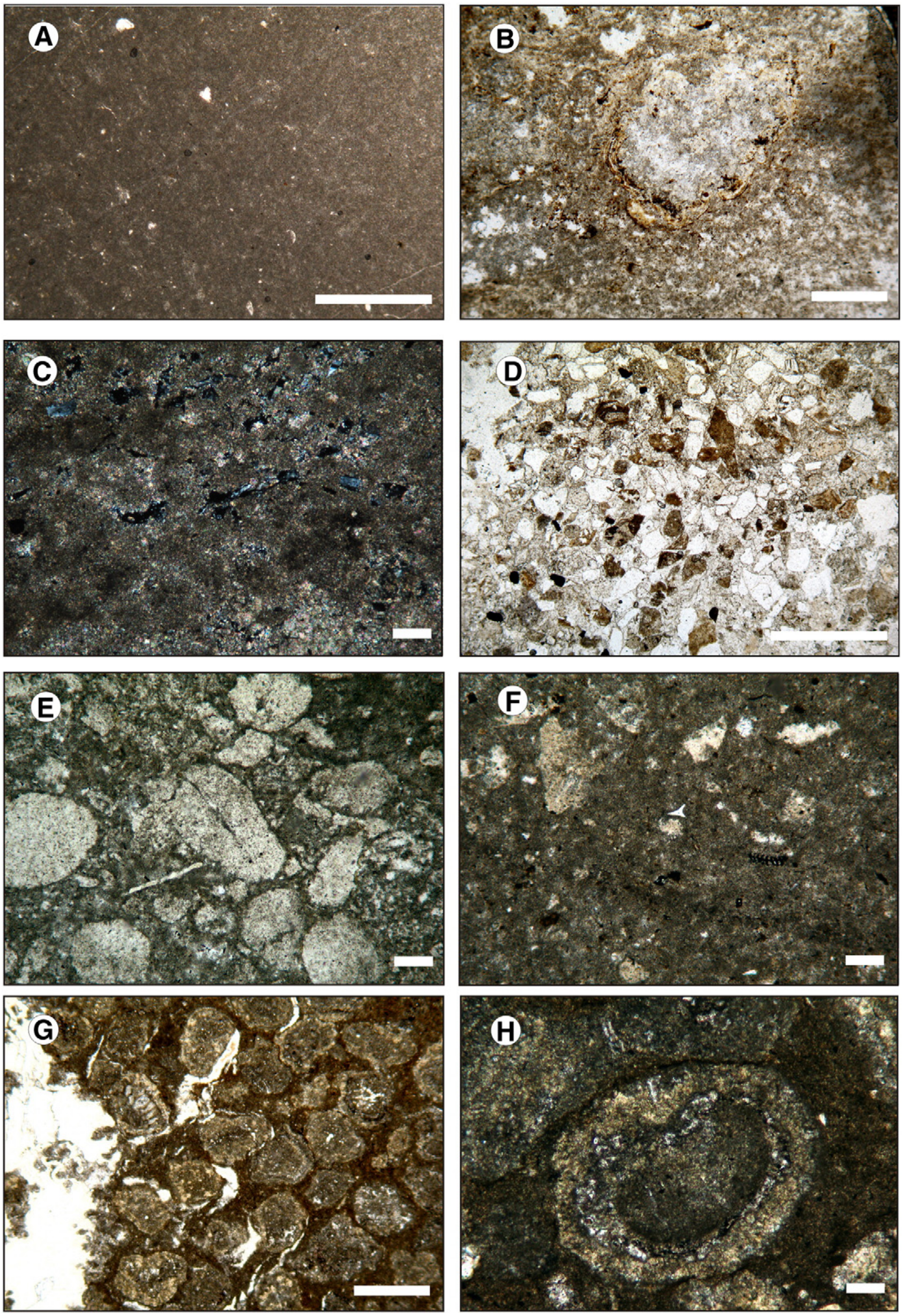

Fig. 4. Photographs of thin sections from microfacies F1, 2, 3, 4 and 5 in the Las Chacritas Member of the Cañadón Asfalto Formation (Jurassic). A) F1: microfacies showing a mudstone with scarce siliciclasts and homogeneous micrite; B) F2: microfacies in which a coated grain with an irregular cortex and spar-containing nuclei can be seen; C) F2: detail of a dark laminae showing numerous quartz, orthoclase and lithic volcanic siliciclasts; D) F3: detail of the Intraclastic sandy packstone facies where quartz, feldspar, basalt lithic fragments, andesite, metamorphic rocks and intraclasts can be observed; E) F4: longitudinal and transversal sections of *Microcodium*; F) F4: detail of shards, intraclasts and phytoclasts associated with *Microcodium* shown in (E) in a micrite matrix with iron oxides; G) F5: Oncolitic packstone facies with a reddish brown micrite matrix; H) F5: detail of an oncolite showing the micrite nucleus and concentric lamination. The scale bar is 1 mm.

is disrupted by circular structures approximately 0.2 to 0.9 mm in diameter. Quartz crystals or volcanic extraclasts are rare. The matrix is formed of micrite, clays, peloids and nodules.

