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Influence of a biohermal belt on the lacustrine sedimentation of the Cañadón Asfalto Formation (Upper Jurassic, Chubut province, Southern Argentina)

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ABSTRACT

The Upper Jurassic Cañadón Asfalto Formation (Cañadón Asfalto Basin, Patagonia Argentina), consists mainly of carbonate deposits accumulated in hydrologically closed lakes, which were especially sensitive to rainfall changes. The lacustrine carbonate sedimentation also interplayed with volcanic episodes recorded by tuffs and lavas, as observed in different basin sectors. These lakes probably underwent warm, alternating humid-subarid and arid conditions that resulted in spreading and shrinkage cycles of the closed water bodies. In the Cerro Cóndor area, carbonates were deposited as part of a 500 m long and 39 m thick microbial biohermal body that extended over 5,5 km2, overlying a hard basalt substratum. This bioherm ridge acted as a physiographic barrier that controlled the sedimentation in the surrounding lacustrine zones, whose environments ranged from shallow and deep littoral to eulittoral (including microbial patch reefs) and palustrine. A hydrologically isolated portion of the lacustrine basin evolved into a pan lake where widespread carbonate-evaporite sequences developed.

KEYWORDS **Lacustrine Biohermal Belt. Cañadón Asfalto Formation. Upper Jurassic. Argentina.**

INTRODUCTION

The Callovian-Oxfordian Cañadón Asfalto Formation occurs in the so-called Cañadón Asfalto Basin and is composed mainly of limestone, calcareous sandstone, tuffaceous sandstone, volcanic tuff, conglomerate, and basalt (Stipanicic et al., 1968). This formation is one of the most significant Jurassic lithostratigraphic units in the Extra-Andean Patagonia, Southern Argentina.

The earlier studies of the Cañadón Asfalto basin in the middle Chubut river valley (between 42° 36‘ S- 44° 00’ S and 70°00’W- 68°30’W) have been carried out in the first half of the XXth century (Piatnitzky, 1936; Flores, 1948; Feruglio, 1949a, 1949b and 1950). Later contributions improved the available information and resulted in better understanding of the stratigraphic and sedimentological record in this basin (Stipanicic et al., 1968; Stipanicic and Bonetti, 1969; Tasch and Volkheimer, 1970; Turner, 1983; Nullo, 1983; Landi and Fuentes, 1988; Homovc et al., 1993; Figari and Courtade, 1993; Geuna et al., 1993, 1999; Cortiñas, 1996; Lizuaín and Silva Nieto, 1996; Cabaleri and Armella, 1999; Silva Nieto et al., 2002a, 2002b; Silva Nieto et al., 2003, among others).

This paper deals with the interpretation of the influence of a large lacustrine biohermal belt on the formation and distribution of different lacustrine (littoral, eulittoral) and palustrine ancient environments of the Cañadón Asfalto Formation, in the Cerro Cóndor locality of the Cañadón Asfalto basin.

GEOLOGICAL AND STRUCTURAL SETTING

The study area is located in Cerro Cóndor (43° 27' 30"S, 69° 8' 45" W) Paso de Indios Department, in the east-central region of Chubut province, Argentina (Fig.1).

The basin basement exposed near the study area consists mainly of Ordovician-Silurian tonalitic migmatites and minor biotite and biotite-muscovite granites with high-grade deformation that belong to the Mamil Choique Formation (Ravazzoli and Sesana, 1977; Dalla Salda et al., 1999; (Figs. 1 and 2). The Middle Jurassic (Aalenian–Callovian) mesosilicic to basic volcanic rocks of the Lonco Trapial Formation unconformably overlie the basement (Nullo and Proserpio, 1975; Figs. 1 and 2). This formation includes a 300 m thick sequence composed of sometimes-brecciated andesitic lavas, dacitic and andesitic tuffs, fine to medium tuffaceous sandstone intercalations, and volcanic agglomerates. Andesitic dykes usually cut across this volcano-sedimentary assemblage.

The Upper Jurassic, Cañadón Asfalto Formation (Stipanicic et al., 1968), overlies the above-mentioned volcanic association (Fig. 2). Cañadón Asfalto Formation consists of lacustrine, fluvial-deltaic sediments, and marginal lacustrine carbonate sediments with volcanoclastic and volcanic intercalations. This formation splits into the lower Las Chacritas Member and the upper Puesto Almada Member. The Las Chacritas Member (Silva Nieto et al., 2003) is mainly characterized by magadiite nodule bearing homogeneous limestones, stromatolite limestones, and black bituminous shales. Thin layers of pyroclastic rocks also occur. The volcanic intercalations are made up by olivinic-basalt flows. At least eleven cycles of alternating basalts and lacustrine limestones have been reported (Silva Nieto et al., 2002a). The Puesto Almada Member is mainly siliciclastic, with a predominance of fine sandstones, tuffaceous sandstones, volcanic tuffs, conglomerates, limestones, and minor basalts (Silva Nieto et al., 2003).

