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THE STRATIGRAPHIC AND PALEOENVIRONMENTAL SIGNIFICANCE OF THE REGRESSIVE MONTE OBSERVACIÓN MEMBER, EARLY MIOCENE OF THE AUSTRAL BASIN, PATAGONIA

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ABSTRACT

The stratigraphy of the Oligocene-Miocene southern Patagonia marine deposits has been extensively discussed. However, the Monte Observación Member (MOM) was vaguely defined and many aspects related to its boundaries, distribution, lithology and paleoenvironments of deposition remain uncertain. In this paper we present results obtained from the field survey of several early Miocene outcrops exposed along the Atlantic coast of southern Santa Cruz Province (Austral-Magallanes Basin). They correspond to the transitional interval between the marine shelf Monte León Formation and the terrestrial Santa Cruz Formation. Sedimentological analysis allowed to define six Facies Associations (FAs) for the studied beds: FA-1 corresponds to inner shelf to lower shoreface deposits; FA-2 corresponds to prodelta to distal delta-front deposits; FA-3 corresponds to proximal delta-front deposits; FA-4 corresponds to terminal distributary channels and meandering channels in the delta plain; FA-5 corresponds to inter-distributary bays and tidal flats; and finally FA-6 corresponds to the upper delta plain deposits. In turn, analysis of fossil concentrations allowed defining three main genetic types: biogenic, sedimentologic, and mixed biogenic-sedimentologic concentrations. Biogenic concentrations are represented by beds and lenses of the marginal marine oyster *Crassostrea orbignyi* (Ihering), which is a significant fossil invertebrate typical of the transitional deposits and is the last invertebrate showing marine influence in all the studied sections and beyond. Sedimentologic and mixed biogenic-sedimentologic concentrations exhibit different attributes and evidence the action of different processes. They include from mostly monospecific within-habitat reworked concentrations, with little post-morten disturbance to polyspecific concentrations bearing the imprint of various taphonomic processes. The distribution of FAs suggest a regressive system that prograded over shelf deposits in the form of deltaic depositional systems with tidal influence. This analysis allowed to define better the MOM, which shows: 1) null to very low bioturbation degrees; 2) a reduced autochthonous invertebrate faunal content; 3) a well-stratified pattern given by the alternating lithologies, and 4) abundant decimetric intercalations of gray to greenish sandstone beds. The fast accumulation of the MOM, which would be part of the regressive phase of the Monte León Formation, could be the consequence of a peak of siliciclastic and volcaniclastic input into the Austral Basin, produced as a result of rapid exhumation of the Southern Patagonian Andes during the early Miocene.

INTRODUCTION

Sedimentary rocks of the early Miocene Monte Observación Member (MOM) (Di Paola and Marchese, 1973) are exposed along the Atlantic coast of southern Santa Cruz Province (Austral-Magallanes Basin). These deposits are relevant for the geologic history of the Austral Basin since they represent the passage from the early Miocene marine shelf to fully terrestrial environmental conditions, with a supposed connection to the Miocene Andean uplift (*e.g.*, Ghiglione *et al.*, 2016).

The lithostratigraphic status, age and paleoenvironmental significance of the rocks today included in the MOM are being discussed since the first studies of Ameghino and Hatcher at the end of the 19th century (*e.g.*, Ameghino, 1894, 1898, 1900-1902; Hatcher, 1897, 1900). Today, a precise sedimentological analysis, as well as a detailed discussion about their stratigraphic meaning, is still lacking. Neither the member boundaries, particularly their relationship with the underlying Punta Entrada Member (Bertels, 1980), nor the type section were well defined. As a consequence, the recognition and mapping of these deposits received little attention in later works. Furthermore, these uncertainties led to the fact that the unit was not considered in geologic studies and mapping at the coast of Santa Cruz Province (*e.g.*, Sacomani *et al.*, 2012).

In order to resolve these problems and improve the utility, individuality, and mapping of the MOM, in this paper we present an integrated analysis of the unit in several localities on the southeast coast of the Santa Cruz province (Fig. 1). A brief review of all the significant published work bearing on the stratigraphy of this unit has been attempted. Also, we better delimit its boundaries and areal extension, and provide a more precise location and drawing of the type section. In addition, the study includes facies analysis, description of the more prominent intercalated fossil concentrations, and a sequence stratigraphic interpretation. The final aim is to contribute to a wider regional synthesis of the geology and paleogeography of the Austral-Magallanes Basin during the early Miocene.

GEOLOGICAL CONTEXT

The rocks studied here are part of the sedimentary fill of the Austral-Magallanes Basin during the development of its retro-foreland basin stage in response to compression arising by subduction of the Pacific oceanic plates (Farallon-Aluk-Nazca-Antartic) beneath the South American plate (Ghiglione *et al.*, 2010, 2015; Fosdick *et al.*, 2013).

Since the study area has not been affected by the Andean tectonic inversion, the oldest rocks exposed are those of the lower Miocene epi- and pyroclastic marine Monte León Formation. This lithostratigraphic unit was formally introduced by Bertels (1970) for part of the rocks formed as the consequence of deposition during the Atlantic *"Patagoniense"* transgression in Patagonia, specifically for those informally known as the *"Leonense"* stage of Ameghino (1898). Bertels (1980) later changed the lithostratigraphic rank of these rocks to the Punta Entrada Member of the Monte León Formation. The typical Monte León Formation (*i.e.*, the Punta Entrada Member) includes mainly siltstones and clayish fine-grained grayish yellow sandstones with abundant pyroclastic material and intercalated coquinas. It lies exposed between the coastal areas just north of Puerto San Julián, southwards to almost the southern boundary of the Monte León National Park (MLNP) (Fig. 1). The rocks of the Monte León Formation were deposited in a shallow marine setting ranging from inner shelf through nearshore subtidal to intertidal environments (Parras and Griffin, 2009). More open marine conditions (probably mid- to outer shelf) were suggested for the bottom of the unit by Náñez *et al.* (2009) at the Puerto San Julián area. As to the age of the unit, some contributions in the past few years have considered it as early Miocene based on foraminifera and palynomorphs (*e.g.*, Barreda and Palamarczuk, 2000; Náñez *et al.*, 2009), as well as on $^{87}Sr/^{86}Sr$ age dates drawn from carbonate shells (Parras *et al.*, 2012). This age was confirmed by radiometric dating of the basal strata of the overlying Santa Cruz Formation in 17.7 Ma (Perkins *et al.*, 2012).