Interpretation: The micritic nodules are interpreted as resulting from the fragmentation, cracking and disruption of limestone by pedogenic processes (Platt, 1989; Alonso-Zarza and Wright, 2010). The circular

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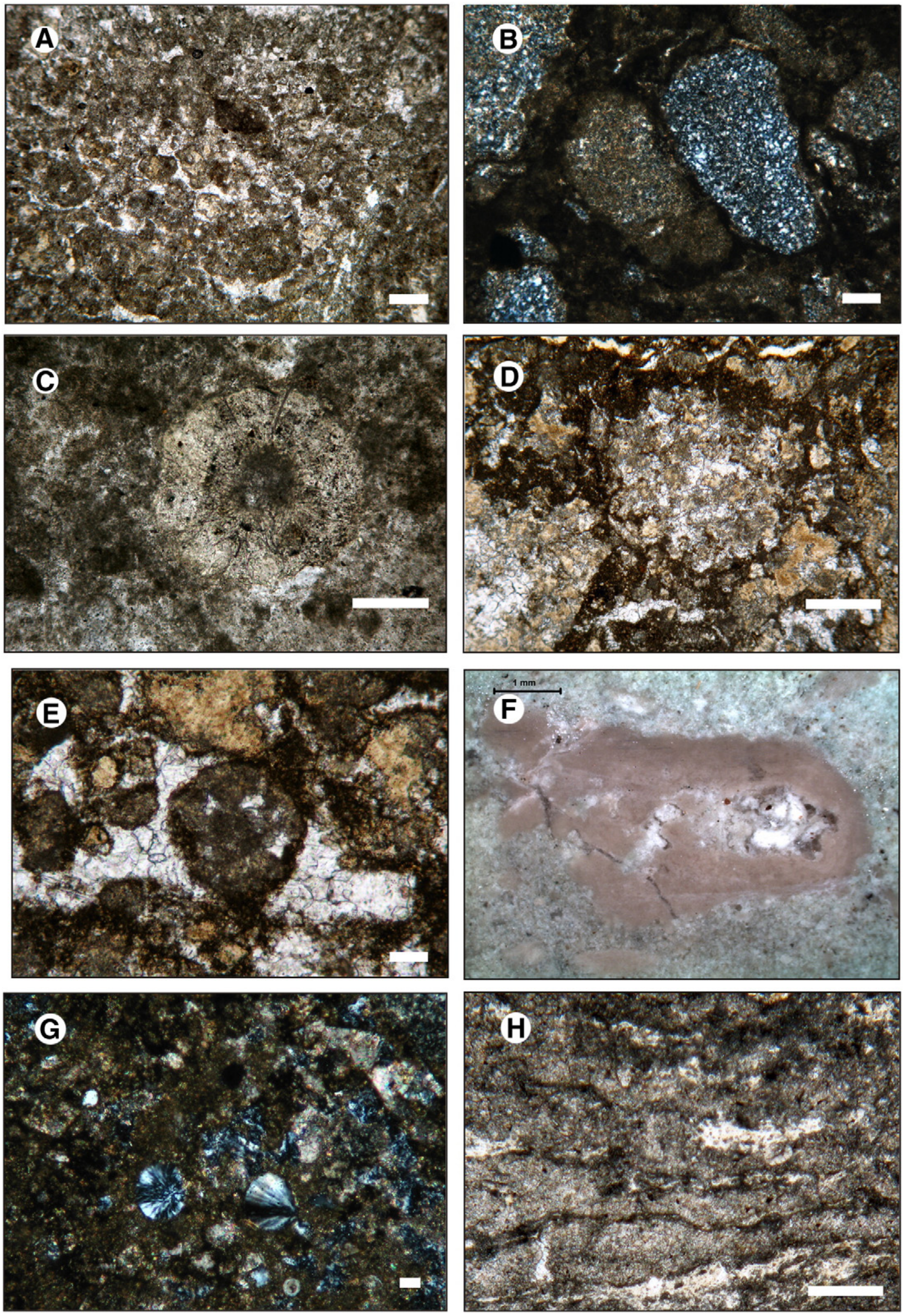