The Cañadón Asfalto Formation is unconformably covered by the Chubut Group (Lesta, 1968), Cretaceous (Fig. 2), constituted by fluvial and continental sedimentary rocks with pyroclastic material. The sequence is formed by a lower section (Los Adobes Formation; Stipanicic et al., 1968) of epiclastic nature (conglomerates, tuffaceous sandstones with intercalations of mudrock and tuff beds and a mainly pyroclastic upper section (Cerro Barcino Formation; Codignotto et al., 1979) composed of tuffs, sandy tuffs, tuffaceous sandstones and claystones.

Paleogene (Fig. 2) is represented by the Eocene La Primavera Formation, the Sarmiento Group. La Primavera Formation (Alric, 1996) consists of alkaline subvolcanic bodies (basanites and basalts). The Sarmiento Group (Simpson, 1941) of Eoceno-Oligoceno age is made up of tuffs, sandy tuffs, sandstones and tuffaceous silts. The small outcrops of this unit can be found in the northwestern sector of the area under study and are covered by Miocene basaltic lava flows of the El Mirador Formation (Volkheimer, 1964).

The Mesozoic basins recognized in the studied area were part of an Upper Triassic-Lower Jurassic half-graben system bounded by normal lystric faults, which developed in relation to the extensional processes that triggered the Middle-Upper Jurassic major volcanic cycle of the Lonco Trapial Formation (Figs. 1 and 2; Silva Nieto et al., 2002b). These lineaments would correspond to ancient regmatic basement directions (the so-called Gastre System; Coira et al., 1975; Rapella et al., 1991) that controlled the location of trascurrent faults. Towards the Upper Jurassic, transtensional basins developed along these faults in those sectors that showed sinuosities or changes in the general strike, and the deposition of the Cañadón Asfalto Formation began. These basins have been interpreted as pull-apart strike-slip basins (Silva Nieto et al., 2002b). The most common environments found in this type of basins are lacustrine, fluvial and evaporitic or tidal and the most conspicuous deformation is synsedimentary. In the Cerro Cóndor area, deep and shallow lacustrine deposits, evaporite levels and landslide and fluvial deposits interbedded with thick olivinic basalt sheets have been observed in the Cañadón Asfalto Formation. The sequences show an intense synsedimentary deformation with slumping and folding that can sometimes be e*n echelón*.

BIOHERMAL BELT FACIES

In the Cerro Cóndor area the Las Chacritas lower member includes a biohermal belt that overlies a hard basalt flow substratum (Fig. 3). This 500 m long microbialitic belt crops out from Cañadón Las Chacritas to Cañadón Carrizal. The bioherm framework is characterized by three facies associations: core, flank and top facies assemblages, which correspond to different growth stages of the biohermal belt (Fig. 4). Green filamentous