Overlying the marine Punta Entrada Member are the marginal-marine deposits of the MOM, a unit introduced by Di Paola and Marchese (1973) as the upper member of the then accepted *"Formación Patagonia"*. Later, it was considered by Bertels (1980) as the upper member of the Monte León Formation (see discussion below). The MOM includes mainly massive to laminated tuffaceous siltstones and fine- to medium-grained clayish sandstones, with intercalations of cross-stratified medium- to coarse-

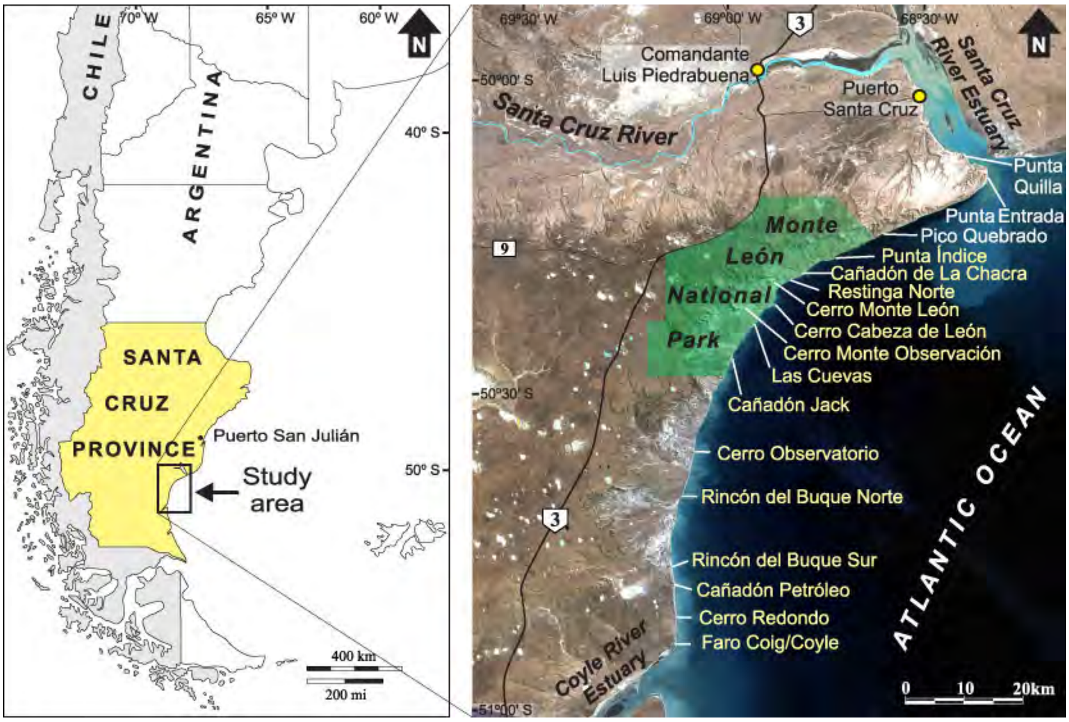

Figure 1. Regional and local maps of the study area, located in the southeastern coast of the Santa Cruz Province. Highlighted in yellow are the studied localities ranging from the north extreme of the Monte León National Park to the Coyle River mouth.

grained sandstones, reworked shell beds, and oyster reefs. According to Raigemborn *et al*. (2015), in Rincón del Buque area (Fig. 1), the levels equivalent to our MOM reflects a changing depositional environment from the outer part through the central to inner part of a tide-dominated estuary. Only one radiometric age of 19.3 Ma has been reported from the MOM based on ^{40}Ar/^{39}Ar data from a volcanic tuff bed positioned at its top (Bown and Fleagle, 1993; Fleagle *et al*., 1995). However, this age is at odds with the ^{87}Sr/^{86}Sr age of the uppermost beds of the underlying Punta Entrada Member (~18.3–17.9 Ma, Parras *et al*., 2012, Cabeza de León locality; Fig. 1). Recently, the 19.3 Ma age has been questioned by Perkins *et al*. (2012) who, based on sediment accumulation rates and the correlation with dated tephra layers in other sections, considered a ~17.7 Ma age for the previously dated tuff bed.

Overlying, and in part intercalated with previous deposits, are the very rich vertebrate fossiliferous sedimentary rocks of the Burdigalian Santa Cruz Formation (Vizcaíno *et al*., 2012). In the coastal area of Santa Cruz Province, this unit consists of mainly tuffaceous mudstones and sandstones with intercalated siliciclastic lenticular sandstones and paleosols (Matheos and Raigemborn, 2012; Raigemborn *et al*., 2015, 2018). The unit was interpreted as formed by coalescing and aggrading alluvial deposits with facies of continental-marine transitional environment at its base (Matheos and Raigemborn, 2012; Perkins *et al*., 2012; Raigemborn *et al*., 2015). The early Neogene rocks are unconformably overlain by the gravels and sands deposited during the late Miocene and early Pliocene, and by fluvial, marine and aeolian Quaternary deposits (Sacomani *et al*., 2012).

The Monte Observación Member: From Darwin's to recent contributions

The stratigraphy of the Cenozoic marine deposits of southern Patagonia has been a matter of debate, leading to a complex terminology since the pioneer studies of Darwin (1839, 1846, see Fig. 2). The notable English naturalist did geological observations in the coastal cliffs of the Santa Cruz Province and along the Santa Cruz River, recognizing marine deposits, which he included in the *"great Patagonian tertiary formation"* (Darwin, 1846).

Towards the end of the 19th century and the beginning of the 20th century arose the question about the subdivision or not of these deposits into units of different ages. Thereby, Ameghino (1894, 1898, 1900-1902, 1906) proposed a subdivision in different formations and stages with a chronological sense, and with different spelling according to the

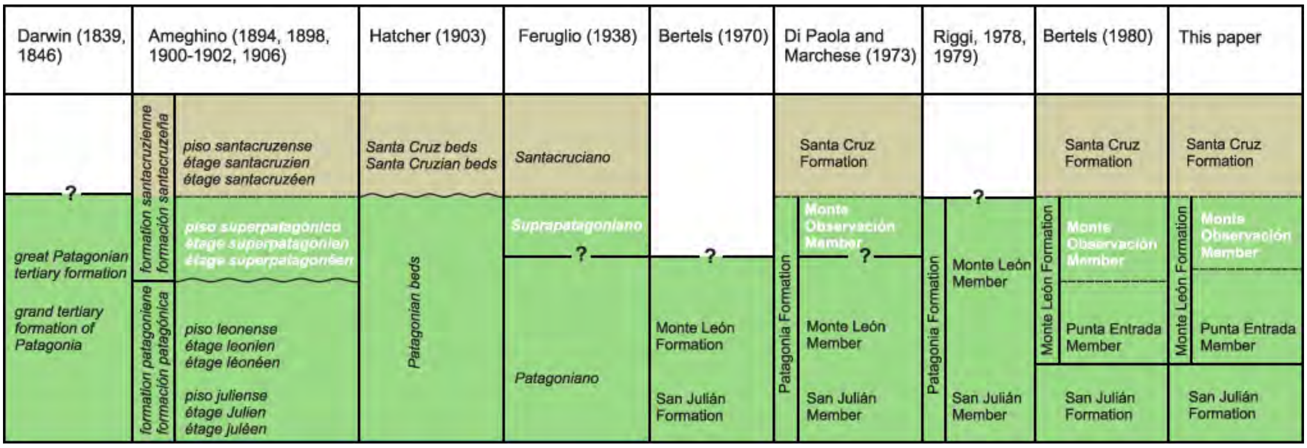

Figure 2. Most representative previous denominations for beds included in the present MOM and related units, at the southeastern coast of the Santa Cruz Province. Green and brown areas correspond to marine/marginal-marine and terrestrial deposits, respectively. When authors did considerations about conformably or unconformably character of the MOM contacts, these are marked with a dashed or wavy line, respectively.