Fig. 5. Photographs of thin sections and polished slabs of microfacies F6, 7, 8 and 10 in the Las Chacritas Member of the Cañadón Asfalto Formation (Jurassic). A) F6: a clotted peloidal micrite matrix with micrite and silica intraclasts; B) F7: detail of microcrystalline silica and micrite with nodules of microcrystalline silica; C) F7: a circular structure interpreted as being a rhizolith; D) F8: detail of orange-reddish diffuse haloes; E) F8: nodules of radial silica; F) F8: detail of polished slab where orange haloes can be seen, indicating areas of rhizobrecciation; G) F8: radial silica (chalcedony) immersed in a matrix of clotted micrite; H) F8: detail of a disrupting structure interpreted as a rhizolith with associated micrite intraclasts. The scale bar is 1 mm.

structures disrupting the fabric are interpreted as being transverse sections of the rhizoliths that facilitated the rhizobrecciation of the facies (Freytet and Plaziat, 1982). These processes resulted in the brecciation of the fabric.

Nodular-Mottled limestones (F8) (Figs. 5D, E, F, G; and H and 6A). The facies is represented by two tabular 10-m-wide carbonate beds (1.1- to 1.5-m thick) interbedded with mudstones. The fabric is grain supported, and the sorting is moderate/poor. Mottling is the

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dominant feature, observed as orange diffuse haloes up to 2 cm in diameter. Abundant nodules are also observed. The nodules are mainly aggregates of heterogeneous micrite (2 to 4.5 mm) and microcrystalline radial silica (chert) (0.5 to 11 mm) containing iron oxides. The microfacies is composed of clotted micrite with a fenestral or an alveolar fabric with areas of different colors, such as extremely dark halos. Irregular and elongated cracks that are approximately 2.2 mm long and 0.2 mm wide are abundant. The intraclasts are poorly sorted and subrounded to angular. They are mainly microcrystalline silica and micrite. The scarce bioclasts belong to bivalves. Rare fragments of *Microcodium* are dispersed in the matrix. The matrix consists of pedogenic micronodules (300 μm to 150 μm). The microfabric is disrupted by widespread circular irregular structures approximately 2.5 mm in diameter that are associated with cutans. There are abundant fine pores filled with silica or calcite. Iron is irregularly concentrated in aggregates or constitutes pseudo-laminations. This microfacies contains scattered dolomite crystals.

Interpretation: The deposits have primary sedimentary features such as peloidal micrite of a subaqueous origin. The mottling is due to the remobilization of iron from fluctuations in the level of the groundwater (Freytet, 1973; Freytet and Plaziat, 1982; Alonso-Zarza, 2003; Alonso-Zarza and Wright, 2010). The alveolar structures indicate the presence of roots (Wright, 1986; Alonso-Zarza, 2003) that were later replaced by micrite and spar. The presence of nodules with an iron oxide coating and dolomite crystals strongly suggests that the facies developed in a vadose environment (Kraus and Hasiotis, 2006; Bustillo and Alonso Zarza, 2007). This likely occurred during a contraction of a body of water. During this period, the adjacent marginal areas would have constituted a truly palustrine setting with a high water table. Moreover, the deposits were affected by later pedogenic alterations as evidenced by the disrupting structures that were interpreted as rhizoliths (rhizobrecciation, pedogenic remobilizations) (Freytet and Plaziat, 1982; Freytet and Verrecchia, 2002). In addition, the presence of *Microcodium* is evidence of a rhizospheric soil environment (Lambers et al., 2009).

Packstones containing *Microcodium* (F9) (Fig. 6B, C). This facies is represented by tabular beds, 0.60 to 2 m thick and 12 m long, interbedded with tuffite layers. This microfacies is composed of poorly sorted particles and predominant angular to subangular intraclasts (25%). The bioclasts (75%) are represented by fish scales, ostracode shells, and algal remains. In addition, there are calcite crystals resembling *Microcodium* in longitudinal and transverse sections. The typical central canal appears as a 20-μm-thick dark micritic line with the external structures replaced by 50-μm-thick fibrous calcite on each surface. In transverse sections, the diameter of the entire canal structure is approximately 200 μm. The matrix is composed of microspar/spar and clotted peloidal micrite. Irregular iron oxides and clays are abundant. Elongated horizontal structures approximately 1 mm long and 160 μm wide obliterate the fabric. These structures were recrystallized by microgranular silica, spar and dolomite.

Interpretation: The tuffite interbeds are interpreted as being materials that had been reworked in a lacustrine environment. The dominant presence of *Microcodium* and the presence of clays and oxides support the development of this facies in a pedogenic environment (Freytet and Plaziat, 1982; Košir, 2004; Lambers et al., 2009). The elongated disruptive structures are interpreted as being bioturbations. Rhizobrecciation was ruled out because no cutans or other signs of vegetal organic matter were observed. Therefore, these structures appear to be of infaunal metazoan origin. According to Buatois and Mángano (1998), such morphologies are related to the grazing and feeding structures produced by metazoan infauna.