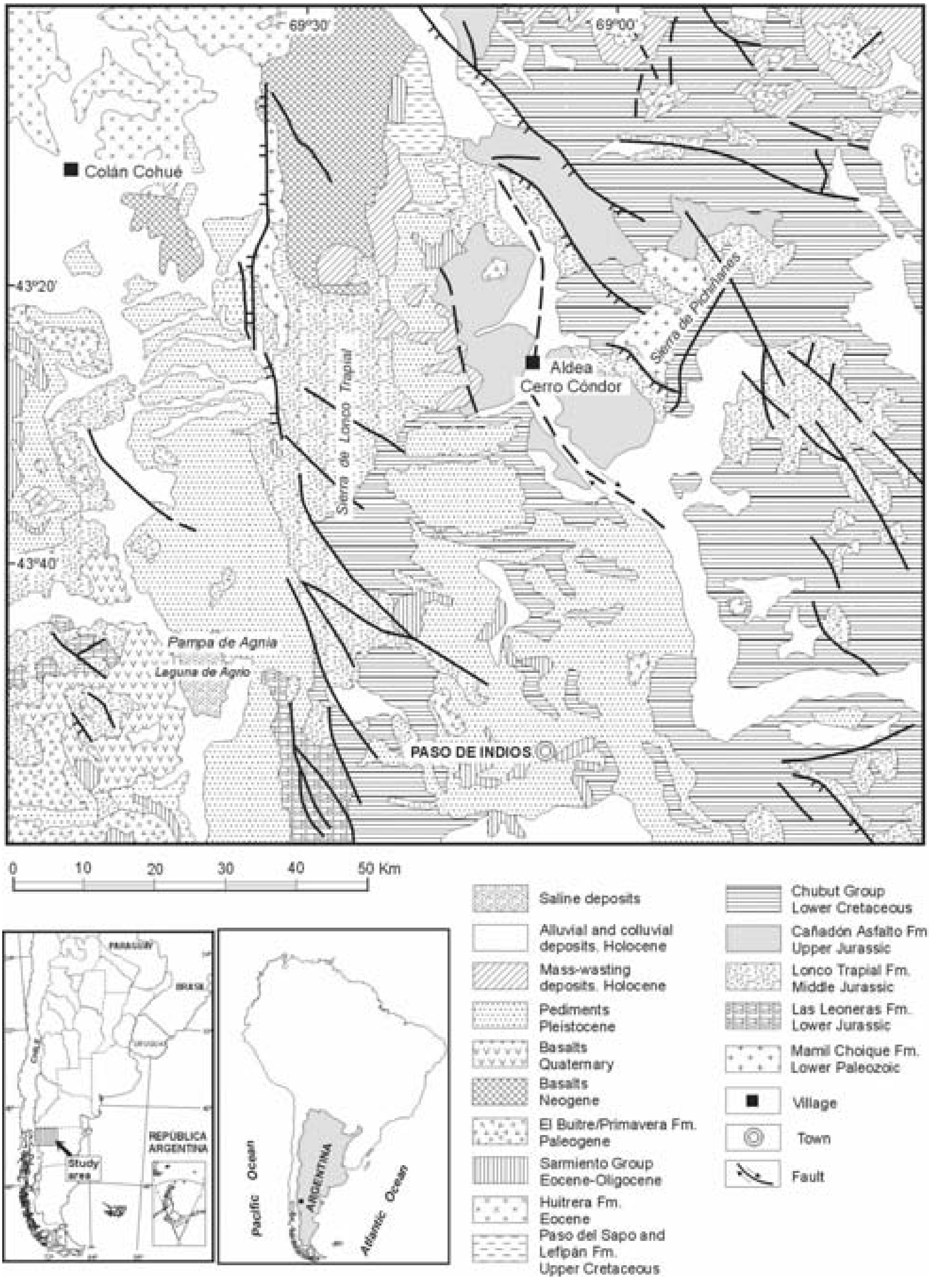


FIGURE 1 **Geologic map showing the outcrops of the Cañadón Asfalto Formation in the Chubut river valley, Argentina. See text and Fig. 2 for further detail.**

algae and stromatolites mainly form each facies (Cabaleri and Armella, 1999).

Bioherm core facies assemblage

The bioherm core facies (Fig. 4) are widespread at Cañadón Las Chacritas. These facies include rhythmic couplets of mudstones and 0.5 cm-thick flat-profiled stromatoids, which alternate with poorly-defined and discontinuous 5 cm-thick wackestone beds with massive micrite (Cabaleri and Armella, 1999). This core facies assemblage represents the first stage of bioherm development and indicates conditions that enhanced the development of algal mats in micrite mud. The rhythmic pattern observed could result from seasonal climatic changes that influenced on sedimentation during a high lake-level stage (Cabaleri and Armella, 1999; 2003).