language of the publication (Fig. 2), including all the beds in the Eocene. This author proposed the name of "*formation patagonienne*" (Ameghino, 1894, 1900-1902, 1906) or "*formación patagónica*" (Ameghino, 1898) for the older Cenozoic marine strata exposed at the coast of Patagonia, and subdivided them in the "*piso juliense*" (Ameghino, 1898), which is well developed in the Gran Bajo de San Julián, and the "*piso leonense*" (Ameghino, 1898), well characterized at San Julián, mouth of the Santa Cruz River, and Monte León. Above these deposits, he recognized a system of marine and terrestrial beds to which he denominated "*formation santacruzienne*" (Ameghino, 1894, 1900-1902, 1906) or "*formación santacruzeña*" (Ameghino, 1898), constituted by two stages of different aspect and origin, but of the same age and interdigitated in their contact. The lower one, which would be marine, was called "*piso superpatagónico*" (Ameghino, 1898). The upper unit was called "*piso santacruzense*" (Ameghino, 1898), of continental character and with mammals. At the coast of the Santa Cruz Province the "*superpatag*ónico" stage would be formed by ~30 m of marine deposits, which extended from south of the mouth of the Santa Cruz River to a little bit south of the mouth of the Coyle River (Fig. 1), where it appears at the bottom of the cliffs (Ameghino, 1900-1902, 1906).

The Ameghino' stratigraphic divisions were criticized by Hatcher (1897, 1900, 1903), who thought that the marine beds (*i.e.*, "*juliense*" and "*leonense*") were part of the same formation, not divisible in stages, with the same fauna, but presenting different facies. With regards to the stratigraphic relations between the marine and terrestrial beds (*i.e.*, the "*superpatagónico*" and "*santacruzense*" stages), Hatcher (1897) also disagree with Ameghino, admitting the existence of an unconformity between them (Fig. 2).

Renewed major contributions to this issue were realized toward the middle part to the 20th century by Feruglio (1938, 1949), who provided the description of various geological sections from the area of the actual MLNP to the mouth of the Coyle River (Fig. 1). This author highlights, in coincidence with Ameghino, that the transition between the "*Suprapatagoniano*" and the "*Santacruciano*" is gradual (Fig. 2), being the passage from the marine to continental deposits characterized by slow regression. Nevertheless, he thought that it was better reserving the name "*Santacruciano*" to the continental deposits and the name "*Suprapatagoniano*" to the marine beds (Feruglio, 1938).

By the end of the 20th century, the controversy about the age of the deposits and the validity of the Ameghino stratigraphic divisions continued. On the one hand, A. Bertels began to perform micropaleontological studies that contributed to the formal lithostratigraphic "*Patagoniense*" nomenclature and divisions. In this sense, Bertels (1970) replaced the chronostratigraphic terms "*Juliense*" and "*Leonense*", proposed by Ameghino, for the lithostratigraphic terms San Julián Formation and Monte León Formation, respectively (Fig. 2). On the other hand, other authors (*e.g.*, Russo and Flores, 1972; Di Paola and Marchese, 1973; Riggi, 1978, 1979; Russo *et al.*, 1980) did not accept this division and included in the "*Formación Patagonia*" all the marine fossiliferous deposits (Fig. 2).

Di Paola and Marchese (1973, pp. 214-216), by means of petrographic studies on samples collected in the surroundings of Monte Observación (=Cerro Observación), introduced for the first time the formal term of the MOM for the uppermost part of the "*Formación Patagonia*" (Fig. 2). In this way the latter would be formed by the "*Miembro San Julián*" (lower), the "*Miembro Monte León*" (middle) and the "*Miembro Monte Observación*" (upper). As defined by Di Paola and Marchese (1973), the MOM includes ~27 m of mostly tuffs and tuffaceous sandstones enclosed between two banks with abundant oysters. The new unit would have features common to the Monte León Member in its lower part, while towards the top it would looks like the overlying Santa Cruz Formation with which was intercalated. For the upper boundary of the unit Di Paola and Marchese (1973) chose arbitrarily the uppermost bed with marine invertebrates, intercalated between sedimentary rocks similar to those of the Santa Cruz Formation.

In the meantime, Bertels continued with her scheme, and based on lithologic criteria subdivided the Monte León Formation in a lithostratigraphic unit of lower rank: the Punta Entrada Member (Bertels, 1980). She also included in the Monte León Formation the upper MOM (Fig. 2). For the lower member, Bertels (1980) established the type section at the mouth of the Santa Cruz River (Monte Entrance). For the upper MOM, she provided neither location nor figure of the type section. Bertels (1980) considered the bottom and top of this member as gradual, and in coincidence with Di Paola and Marchese (1973) established the top in the last oyster bank, intercalated between sandstones of the Santa Cruz Formation. Bertels (1980) indicated that the MOM replaces the chronostratigraphic term "*Piso superpatag*ónico" of Ameghino, without giving explanations about her decision of including this member in the Monte León Formation. Bertels (1980) did not discuss the opinion either of Di Paola and Marchese (1973), who had defined this unit as a member of the then accepted "*Formación Patagonia*", overlying the Monte León member of that formation.

After this long and confusing history, as presently defined, the MOM represents only in part the chronostratigraphic "*superpatag*ónico" stage of Ameghino (1898). During the last years, the sedimentary rocks of this member has been included either in the Monte León Formation or as a marine intercalation at the bottom of the overlying continental Santa Cruz Formation (*e.g.*, Parras and Griffin, 2009; Griffin and Parras, 2012; Fernicola *et al.*, 2014; Raigemborn *et al.*, 2015).

METHODS

We carried out field surveys along ~80 km of the southeast coast of the Santa Cruz Province, where the MOM was present. This region extends from nearly the northern boundary of the MLNP in the north to the mouth of the Coyle River in the south (Fig. 1). Exposures form part of the coastal cliffs and reach as much as 90 m high, although most range between 15 and 30 m. Poor-quality, partly covered outcrops appear inland along creeks and small hills. To characterize lithology, we used high resolution photography for the cliffy outcrops, whereas in low relief outcrops we measured sedimentary sections and made detailed facies observations.