Tabular stromatolites (F10) (Fig. 6D). This facies is represented by beds of 20 m in lateral extent, composed of flat laminae with a crenulated profile that form discontinuous couplets from 4 to 6 cm in thickness. The couplets constitute stromatoids that are 0.5 to 2 mm thick. The microstructures are represented by light laminae (100 μm thick) composed of microspar and micropeloidal micrite. The dark laminae are represented by homogeneous micrite (40 μm to 160 μm thick) containing organic matter and extremely small, poorly preserved algal filaments (<7 μm). The fabric is fenestral, containing pores filled with microcrystalline (chert) or fibrous (chalcedony) silica or sparite crystals. Elongated vertical structures (approximately 3 cm long and 400 μm wide) filled with sparite crystals obliterated the lamination.

Interpretation: The laminar structures reflect the physicochemical conditions of the water (Woo et al., 2004) in wet regions that experience long arid periods producing drastic changes in carbonate precipitation and water evaporation from the substratum. The changes in the stromatolitic structures reflect the chemical properties of the lake water composition and the fluctuations in the local paleoclimate (Chafetz et al., 1991). The stromatolitic growth pattern is characterized by the microbial activity in water saturated with calcium carbonate (Riding, 2000) and is related to the carbonate precipitation induced by cyanobacteria-like algae (Bellanca et al., 1992). The presence of the small filaments suggests algae activity during the periods of microbial growth (Casanova, 1991; Casanova and Hillaire-Marcel, 1992; Bertrand-Sarfati et al., 1994). The elongated disruptive structures are interpreted as being root bioturbations (Freytet and Plaziat, 1982).

4.2. Facies associations

Lacustrine limestones (F1–F6–F10). This facies association includes three facies: Mudstone/Wackestone containing porifera spicules (F1), Intraclastic packstones (F6), Tabular stromatolites (F10) and tuffite and shale interbeddings (Fig. 7).

F1 is related to the flooding event in the Lonco Trapial Formation that forms the basement of the basin at the Estancia Fossati locality. The facies are vertically related to the F2, 3, 7, 8 facies (palustrine limestones) and overlay the F10 facies.

These facies are characterized by microbialites, sponge spicules and oncolites. They are observed in three different vertical and lateral situations (Fig. 7a, b and c): a) they overlay transgressive shale indicative of a deep lake subenvironment; b) they have planar cross-stratification and dark shale interbeddings characteristic of the high-energy marginal zones of a paleolake, or; c) they are interbedded with channelized tuffite deposits and show features of rare subaerial exposure indicative of a more marginal zone.

Interpretation: This facies association represents subaqueous depositions with scarce or minor indications of pedogenic alterations. Therefore, it is interpreted as resulting from a paleolake carbonate system. The shale interbeddings were deposited in subaqueous lacustrine environments. Their thickness suggests an increase in the accommodation space that allowed the development of a stable body of water. The tuffites are interpreted as being drop deposits. These processes are common when volcanic material with higher temperatures than those of the surrounding deposits causes a rapid cooling and subsequent contraction of pyroclastic materials (Koukharsky et al., 2002).

Palustrine limestones (F2–F3–F5–F7–F8) (Fig. 6E). The facies association includes *Microbial Mudstones* (F2), *Intraclastic sandy packstones with ostracode remains* (F3), *Oncolitic packstone* (F5), *Brecciated limestones* (F7), *Nodular-Mottled limestones* (F8) and conglomerate deposits.

They are vertically overlaying the F4 and 9 facies (pedogenic facies) and laterally related to facies F3, 6 and 10. The conglomerate deposits are subordinated and predominant toward the top of the succession (Fig. 7).

These facies are characterized by *Microcodium*, nodules, mud cracks, root traces, and rare microinvertebrates and oncolites. They are observed interbedded with shale, rarely with tuffites, and, toward the top of the succession, with conglomerates. They can be found in two different situations (Fig. 7d and e): d) in shale interbeddings with evidence of minor subaerial exposure and e) underlying conglomerates with evidence of major subaerial exposure.