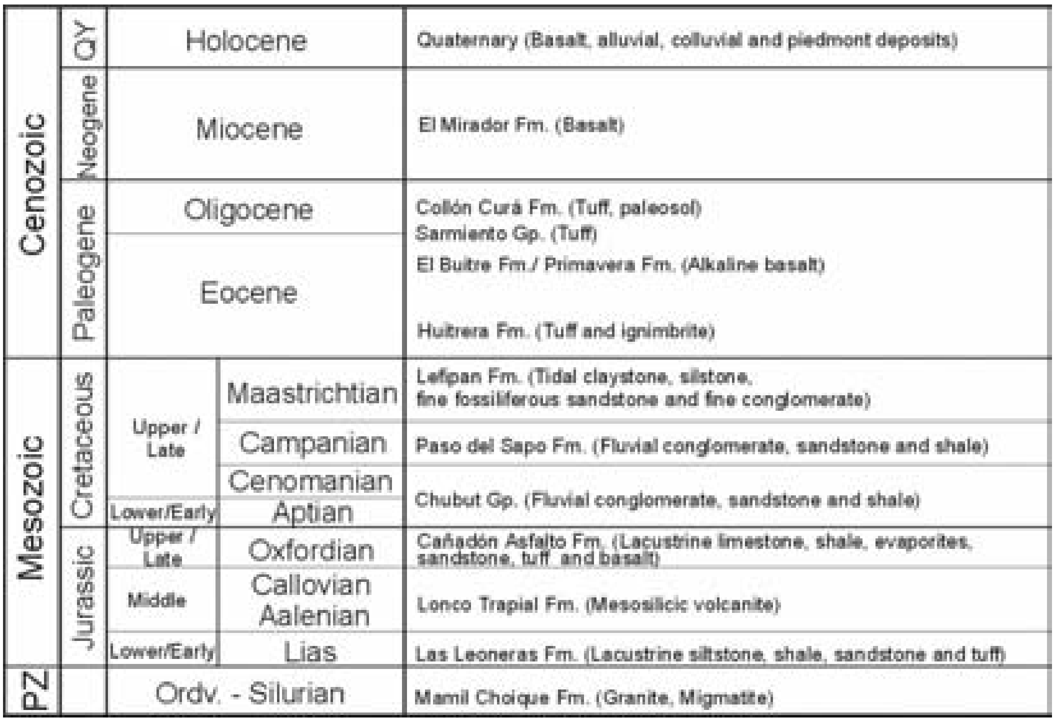
Bioherm flank facies assemblage

The bioherm flank facies are recognized at Cañadón Las Chacritas and Cañadón Carrizal and are characterized by stratiform stromatolites (Fig. 4). They appear on and laterally associated with the core facies and correspond to a later growth stage. The 0.3-0.4 cm thick stromatolite laminae sets are composed of micrite with a paleobiotic association of limnic organisms (cyanobacterial filament remains, charophyte and ostracod fragments) and Magadi-type chert laminae (Cabaleri et al., 1999a). Thin levels with a silty-clayey matrix that present pedogenic evidences (roots, burrows, and vertical cracks) occur in these facies. Mudcrack complexes infilled with peloidal micrite and sparite or silica also occur.

The facies characteristics suggest that the periods of lacustrine spreading favoured microbial accretionary growth. These conditions were interrupted by seasonal lake-contraction episodes that exposed subaerially the bioherm, as suggested by the presence of mudcracks infilled with microcrystalline silica. The pedogenic evidences recorded in some beds would also indicate a good drainage of the area (Freytet and Plaziat, 1982).

Biohermal top facies assemblage

This biohermal belt facies assemblage crops out at Cañadón Las Chacritas and Cañadón Carrizal. These facies (Fig. 4) represent the third growth stage of the biohermal belt and consist of thick hemispheroidal stromatolites with low-synoptic relief that are interbedded with magadiite laminae, calcrete, and paleosols (Cabaleri and Armella, 1999). Hemispheroidal stromatolites consist of couplets of fenestral-textured micrite laminae and spongy micrite laminae with pores of 3 mm in diameter. A second set composed of couplets of fenestral peloidal micrite laminae and magadiite laminae was also identified. Charophyte bioclasts, carbonaceous remains and insect eggs are widespread in these facies. This microbialitic facies represent a long period of lake expansion and form



Cenozoic	QY	Holocene		Quaternary (Basalt, alluvial, colluvial and piedmont deposits)
	Neogene	Miocene		El Mirador Fm. (Basalt)
	Paleogene	Oligocene		Collón Curá Fm. (Tuff, paleosol) Sarmiento Gp. (Tuff)
		Eocene		El Buitre Fm./ Primavera Fm. (Alkaline basalt) Huitrera Fm. (Tuff and ignimbrite)
Mesozoic	Cretaceous	Upper / Late	Maastrichtian	Lefipan Fm. (Tidal claystone, siltstone, fine fossiliferous sandstone and fine conglomerate)
			Campanian	Paso del Sapo Fm. (Fluvial conglomerate, sandstone and shale)
			Cenomanian	Chubut Gp. (Fluvial conglomerate, sandstone and shale)
		Lower/Early	Aptian	
	Jurassic	Upper / Late	Oxfordian	Cañadón Asfalto Fm. (Lacustrine limestone, shale, evaporites, sandstone, tuff and basalt)
		Middle	Callovian Aalenian	Lonco Trapial Fm. (Mesosilicic volcanite)
		Lower/Early	Lias	Las Leoneras Fm. (Lacustrine siltstone, shale, sandstone and tuff)
PZ		Ordv. - Silurian		Mamil Choique Fm. (Granite, Migmatite)

FIGURE 2 | **Stratigraphy of the middle Chubut river valley (see map in Fig. 1). The Late Jurassic Cañadón Asfalto Formation includes a variety of volcanic and sedimentary alluvial-lacustrine rocks.**

an elongated body and would record a long period of lacustrine spreading. These expansion periods were interrupted by contraction episodes during which paleosols and calcrete levels developed. Magadiite laminae are characteristic of saline lakes that have undergone changes in pH and salinity due to evaporation during the lacustrine-contraction stage (Cabaleri et al., 1999a, Renaut et al., 2002). The characteristics of the stromatolite top facies and the existence of calcrete crusts and mudcracks indicate a gradual transition from eulittoral to supralittoral environments.

LACUSTRINE FACIES RELATED TO THE BIOHERMAL BELT IN THE CERRO CONDOR AREA

The analysis of the Cañadón Asfalto Formation at Cañadón Las Chacritas (Cabaleri and Armella, 1999) suggests a littoral lacustrine paleoenvironment. This ancient littoral-lacustrine environment consists of an extensive supralittoral zone, an eulittoral zone where the biohermal belt developed, and a very shallow infralittoral area. Figure 5 shows the distribution of the lacustrine facies in Cañadón Las Chacritas, and the semi-quantitative facies distribution in a sketchy cross section.