Sedimentological observations were made in 14 localities (Fig. 1) and detailed stratigraphic-sedimentologic sections were measured at five representative localities. From north to south, measured sections are Cañadón de La Chacra (S 50º 18' 30''; W 68º 48' 41''), Restinga Norte/Cerro Monte León (S 50º 19' 16''; W 68º 53' 12''), Las Cuevas/Cerro Monte Observación (=Cerro Observación) (S 50º 21' 44''; W 68º 57' 20''), Cañadón Jack (S 50° 27' 35"; W 69° 0' 1"), and Cerro Redondo (S 50º 51' 47''; W 69º 7' 42''). We also included in our analysis, the observations and sections measured by Raigemborn *et al.* (2015) in Rincón del Buque.

For each measured section, bed thickness, lithology, grain-size, sedimentary structures, fossil content, color, and nature of limiting surfaces were registered. When possible, paleocurrents were measured for current ripple lamination or cross bedding structures. In the fossil concentrations, additional stratigraphic (lateral extent and geometry), sedimentologic (orientation, close-packing, and size-sorting of the bioclasts), and taphonomic (disarticulation, fragmentation, abrasion, dissolution, encrustation, and bioerosion) data were recorded. Close-packing and

Facies code	Lithology	Physical sedimentary structures	Bioturbation and trace fossils	Invertebrate fossil content	Depositional process
B	Dominated by bioclastic particles of variable size and packing. Matrix composed of either sandstone or mudstone	Structureless, parallel laminated or cross-bedded	Variable bioturbation. Some horizons show no trace fossils whereas others are strongly bioturbated	Dominated by marine bivalves like oysters and Mactridae. Gastropods common. Abundant undetermined bioclastic particles	Concentration of biogenic hard parts of marine invertebrates in different environmental and stratigraphic contexts
St	Medium to coarse sandstones	Trough cross-bedding. Occasionally with mud drapes on the foresets	Scarce. Mainly *Skolithos*	Scarce. Fragmented bivalve remains	Migration of 3D subaqueous dunes and subsequent bioturbation
Sp	Medium to coarse sandstones	Planar cross-bedding. Occasionally with mud drapes on the foresets	Scarce. Mainly *Skolithos*	Scarce. Fragmented bivalve remains	Migration of 2D subaqueous dunes and subsequent bioturbation
Sr	Fine sandstones	Ripple lamination. Climbing ripples usually observed	Scarce bioturbation. *Planolites*	——	Tractive deposition by wave or current ripple migration and subsequent bioturbation
Sh	Fine to medium sandstones, well sorted. Gray to light gray	Plane-parallel lamination	Scarce bioturbation. *Ophiomorpha, Skolithos*	Scarce. Fragmented bivalve remains	Tractive deposits formed through upper flow regime plane bed and subsequent marine bioturbation
Sd	Fine sandstones, sometimes with mudstone layers forming heterolithic patterns	Convolute bedding or load structures	——	——	Deformation of water-saturated horizons due to overloading
Smb	Sand-dominated mixture of fine sand and mud. Sometimes tuffaceous	Structureless. Some calcareous concretions	Highly bioturbated. *Thalassinoides, Rosselia*, *Planolites*, *Palaeophycus*, *Asterosoma*, *Chondrites*, *Teichichnus*, *Cylindrichnus* and *Taenidium*	Abundant thick-shelled oysters. Also pectinids, gastropods and other bivalves. Variable degree of reworking	The lack of tractive sedimentary structures is interpreted as the result of intense reworking of bottom sediments by organisms in shallow marine environments
Ht	Intercalation of mudstones and fine sandstones	Plane-parallel lamination, current and wave ripple lamination	Scarce to moderate. *Planolites, Skolithos, Teichichnus*	Occasionally *Crassostrea orbignyi*	Alternate conditions of traction and decantation processes and subsequent marine bioturbation
IHS	Intercalation of mudstone and fine sandstone layers showing low angle of inclination	Plane-parallel lamination, current ripples	Poorly to moderately bioturbated. *Planolites, Teichichnus, Thalassinoides*	Occasionally *Crassostrea orbignyi*	Alternate conditions of traction and decantation processes occurring on an inclined surface, probably a point bar of a meandering channel. Subsequent marine bioturbation

Fmb	Dominated by tuffaceous silt. Clay and fine-sand mixed in low proportions. Whitish to light yellow	Structureless	Highly bioturbated. *Thalassinoides*, *Rosselia*, *Planolites*, *Palaeophycus*, *Asterosoma*, *Chondrites*, *Teichichnus*, *Cylindrichnus* and *Taenidium*	Scarce to moderate. Dominated by bivalves and turritellid gastropods. Articulated decapods common	The lack of tractive sedimentary structures is interpreted as the result of intense reworking of bottom sediments by organisms in shallow marine environments. Distal position in relation to Smb
Fm	Light colored mudstone	Structureless	Scarce to absent	—	Fast deposition of mud from a water column with elevated suspended sediment concentration
Fl	Silt and clay	Plane-parallel lamination	Low to null bioturbation degree. *Planolites*, *Skolithos*, root traces	—	Decantation of fine particles under low flow energy conditions. Lamination produced by fluctuating energy conditions. Occasional subaereal exposure and pedogenic modification
Fp	Silt and clay, with subordinate fine sand. Usually greenish or gray	Structureless. Remains of plane-parallel or current ripple lamination. Slikensides and cutans	Moderate to absent. Rhizoliths common	—	Accumulation of fine sediments in low energy environments and subsequent modification by soil processes

Table 1. List of sedimentary facies defined for the upper part of the Punta Entrada Member and the MOM.

size-sorting were estimated following the semi-quantitative scale of bioclastic fabric types of Kidwell and Holland (1991). Terminology for geometry of concentrations and orientation of bioclasts followed Kidwell *et al*. (1986).

A series of thick, laterally continuous tuff horizons lying in the transition zone between the Monte León and the Santa Cruz formations allow a physical correlation between the studied localities. One of these tuffs can be recognized from the actual MLNP to the Coyle River and was early recognized by Feruglio (1949), who named it "B" bank, while Perkins *et al*. (2012) named it "PAT" at Cerro Monte León. When possible, the observations were stratigraphically positioned in relation to this tuff horizon.

SEDIMENTOLOGY AND DEPOSITIONAL SETTINGS

An integrated sedimentological description of the MOM and adjacent lithostratigraphic units in all the surveyed localities was done following the classic criterion of facies analysis (Walker, 1992). We defined basic descriptive facies (Table 1), which allow interpreting sedimentary processes. Facies, in turn, were grouped into facies associations (FAs), representing depositional environments (Table 2). Six FAs were defined which, following their stratigraphic order, are described and interpreted below.