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Interpretation: The presence of microbialites, oncolites, abundant algae and fauna, minor carbonaceous remains and the iron content indicate deposition under subaqueous conditions with dominant subaerial exposure and minor pedogenic processes. The characteristics of the facies suggest a wetland setting, as proposed by Wright and Platt (1995), related to the marginal zones of a paleolake. The presence of rhizoliths and OM suggests that the phytoclasts were derived from vegetated areas as Vázquez-Urbez et al. (2002) and Arenas et al. (2007) have observed in similar settings. The lack of evaporites is consistent with the intermediate type of wetland defined by Platt and Wright (1992). It would have developed in a climate intermediate between arid and sub-humid conditions. The conglomerate deposits represent a prograding system with changes in the lateral palustrine margins of the sub-basin. Similar facies associations have been proposed for Mesozoic and Cenozoic carbonate lakes with palustrine settings found in Spain (Meléndez et al., 2009; Alonso-Zarza et al., 2012), England (Armenteros and Daley, 1998), the USA (Dunagan and Turner, 2004) and Kuwait (AlShuaibi and Khalaf, 2011), among other countries. Furthermore, recent systems, such as the Florida Everglades (Platt and Wright, 1992), the Boringo Lake in the Kenyan rift (Ashley et al., 2004), and Las Tablas de Daimiel (Alonso-Zarza et al., 2006), have been proposed as possible modern analogs of ancient wetlands.

Pedogenic limestones (F4–F9). This facies association includes the facies *Intraclastic limestones* (F4) and *Packstones with Microcodium* (F9).

These facies are overlying the F3 facies and facies with the lacustrine facies association and are underlying the palustrine facies association (Fig. 7).

The facies association is characterized by abundant *Microcodium* and major pedogenic features such as mud cracks, root traces, mottling, brecciation, nodules, high iron content and disrupted fabrics. They are observed capping the repetitive shallow upward successions (sequences).