Supralittoral Facies

Mudstone with thin microbialite lamination (F1). This facies is composed of dark, organic rich, clotty micrite, which shows fenestral fabric and pedogenic traces.

Floatstone with biohermal intraclasts and grain-supported fabric (F2). The components in this facies are poorly sorted and present pedogenic coatings with micrite lamination (Arp,1995). The upper beds are associated with 4 cm-thick anhydrite layers that underlie a 2.5 cm thick volcanic shard deposit.

Mudstone composed of clotty micrite with mudcracks and anhydrite-filled fenestrae (F3).

The supralittoral subenvironment extended over a wide area and its deposits included calcareous mud deposits formed under stagnant-water conditions that were favorable for development of microbial and algal mats (F1). These mud deposits interfingered with layers resulting from storm events (F2). The above-mentioned features suggest the existence of climatic changes, with alternating more humid periods (characterized by discharge of materials brought by ephemeral streams) and extreme arid periods with pore-related sulphate precipitation (F3).

Eulittoral Facies

Microbialite peloidal mudstone/wackestone, with fenestral fabric (F4). Algae, gastropod, foraminiferal and ostracod remains are found in this facies. Intraclasts are made up by micrite with peloidal texture.

Intraclastic grainstone/rudstone (F5). This facies is poorly sorted, has a grain-supported fabric and can be affected by mudcracks.

Two zones can be differentiated within the eulittoral subenvironment. The zone adjacent to the supralittoral zone and associated with weak currents is represented by facies F4. The other zone located near the infralittoral subenvironment is represented by facies F5. The biohermal belt facies developed in this eulittoral subenvironment (see the Biohermal Belt Facies section for further detail).

Infralittoral Facies

Oncoidal floatstone with mud-supported fabric and fining-upward arrangement (F6). Micrite intraclasts,

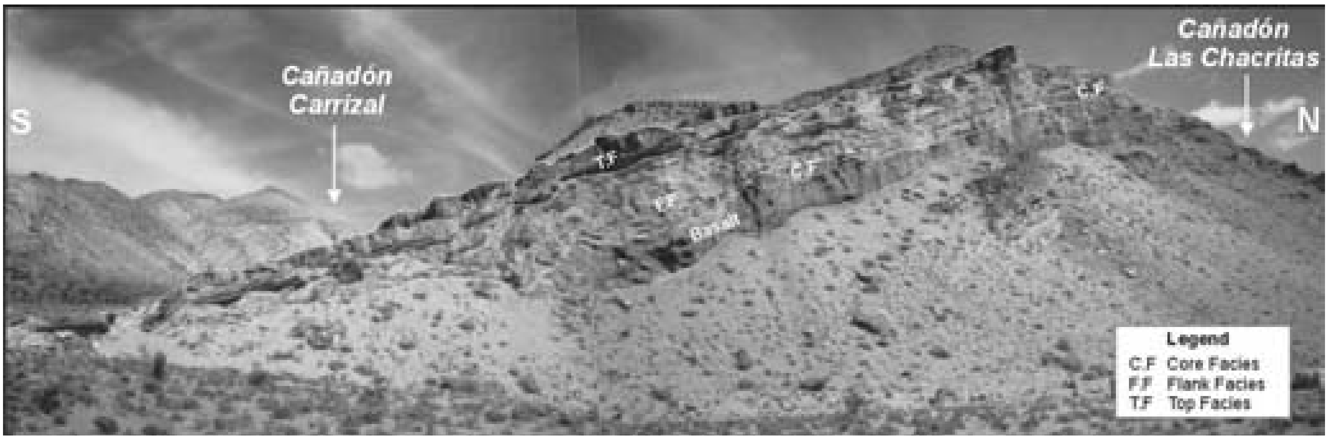


FIGURE 3 **Landscape view of Cerro Cóndor Biohermal Belt that stretches from Cañadón Las Chacritas to Cañadón Carrizal. Notice the distribution of the biohermal facies that overly the basalt rocks. The biohermal carbonate body is 0,5 km long and up to 39 m thick and extends over an area of 5,5 km2 . See location in Fig. 1.**

ostracod remains, calcareous algae, foraminifera and extraclasts occur. Vertebrate remains, araucaria trunks and cones, and fern remains have been yielded by this facies at Cañadón Las Chacritas.

Biointrasiliciclastic packstone/wackestone (F7). This facies is composed of ostracod shells, foraminifera, unidentified plant remains, charophyte oogonies and algal filaments. Intraclasts are made up by micrite and present pedogenic coatings. Rhizolites and insect eggs occur. Joint planes-type mudcracks (Arp, 1995) are also occur.