Facies Association 1

Description. FA-1 is composed of thoroughly bioturbated very fine-grained sandstones, silty sandstones, fine-grained tuffs, and siltstones (Facies Smb and Fmb; Table 1 and Fig. 3a). Primary sedimentary structures are completely obscured by bioturbation (Fig. 3a). The high degree of bioturbation and the high ichnodiversity resulted in a complex ichnofabric, making identification of ichnogenera difficult. The trace fossil association is composed mainly by *Thalassinoides* isp., *Rosselia* isp., *Scolicia* isp., *Planolites* isp., *Palaeophycus* isp., *Asterosoma* isp., *Chondrites* isp., *Teichichnus* isp., *Cylindrichnus* isp., and *Taenidium* isp. Marine calcareous invertebrates are abundant, showing high diversity, low abrasion, and mostly loose packing, including diverse bivalves, gastropods, brachiopods, and crustaceans. Thin beds with concentration of *Turritella* specimens can be observed. Thin patches with high density of

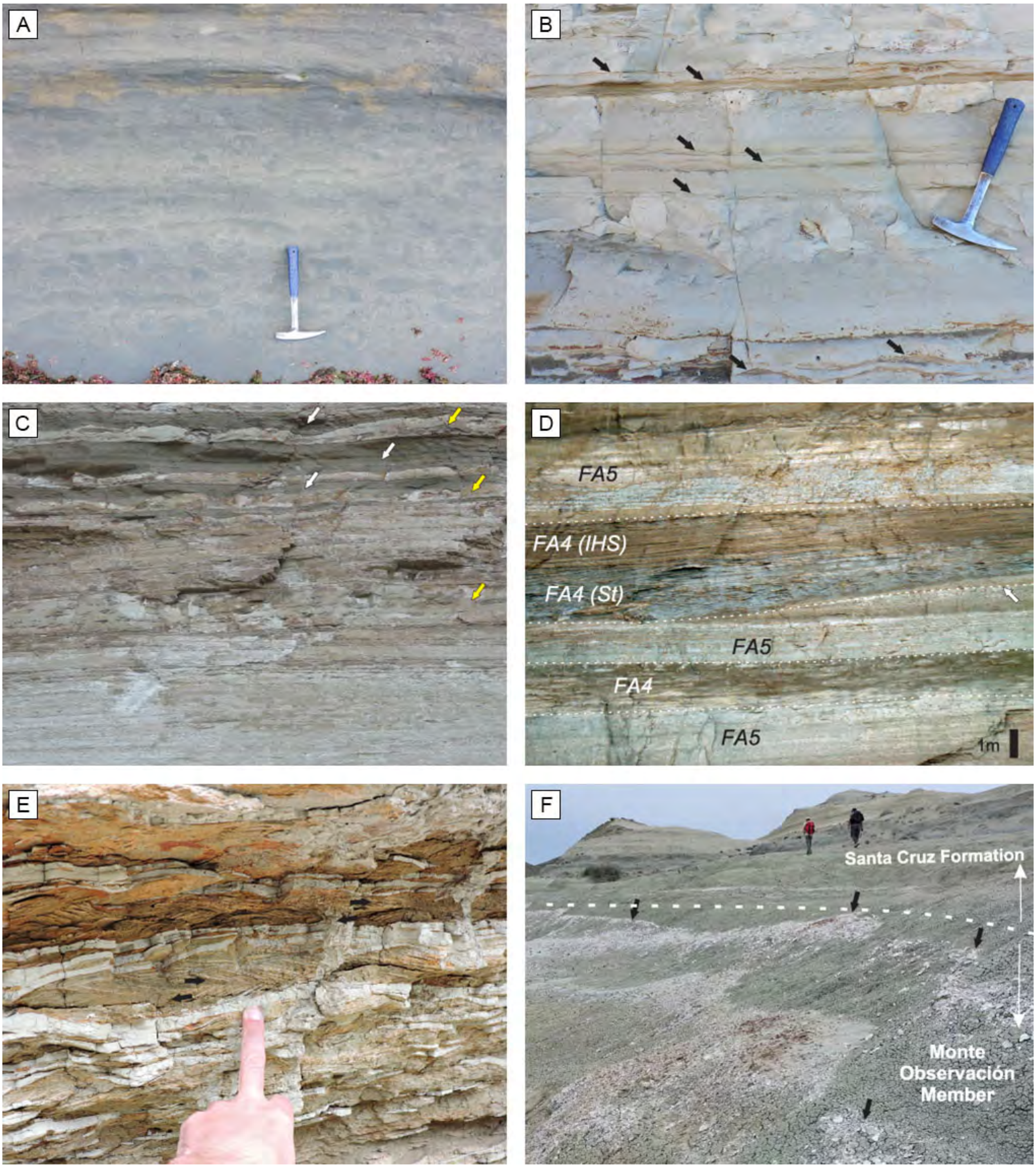

Figure 3. Representative views of FAs in outcrops. **a)** Thoroughly bioturbated deposits (Facies Smb) of FA-1 at Cerro Cabeza de León, in this case dominated by the trace fossil *Scolicia* isp. **b)** Thin fine-grained sandstone layers (black arrows) with current ripple (Facies Sr) or plane-parallel lamination (Facies Sh) intercalated between structureless mudstones (Facies Fm or Fmb). Restinga Norte locality. These intercalations form the prodelta deposits of the FA-2. **c)** Centimetric to decimetric intercalations of sandstone and mudstone beds of FA-3 at Cañadón Jack. Note thickening-upward of sandstones beds, the abundant soft sediment deformation structures (Facies Sd; yellow arrows) and the laminated sandstones (Facies Sh) in the thickest beds (white arrows). As scale, the uppermost thick sandstone bed is about 1 m thick. **d)** Intercalations of lenticular sandstone channel deposits of FA-4 and interdistributary fine-grained deposits of FA-5 at Restinga Norte. The base of the main channel in the center of the photograph is covered by a bioclastic lag (Facies B; white arrow), which is truncated by trough cross-bedded sandstones (Facies St), which in turn grade upward to IHS deposits. **e)** Delicate intercalation of whitish mudstone and -current ripple laminated

bioclastic particles (Facies B; see Table 1) are also observed, usually dominated by large-sized oysters.

Interpretation. The fine grain-size of these deposits indicates sedimentation in low energy environments. The abundant invertebrate and trace fossil assemblage suggest open marine settings with normal marine salinity in the photic zone, with several ichnogenera composing the *Cruziana* ichnofacies (MacEachern *et al.*, 2007). The high degree of bioturbation suggests low sedimentation rates which give time enough for the benthic fauna to completely rework the substrate. Marine invertebrates are mostly autochthonous or parautochthonous, and the scarce beds with reworked shells indicates the absence or minor influence of major reworking events. Beds showing high proportion of fine-grained volcanic ash suggest short periods of increased sedimentation rates, allowing exceptional preservation of some marine fossils (*e.g.*, Crawford *et al.*, 2008). Thin beds with concentration of invertebrates (especially *Turritella* and oysters) suggest sporadic reworking of the bottom by storm waves. All these evidences suggest deposition in a shallow marine setting with normal salinity, such as the inner shelf to the lower shoreface environment.