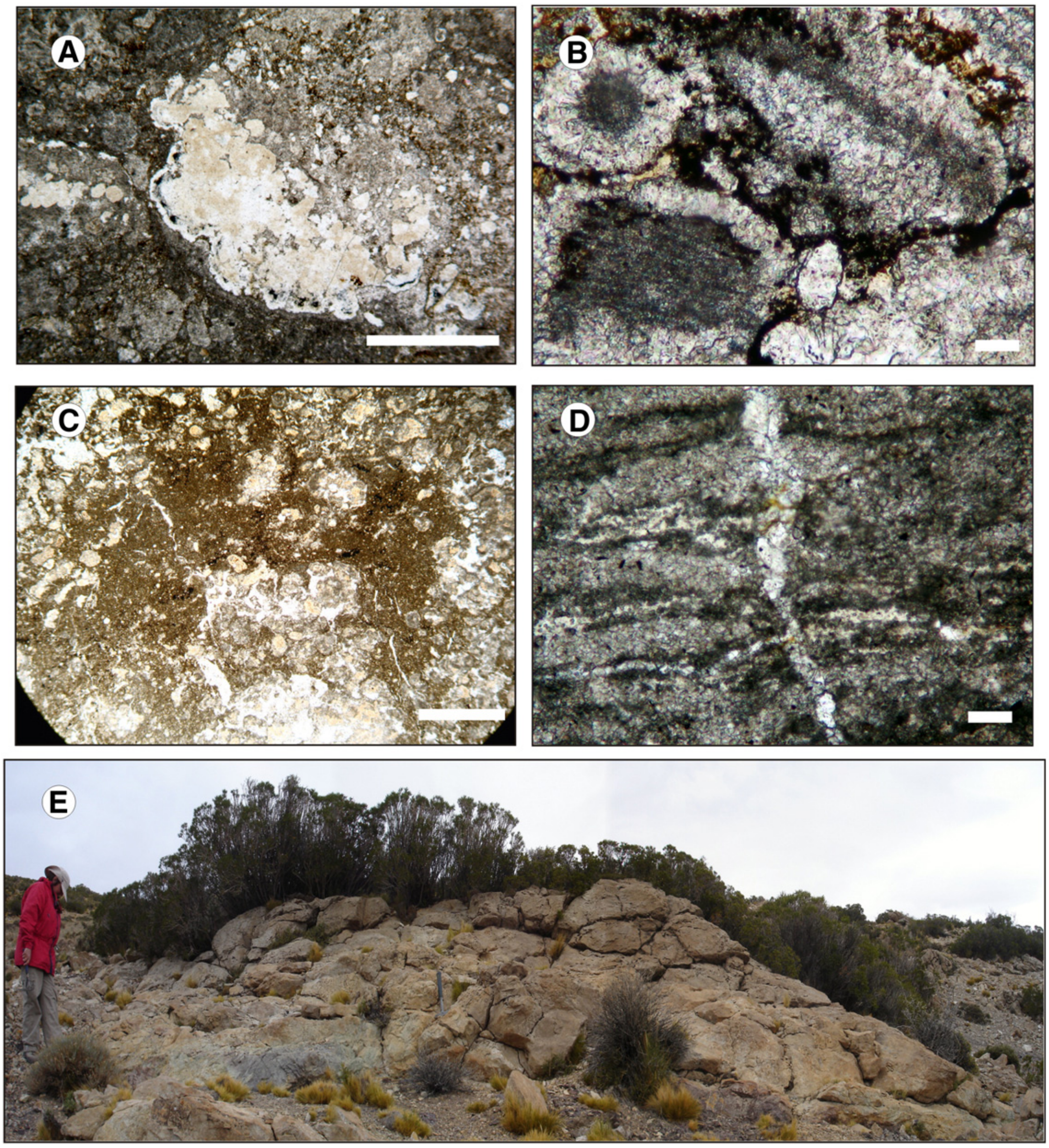

Fig. 6. Photographs of thin sections of microfacies F8, 9 and 10 in the Las Chacritas Member of the Cañadón Asfalto Formation (Jurassic) and an overview photograph. A) F8: pseudo-lamination with vertical cracking; B) F9: detail of longitudinal and transverse sections of *Microcodium* showing the dark central canal; C) F9: detail of brown haloes typical of mottled microfabric; D) F10: dark-light laminar alternation of Tabular stromatolites disrupted by vertical cracking. The scale bar is 1 mm. E) Photograph of the outcroppings containing palustrine limestone facies associations at the top of the Las Chacritas Member at the Estancia Fossati locality.

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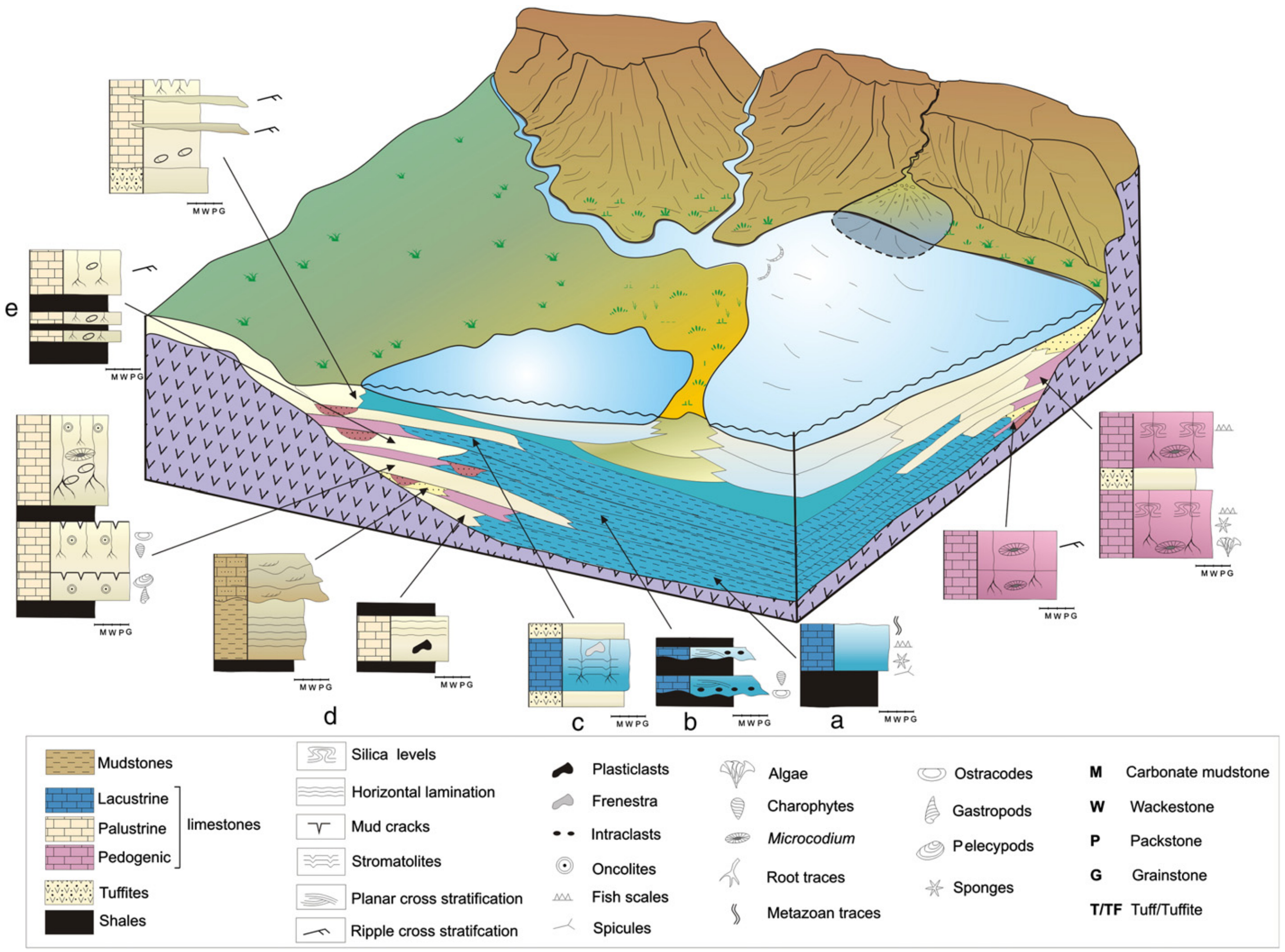