The infralittoral area was related to shallow, probably nutrient-rich waters as shown by the abundance of macrophytes in facies F7. This environment was affected by high-density currents (hyperconcentrated flows) that brought material from the littoral environment (oncoids, intraclasts, sauropod remains,

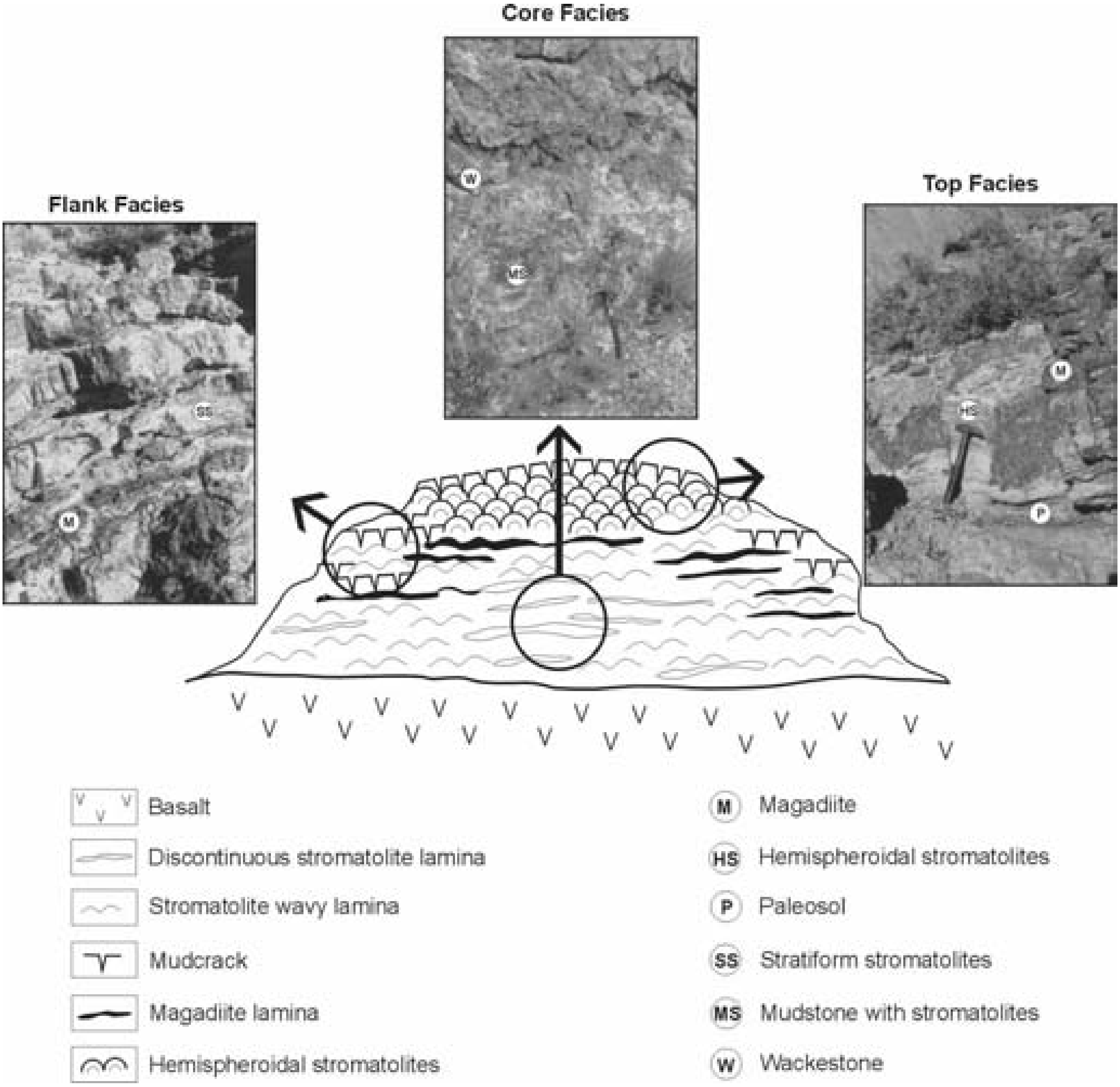


FIGURE 4 **Internal structure of the biothermal body (500 m long and 39 m thick) showing the three growth stages identified. The first stage core facies (up to 6 m in thickness) consists of interbedded mudstone and discontinuous stromatolite laminae that result in a discontinuous banding. The second stage flank facies vary between 10,5 to 22 m thick and is made up by stratiform stromatolites. Silica (pseudomorphized magadiite) and microbial levels alternating with carbonate algal laminae occur. The third stage top facies deposits vary between 7,5 to 11 m thick and include hemispheroidal stromatolites constituted by magadiite laminae. The geologist´s hammer leans on a paleosoil level associated with calcrete.**