Facies Association 2

Description. FA-2 is composed of a mud-dominated succession punctuated by centimeters-thick intercalations of fine-to very fine-grained sandstones with flat stratification architecture (Fig. 3b). Mud beds are of decimeter-thick scale, up to 50 cm thick. When present, lamination is diffuse (Facies Fl, see Table 1) and many beds are structureless (Facies Fmb or Fm; Table 1 and Fig. 3b). Thin sandy layers fines upward and show tractive sedimentary structures, such as current-ripple (Facies Sr, see Table 1) or parallel lamination (Facies Sh, see Table 1). More rarely, wave ripple lamination (Facies Sr, see Table 1) is observed. They are usually few centimeters thick and an upward stratigraphic thickening trend can be recognized. Some layers are laterally discontinuous, showing ripple form-sets. The dominant paleocurrent direction from current ripple laminations is towards the east. Bioturbation is heterogeneously distributed specially in the mudstone beds, with some beds showing sparse traces and others showing high abundance of traces. The trace fossil suite consists of a low diversity association dominated by *Planolites* isp. and *Teichichnus* isp. FA-2 grades upward to FA-3 (see below).

Interpretation. The elevated proportion of mud, the paucity of marine bioturbation, and the intercalation of sandy layers with tractive current structures suggest a depositional zone within the distal reaches of a delta front. Sand layers with current ripple lamination suggest the action of tractive flows produced during peaks of fluvial discharge, which are capped by thicker mud layers produced after the decantation of the fine-grained material in suspension. In some cases, a transitional passage between both stages can be observed. The alternation of sand-mud layers suggests an episodic (seasonal?) character of the adjacent fluvial system. The thickening-upward trend observed in sandstone layers suggests the progradation of the delta front/ mouth bar complex into the basin (Bhattacharya, 2010). The low diversity trace fossil assemblage is interpreted as an impoverished expression of the *Cruziana* ichnofacies (Buatois *et al.*, 2005; MacEachern *et al.*, 2007). This is especially evident when compared to that of FA-1.

Facies Association 3

Description. In all localities where FA-3 could be observed, it lies transitionally above the FA-2, forming a thickening upward succession (Fig. 3c). It is composed of intercalations of decimeter-thick fine-grained sandstone and mudstone beds with tabular or wedge geometry (Fig. 3c). Most sandstone beds are tabular, whereas few show lenticular shape at the outcrop scale, showing concave-up base and flat top, and others wedge out laterally when long distances are considered. Thicknesses of sandstone

sandstone layers (Facies Ht) of FA-5 at Cañadón de La Chacra. Note adjacent opposing paleocurrent directions of the cross-lamination highlighted by arrows, as well as abundant thick and white mud drapes. **f)** Greenish mudstones with pedogenic features (Facies Fp) showing lenticular intercalations of *Crassostrea orbignyi* concentrations (Facies B, black arrows) at Cerro Monte León. These deposits form part of the FA-6.

Code	Facies	Stratal arrangement	Dominant paleocurrents	Depositional environment
FA1	Smb; Fmb; B	Thick tabular beds	-----	Inner shelf to lower shoreface
FA2	Fl; Fmb; Fm; Sr; Sh	Intercalated centimeter-thick tabular beds; thickening upward	E	Prodelta to distal delta-front
FA3	Sr; Sh; Fm; St; Sd	Intercalated decimeter-thick tabular beds; thickening upward	ESE	Proximal delta-front
FA4	St; Sp; Sh; IHS	Lenticular; concave-up base and planar top	ENE	Deltaic distributary channels
FA5	Fl; Fm; Sr; Sh; Ht; B	Meter-thick tabular beds	-----	Inter-distributary bays and tidal flats
FA6	Fp; Fl; Sh	Meter-thick tabular beds	-----	Upper delta plain

Table 2. Facies Associations defined for the upper part of the Punta Entrada Member and the MOM.

beds are up to 50 cm, showing current ripple lamination sometimes with climbing arrangement (Facies Sr, see Table 1), and horizontal laminations (Facies Sh, see Table 1), whereas mudstones are mostly structureless (Facies Fm, see Table 1). Some tabular cross-bedded sandstone beds (Facies St, see Table 1) intercalate, especially up in the section. The dominant paleocurrents, measured in current ripple lamination and cross bedding, point towards the ESE. Bioturbation is generally low, similar to that of FA-2 although with less development, and marine invertebrates are absent. Levels with pervasive soft sediment deformation structures (Facies Sd, see Table 1) are common, showing mostly ball-and-pillow structures involving several sandstone-mudstone layers with diameters up to 1 m (Fig. 3c).

Interpretation. The intercalation of decimetric-scale sandstone beds with tractive structures and structureless mudstones suggest the alternation of periods of high and low fluvial discharge. This pattern, in combination to the reduced bioturbation, the lack of marine invertebrates, and the presence of deformation structures suggest overall high sedimentation rates in short periods of time. Sandstone beds are interpreted as mouth-bar deposits, which form as the flow condition at the channel mouth changes from confined to unconfined and velocity decreases (Bhattacharya, 2010). The small lenticular sandstone bodies interfingered with mouth bars are interpreted as terminal distributary channels with erosive base (Olariu and Bhattacharya, 2006). The coarsening upward trend observed for FA-3 suggests the progradation of deltaic mouth bars into the delta front.

Facies Association 4

Description. FA-4 is composed of lenticular bodies 1-5 m thick, showing planar tops and erosive, concave up bases that truncate the underlying FA-3 or FA-5 deposits (see below). These bodies show two types of infilling. One is composed of fine to medium-grained sandstone showing mainly trough-cross bedding (Facies St; Table 1 and Fig. 3d), although planar-cross bedding (Facies Sp, see Table 1) and plane-parallel lamination (Facies Sh, see Table 1) are also present. Internally, these bodies show a fining-upward trend (Fig. 3d) and usually low-angle inclined surfaces can be recognized. In some occasions these inclined surfaces are draped by a mudstone layer several centimeters-thick. The other type is composed of mud-rich sedimentary bodies showing inclined heterolithic stratification (IHS) deposits, forming lenticular bodies of 2-4 m thick. Internally, they are composed of alternating fine to very fine-grained sandstone and mudstone inclined layers that in some cases show rhythmic thickness variations. Sandstone layers display cross-lamination or planar-lamination. Some of these bodies show a coarsening upward trend. The dominant paleocurrents, measured in cross bedding point towards the ENE, although some reversions are observed. Bioturbation in the sandy bodies is low with a trace fossil suite dominated by *Ophiomorpha* isp. and locally by *Phycosiphon* isp. Bioturbation in the IHS is generally low and composed of the trace fossils *Skolithos* isp., *Palaeophycus* isp., *Teichichnus* isp. and *Planolites* isp. At the base, FA-4 shows lag deposits covering erosion surfaces (Fig. 3d), composed of medium-grained sandstones with broken and abraded marine bioclasts (mainly bivalves). In some occasions a mixture of both types of lenticular sedimentary bodies can be observed (Fig. 3d).