Fig. 7. Schematic model of the paleoenvironmental facies proposed for the lacustrine system of the Las Chacritas Member in the Cañadón Asfalto Formation (Jurassic) at the Estancia Fossati locality.

Interpretation: This association is interpreted as the result of soil processes occurring in a pedogenic environment. According to Alonso-Zarza and Wright (2010), these features are commonly associated with palustrine facies (wetland subenvironments) and represent the maximal contraction of a paleolake, and the lowest accommodation space in the sub-basin, as has been observed by Yang et al. (2010).

5. Depositional evolution of the lacustrine system

During the extensional event in the Cañadón Asfalto Rift (*synrift*), the fluvial and lacustrine deposits of the Las Chacritas Member filled the depressions in the sub-basins (Figari, 2005) immediately overlying the basement (Lonco Trapial Formation). The changes in the thickness of the *lacustrine limestone facies association* reflect a differential pattern of subsidence with an increase in the accommodation space. Unfortunately, there are no data on the half-grabens of subsurface basins, and clear horizontal tendencies in the Cañadón Asfalto Basin are difficult to recognize because of the widespread syn-sedimentary deformation that affected the successions. Moreover, the outcrops are disposed in a narrow belt delimited by the deformations from the rise of the Andes Mountains (Silva Nieto et al., 2002a,b). The vertical variations in the facies of the successions and their sedimentary features allowed for two episodes of shallow paleolake expansions at the basin margins to be differentiated.

The facies associations identified for the Las Chacritas paleolake comprise a complete shallow upward succession (Fig. 3) that can be represented as *lacustrine limestone* > *palustrine limestone* > *pedogenic limestone*.

The succession is repeated (cycles) along the unit forming shallowing upward sequences and can present the F3 facies overlaying the *palustrine limestone facies association* and underlying the *pedogenic limestone facies association*, delimited by subaerial surface exposure. Incomplete sequences were registered and they present the *palustrine limestones facies associations* with a subaerial exposure surface at the top. The cycles represent two expansive phases of the paleolake, delimited by erosive surfaces and controlled mainly by the subsidence rate. The first expansion was regional and overlaid the basement (Lonco Trapial Formation) 19 m from the base of the log (Fig. 3). It is characterized by fine-grained sediments, limestone and distinctive dark shale. The second expansion (51 m of the log, Fig. 3) is represented by limestone of the F6 facies interbedded with shale with high OM content; distal fluvial input was not observed at the locality studied. The expansion stages correspond to a high accommodation rate in the Fossati sub-basin. Between the two expansions, the accommodation rate diminished, as reflected in the F10 facies. Platt (1989) has proposed that the marginal facies of a succession represent the low accommodation space (maximal contraction). Within the marginal facies, a gradual transition occurred from the marginal subaqueous facies (F2, F5) to the marginal palustrine facies

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(F7, F8) to pedogenic facies (F9) with paleosol development (F4). Yang et al. (2010) indicated that this trend is due to limited accommodation space, while Platt (1989) suggested that the accommodation space decreased. The stacking pattern in the Las Chacritas succession suggests a decreasing accommodation space within these facies.

Rare deposits from fluvial systems (F3) became interbedded in the succession layers during the paleolake contractions and increased in thickness toward the top of the successions. This tendency indicates increases in the accommodation space in the Fossati sub-basin. Moreover, the predominance of the *palustrine limestone facies associations* in the first section of the sequence and their incremental increase in thickness toward the top of the *lacustrine limestone facies associations* does indeed suggest the creation of new accommodation space.

The general tendency of the successions can be interpreted in the context of the *synrift* stage of the Cañadón Asfalto Formation (Figari, 2005). Deposits of *lacustrine limestone facies associations* are predominant in the upper part of the log (from the 52-m position toward the top of the log section) and represent the moment of maximal lake expansion in the development of the Las Chacritas paleolake.