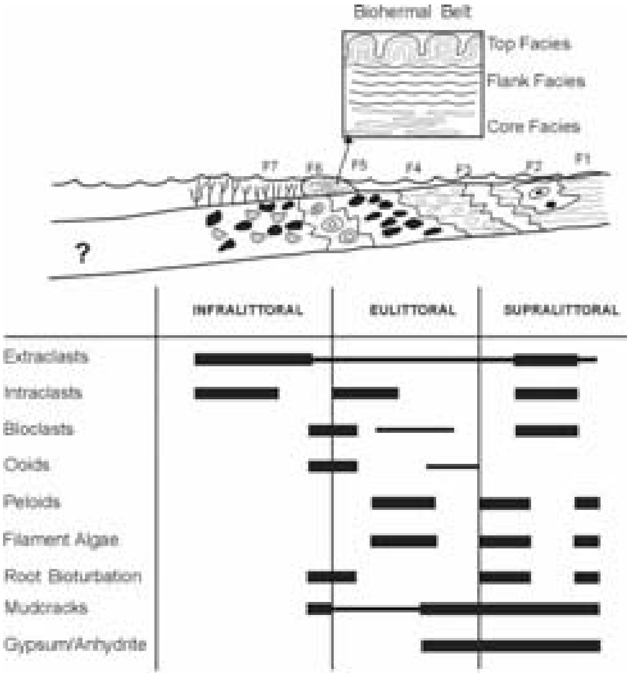


FIGURE 5 **Lacustrine facies and semiquantitative distribution of their components at Quebrada Las Chacritas (Cerro Cóndor). Supralittoral Facies : F1, Mudstone with thin microbialite lamination. F2, Floatstone with biohermal intraclasts. F3, Mudstone composed of clotty micrite with mudcracks and anhydrite-filled fenestrae. Eulittoral Facies: F4, Microbialite peloidal mudstone/wackestone; F5, Intraclastic grainstone/rudstone. Infralittoral Facies: F6, Oncoidal floatstone F7, Biointrasiliciclastic packstone/wackestone. See further detail in text. (Based on Caballeri and Armella, 1999)**

tree cones and trunks) resulting in deposition of facies F6.

LACUSTRINE SUBENVIRONMENTS AND DEPOSITIONAL FRAMEWORK

The sequences of the Cañadón Asfalto Formation were deposited in small hydrologically-closed, climatically sensitive lacustrine basins, where minor climatic changes resulted in relevant lacustrine expansion and contraction cycles. These cycles were paralleled by physical and hydrochemical variations that resulted in silica and sulphate precipitation during the evaporative water concentration stages (Cabaleri and Armella, 1999; Cabaleri et al., 1999b)

The Cerro Cóndor Biohermal Belt acted as a physiographic barrier that controlled the sedimentation and the distribution of various subenvironments (Fig. 6). The development of the bioherm was affected by lake- expansion and contraction cycles under arid to semiarid climatic conditions where rainfall was probably the principal water-level control.

In shallow and marginal low gradient lacustrine environments, such as the one interpreted in the study area, relatively small changes in the lacustrine level may have a large impact on the depositional regimes and the environmental distribution. As a result, a great variation of facies, along with lateral and vertical changes, is frequently observed in the studied sequences together with shallowing-upward cycles that show widespread subaerial exposure features (Platt and Wright, 1991).

The Cerro Cóndor Biohermal Belt divided the lacustrine basin into two well-differentiated sectors (Fig. 6): an extensive littoral area represented by littoral to supralittoral facies (Cañadón Las Chacritas), and a wide zone characterized by a shallow littoral subenvironment with estromatolitic patch reef and palustrine areas (Sierra de Pichiñanes). The reported palustrine features include subaerial exposure surfaces with soil crusts, brecciation, mudcracks and rhizolites. These characteristics are similar to the palustrine features mentioned in Dunagan and Driese (1999). Climate largely influenced the evolution of palustrine facies and specific palustrine features have been tied to three climatic regimes: “sub-arid, intermediate and sub-humid” (Platt and Wright, 1992). In the case of the Cañadón Asfalto Formation, palustrine facies were probably formed under sub-arid conditions and are generally dominated by calcrete developments, evaporites, brecciation, black sulphate stromatolites, and laminar coatings of cyanobacterial origin.

The Cerro Cóndor Biohermal Belt also acted as a physical barrier within the lacustrine basin producing a small pan lake (Cañadón Carrizal). This part of the lacustrine system was isolated from the main carbonate-producing basin, where carbonate-evaporite sequences with levels of Magadi-type chert, tabular glauberite and enterolithic anhydrite developed. Sedimentation was controlled by the cycles of expansion (carbonate formation) and contraction which favoured silica and sulphate precipitation (Arp, 1995).

Littoral facies include largely bioclastic deposits with abundant charophyte (stems and gyrogonites), foraminifer, gastropode and ostracode remains, as well as microbially laminated limestones (Cabaleri and Armella, 1999). Eulittoral facies were formed due to subaerial exposure of the littoral carbonate sediments and indicate periodic fluctuations of the water level in the lake (Freytet and Plaziat, 1982; Platt and Wright, 1991).