Interpretation. The erosional bases, the lenticular geometry, the fining-upward trend and the abundance of cross-bedded sandstones suggest that FA-4 is the result of the infilling of channels with sandy or muddy material. Low-angle IHS are interpreted as lateral accretion deposits within tide-influenced meandering channels transporting both tractive and suspended load (*e.g.*, Choi *et al.*, 2004), and highlight changes in the energy of the currents. Mud drapes covering these surfaces suggest (seasonal?) events of elevated suspended sediment concentrations. These channels are interpreted as formed in a deltaic environment, such as terminal distributary channels or channels crossing the delta plain with different influence of tidal and fluvial sedimentary processes (Dalrymple *et al.*, 2003; Bhattacharya, 2010; Martini and Sandrelli, 2015). This fluvial-marine mixing is also supported by the low diversity trace fossil suite formed by marine elements.

Facies Association 5

Description. FA-5 intercalates with FA-4 and is composed of tabular beds 5 to 10 m-thick dominated by fine-grained deposits with a general heterolithic pattern (Fig. 3e). It is composed of laminated or structureless mudstones (Facies Fl/Fm, see Table 1) with thin sandstone intercalations showing current ripple (Facies Sr, see Table 1) or horizontal lamination (Facies Sh, see Table 1). In some occasions, mudstone beds reach up to 0.5 m thick. When mudstone/sandstone intercalations are closely alternated, they are defined as heterolithic stratification (Facies Ht, see Table 1), showing dominance of either sandstone or mudstone deposits (Fig. 3e). Alternating layers with current ripple lamination usually show bipolar paleocurrent directions (Fig. 3e). In some occasions, thickening-upward successions of about 1 m thick can be observed. Bioturbation is variable although generally low, mostly concentrated in specific horizons and represented by isolated traces of *Ophiomorpha* isp. Some monospecific *Crassostrea orbignyi* reefs (Facies B; see Table 1) appear intercalated within these fine-grained deposits showing specimens articulated and in life position. In general, a fining-upward trend is recognized and, in some places, small lenticular fine-grained sandstone bodies appear intercalated.

Interpretation. The mud dominance of this FA suggests decantation of fines in low energy environments which undergo sporadic, and sometimes repetitive, reworking by currents. Thinly intercalations of sandstones and mudstone layers and bipolar paleocurrent directions suggest influence of tidal currents, probably in wide sub to intertidal flats (Dalrymple and Choi, 2007). The small thickening-upward successions suggest deposition by crevasse splays that prograde on the interdistributary areas (Rossi and Steel, 2016). In situ oyster accumulations could represent high-frequency marine flooding events. The presence of *Ophiomorpha* isp. traces in this FA suggests this brackish-water environments were colonized by opportunistic crustaceans, possibly in short moments of normal salinity.

Facies Association 6

Description. FA-6 is composed mostly of alternated tabular meter-scale strata of claystones, mudstones, and fine-grained sandstones, with some intercalated thick whitish tuff horizons. Greenish and light gray colorations are characteristic of this facies (Fig. 3f). Most of the sedimentary bodies are structureless; however, in some occasions horizontal lamination can be observed in mudstones (Facies Fl, see Table 1) and sandstones (Facies Sh, see Table 1). On the contrary, pedogenic features such as rhizoliths, slickensides and cutans, are frequently observed (Facies Fp, see Table 1). Terrestrial fossil vertebrates are common; thin horizons bearing articulated *Crassostrea orbingyi* specimens were recorded (Fig. 3f), representing the uppermost bed with marine invertebrates. FA-6 represents the uppermost deposits of the MOM and is usually observed in gradational contacts with the underlying FA-5. Additionally, it shows an upward gradation to the fully terrestrial deposits of the Santa Cruz Formation (Fig. 3f).

Interpretation. Based on the presence of paleosols and terrestrial vertebrates similar to that described by Raigemborn *et al*. (2015, 2018, in press), this setting is interpreted as deposited mostly in subaerial environments, likely the uppermost part of a coastal plain, with some influence of marine waters from the inter-distributary areas. The preservation of primary sedimentary structures suggests a low degree of paleosol development. The presence of layers with oysters in life position suggests that the low-lying areas were occasionally flooded by shallow marine waters, probably from the interdistributary bays of FA-5.

INVERTEBRATE FAUNA AND NATURE OF THE FOSSIL CONCENTRATIONS

The most conspicuous fossil invertebrate of the MOM is the oyster *Crassostrea orbignyi* (Ihering, 1897). This oyster forms biogenic, sedimentologic, and mixed biogenic-sedimentologic concentrations (*sensu* Kidwell *et al*., 1986) represented by oysters in life position and by beds and lenses of transported remains of this species and other invertebrates, mostly mollusks.

Biogenic concentrations

Biogenic concentrations range in size from small scattered clumps to massive beds and lenses (reefs), with oysters in life position (Figs. 3f, 4a-c). They are embedded in massive mudstones to fine-grained silty tuffaceous sandstones of the FA-5 and FA-6. Exceptionally, they were observed within the inclined heterolithic stratification type of FA-4. Isolated clumps are formed mostly by up to eight juveniles and thin shelled adult specimens (Fig. 4a). For its part, the reefs are mostly lenticular– measuring 0.1 up to 2 m thick and several meters in length (Fig. 4b-c), and are formed by large massed oyster clusters of both juveniles and small-sized or large and thick-shelled adult individuals. Bioerosion is low, either in richness or in abundance, being polychaete borings the more frequent traces. Encrusters are represented only by scarce cirripedians.