5.1. Major controls: tectonics and climate

The Las Chacritas paleolake (Fig. 7) corresponds to a lacustrine system with low-energy ramp-like margins (gentle gradient), according to the classification of Platt and Wright (1991), where the palustrine setting is greatly developed. Pedogenic features are common in this type of system (shallow and small in extent) because minor decreases (contraction) in the water level expose large surfaces (Freytet and Plaziat, 1982; Freytet, 1984; Alonso-Zarza, 2003). The fluctuations in the size of a paleolake (expansions and contractions) can be attributed either to variations in the climate or to subsidence. As has been proposed by Alonso-Zarza et al. (2012), the variations in short-term sequences can be attributed either to pulses of subsidence or to climatic cycles. In contrast, Dunagan and Turner (2004) suggested that variations in wetlands are better explained by groundwater fluctuations.

As to probable tectonic influences, the progression of the successions indicates that tectonics and subsidence influenced the stacking pattern of the unit. The regional unconformity suggests a strong tectonic influence in the basin during the first extension of the rift (Gawthorpe and Leeder, 2000).

In addition, the sedimentary features of the palustrine limestone (cracking, rhizobrecciation, nodularization, mottling) can provide indications of the role of the climate (Alonso-Zarza and Wright, 2010; Alonso-Zarza et al., 2012). The sedimentary features of the *palustrine limestone facies association* in the Fossati sub-basin (including the presence of dark shale with OM content, the abundance of microinvertebrate fauna, the rarity of mud cracks, the minor brecciation, the pedogenic caps of the successions, and the absence of evaporites), indicate a climatic context intermediate between arid and sub-humid conditions (Platt and Wright, 1992). The minor sedimentary changes observed in the successions might reflect variations in the exposure index of the wetlands during the climatic seasonal transitions (Platt and Wright, 1992) and fluctuations in the water table (Meléndez et al., 2009; Hanneman and Wideman, 2010). The pedogenic influence is particularly evident in assemblages 1 and 4 of the units, indicating low levels of the water table. Local fluctuations in the water table have been attributed to climate control. This is consistent with the climatic model proposed for the Chubut region in the Middle Jurassic (Patagonia, Argentina). The climate was seasonal with dry (summer) and wet (winter) seasons (Rees et al., 2000; Volkheimer et al., 2011). Moreover, palynologic studies of the Cañadón Asfalto Formation in the Cerro Cóndor sub-basin demonstrated high percentages of *Classopollis* spp. (thermophilic Cheirolepidiaceae), indicating the warm climatic conditions and well-drained soils associated with lacustrine systems (Volkheimer et al., 2010). Therefore, the variations registered in the studied unit may reflect responses to a combination of tectonic and climatic controls as has been described by Gierlowski-Kordesch (2010) and Alonso-Zarza et al. (2012).

5.2. Provenance of limestones

With respect to the provenance of the calcium-rich waters that fed this system, the origin is unknown. Several hydrology paths can be proposed such as groundwater reaching a lake through either seeps or springs (Renaut and Tiercelin, 1994; Liutkus et al., 2010) or fluvial input (Pla-Pueyo et al., 2009), but no probable carbonate-rich source area has been identified in the outcroppings or the subsurfaces of sub-basins. Sinter deposits in the Cerro Cóndor sub-basin were considered to result from hydrothermalism (Cabaleri and Armella, 2005). These deposits would indicate the possibility that hydrothermal activity also occurred in the Fossati sub-basin.

6. Conclusions

The sedimentary facies analyses have allowed for interpretation of the sediments of the Las Chacritas Member as a carbonate lacustrine system. The three representative depositional subenvironments of this system are lacustrine, palustrine and pedogenic settings represented by the corresponding facies associations (lacustrine limestones, palustrine limestones and pedogenic limestones). These facies associations are arranged in shallow upward successions in which two expansive stages of the paleolake were identified. The contraction stages are represented by the deposits of fluvial systems and the association with pedogenic limestone facies.

The Las Chacritas paleolake developed in the margin of the Cañadón Asfalto Rift Basin during the *synrift* stage. In the Fossati sub-basin, the succession reflects a response to tectonic control (differential pattern of subsidence) that dominated the local climate variables at the beginning of the succession. This is due to the dominant extensive efforts of the *synrift* stage being more active and triggering the creation of accommodation space. The decreasing tendency of the accommodation space is recognized in the stacking pattern and the facies associations in the succession.

In the Fossati sub-basin, the sedimentary features of the palustrine limestone facies association reveal an intermediate climate (arid to subhumid conditions) and suggest that minor sedimentary changes were caused by variations in the exposure index of the Las Chacritas wetland.

Acknowledgments

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