The biohermal belt fringed an extensive area of the lacustrine basin (Sierra de Pichiñanes) where deep infralittoral to shallow eulittoral facies developed, with stromatolite patch reef formation.

The lacustrine systems received sporadic fluvial discharges of different energy that deposited sands with different grain sizes (fine to coarse). Small-size delta lobes,

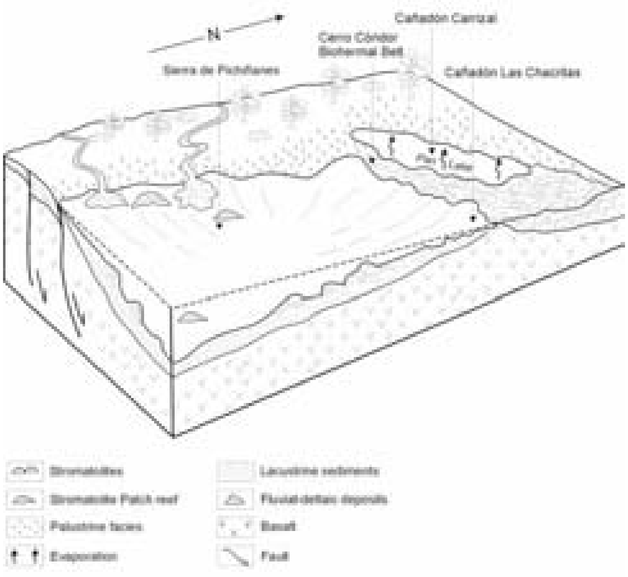


FIGURE 6| **Schematic representation of the lacustrine subenvironments of the Cañadón Asfalto Formation in the Cerro Cóndor area showing the influence of the biohermal belt on the lacustrine system of Cerro Cóndor. The diagram shows a southward perspective (see Figs. 1 and 3 for location of the localities represented in the sketch). Notice the distribution of the palustrine facies and pan lake of the Cañadón Carrizal (to the South) that developed behind the bioherm belt, the littoral-supralittoral facies of the Cañadón Las Chacritas (to the North), the littoral facies including stromatolite patch reefs and the palustrine facies of Sierra de Pichiñanes. The fluvial-deltaic influence on the lacustrine basin is shown at the upper part of the sketch. Not to scale.**

channeled levels with poorly sorted conglomerates, and mouth bars can be recognized at Cañadón Las Chacritas. Isolated bulbous stromatolites were formed in the infralittoral zone. This type of stromatolites is commonly associated with mouths of ephemeral fluvial channels (Bertrand-Sarfati et al., 1994).

Hyperconcentrated-flow deposits with vertebrate remains were observed in the upper section of the Las Chacritas Member, at Cañadón Las Chacritas. These flows were the result of fault reactivation in the pull-apart-type.

CONCLUSIONS

The Cañadón Asfalto Formation in the Cerro Cóndor area records lacustrine deposition in a probable pull-apart strike-slip basin. Paleoenvironmental conditions were controlled by climatic changes with a predominance of warm sub-arid climatic conditions. These climatic changes resulted in expansion and contraction cycles of the hydrologically closed water bodies that were influenced by rainfall changes.

The analysis of the Cañadón Asfalto Formation suggests that its sequences were deposited in a littoral-lacustrine depositional framework that would include supralittoral, eulittoral and shallow infralittoral subenvironments.

The supralittoral subenvironment is characterized by mudstones that show storm event deposits and dry period evidences, including evaporite layers. On the other hand, the eulittoral subenvironment was affected by weak water currents during humid periods, and remained exposed only during persistently dry periods. The infralittoral subenvironment was very shallow, nutrient-rich and affected by macrophyte growth and rooting. This subenvironment could be also affected by the water level lowering during lacustrine-contraction stages and remain temporarily exposed.

In the eulittoral facies of the paleolake complex, especially near Cerro Cóndor locality, Cañadón Las Chacritas, Cañadón Carrizal and Sierra de Pichiñanes, an extensive biohermal belt developed. This belt acted as a physiographic barrier that controlled the sedimentation and modified the distribution of various lake subenvironments: littoral-supralittoral (Cañadón Las Chacritas), pan lake (Cañadón Carrizal), and palustrine and deeper facies with stromotolitic patch reef development (Sierra de Pichiñanes).

The lacustrine record of the Cañadón Asfalto Formation is a clear example of the large influence exerted by depositional features developed during high water level stages (i.e. microbial biohermal belts and ridges) on the lacustrine sedimentation that may take place during later low water level stages. This influence would be mainly exerted through the hydrological and physical isolation of extensive lacustrine zones from the main lacustrine water body and would be especially efficient in hydrologically closed, low gradient basins.

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