Interpretation. Extant *Crassostrea* specimens can tolerate a wide range of salinity, temperature, turbidity, and oxygen tension, and therefore are adapted to the periodic and aperiodic changes in water quality (Bahr and Lanier, 1981). They flourish in low salinity environments where the number of shell-boring organisms and other predators living on the oysters are greatly reduced (Wells, 1961). The low richness and abundance of bioerosion traces and the almost absence of encrusters suggest that also the Miocene *C. orbignyi* reefs were established in shallow low salinity water, probably subject to temporary subaerial conditions and sporadic fresh water input. This agrees with the sedimentological interpretation for FA-5 and FA-6 (*i.e*., tidal flats and lower and upper interdistributary bays), where these biogenic concentrations commonly occur. Similar conditions were established by Cuitiño *et al*. (2013) by analysis of the isotopic composition of *C. orbignyi* specimens from equivalent beds that represent the transition from marine to fluvial deposits of the Estancia 25 de Mayo Formation and the overlying Santa Cruz Formation, at the western sector of the Austral-Magallanes Basin. There, $\delta^{13}C$ and $\delta^{18}O$ values and the $\delta^{13}C$-$\delta^{18}O$ positive correlation in *C. orbignyi* shells indicated that these oysters lived in an environment subjected to reductions in salinity and environmental stress, with mixing of fresh and marine waters in varying amount (Cuitiño *et al*., 2013).

Sedimentologic concentrations

These concentrations, embedded in structureless and cross-bedded sandstones of the FA-4 and FA-5, consist mostly of reworked specimens of *Crassostrea orbignyi* (fragmented and entire valves, articulated specimens and nests), forming part of polytypic or monotypic shell-beds and lenses (Fig. 4d-e).

1. Polytypic concentrations consist of 0.1 to 0.3 m thick beds containing mostly disarticulated, fragmented, and highly abraded valves of oysters, both juveniles and adults, and shells of another invertebrates, mostly mollusks (Fig. 4d). Specimens show a chaotic to concordant to bedding orientation, and are embedded in a brown to green, massive medium to coarse-grained sandstone matrix. Basal contacts are sharp planar to undulated. In some concentrations rounded to subangulose volcanic black clasts up to 10 mm in diameter, as well as detrital glauconite are abundant. Bioerosion and encrustation are moderate to high especially on oysters, including boring sponges, polychaetes,

Figure 4. Field photographs of fossil concentrations of the MOM. **a-c)** Biogenic concentrations. **a)** Isolated clumps of *Crassostrea orbignyi* at Cañadón de La Chacra, formed by mostly white small and thin shelled specimens embedded in fine-grained silty tuffaceous sandstone matrix. **b)** View of one of the *C. orbignyi* reefs at Cerro Observación. **c)** Close-up views of one *C. orbignyi* reefs at Cerro Observación, including mostly white thin shelled specimens embedded in silstone matrix. **d-e)** Sedimentologic concentrations. **d)** Polytypic sedimentologic concentration at Cerro Monte León showing densely-packed and bimodal fabric, formed by highly abraded valves of *C. orbignyi* and valves and fragments of other mollusks in chaotic orientation. **e)** Monotypic sedimentologic concentration at Cerro Redondo locality, composed of fragments, valves and articulated specimens of *C. orbignyi* mostly concordant to bedding, inside of cross-stratified coarse-grained to conglomeratic sandstone. **f)** Mixed biogenic-sedimentologic concentration at Cañadón de La Chacra, composed mostly of specimens of Mactridae parallel to the stratification and convex-up oriented. Hammer handle for scale ~28 cm.

bivalves, and bryozoans, as well as encrusting bryozoans and serpulids on both surfaces of the valves. The close-packing is loose to dense and the size-sorting is poor to bimodal, formed by oysters and other abraded large-size mollusk specimens (*e.g.*, *Glycymeris*, *Pachycymbiola*) together with smaller complete specimens and fragments of bivalves, gastropods, scaphopods, brachiopods, echinoids, cirripedians, bryozoans, and decapods.

Interpretation. These polyspecific concentrations bearing the imprint of various taphonomic processes are interpreted as originated by concentration and mix of reworked specimens. Shells would have experienced prolonged exposure on the sea floor previous to the final concentration event, as demonstrated by the high bioerosion and encrustation pattern. In addition, the highly unequal fragmentation, abrasion, bioerosion, and encrustation degree and diagenetic styles of shells in these concentrations, associated to the presence of glauconite, indicate a complex taphonomic history and great time-averaging (Fürsich and Oschmann, 1993; Behrensmeyer *et al.*, 2000). These evidences, plus the undulated bases of the sedimentary bodies, suggest that these concentrations could be associated to erosion and/or low sedimentation rates episodes. Some of these concentrations were observed occurring at the base of deltaic/tidal channels, suggesting they are channel lag. Others, in turn, were observed occurring at the base of tabular muddy strata (FA-5), and are interpreted as the consequence of high frequency flooding events in the interdistributary bays of the delta. In addition, flooding events in low-gradient shallow marine settings can cause strong tidal ravinement, which is usually recorded as the tidal channel lag deposits (Scasso and Cuitiño, 2017).

2. Monotypic concentrations consist in beds and lenses measuring 0.2 to 2 m-thick. Matrix is cross-stratified fine-grained to conglomeratic sandstone, containing fragmented and abraded valves and articulated specimens and nests of *Crassostrea orbignyi* (Fig. 4e). Sub-rounded dark volcanic clasts measuring 2 to 20 mm in diameter are common. Basal contacts are generally sharp irregular (erosive) and top contacts are gradational. The oysters are in chaotic orientation or disposed concordant to bedding, oriented both convex-up and convex-down. The close-packing is dense and size sorting is poor. Bioerosion and encrustation are low. Associated fauna includes only scarce muricid gastropods.

Interpretation. The sharp erosive base, cross-bedding structure, dense packing, lack of sorting and variable orientation of the *C. orbignyi* specimens are indicative of high energy transport. In contrast to the polytypic concentrations, these concentrations can be interpreted as reworking of oysters by means of lateral migration of tidal/deltaic channels of variable sizes, incising in tidal flats or interdistributary areas. Shortly after the incorporation of the resistant oyster bioclasts into the channel, if the energy of the currents is high enough, they can be actively transported and deposited as part of sand dunes or bars.

Mixed biogenic-sedimentologic concentrations

These concentrations include shell-beds and lenses of *Crassostrea orbignyi* lying directly or some centimetres over the reefs as well as scarce shell-beds and lenses dominated by bivalves of the family Mactridae (Fig. 4f).

1. *Crassostrea orbignyi* biogenic-sedimentologic concentrations consist in 0.05 to 0.4 m-thick beds and lenses containing disarticulated valves and fragments of this oyster lying directly or some centimetres over the reefs. They are embedded in the massive mudstone to silty fine-grained sandstone of FA-5 and FA-6. Specimens are in chaotic orientation or lying concordant to bedding, mostly oriented convex-up. Basal contacts are undulated, and top contacts are planar or undulated. Also articulated specimens and nests moved of their life position are included in these concentrations. The biofabric can be densely-packed to disperse, and well to poorly sorted. Abrasion and fragmentation are moderate to low, and bioerosion and encrustation are low. Associated fauna includes scarce gastropods (*Calyptraea* sp.).

Interpretation. These concentrations overlying the reefs evidence a deterioration of the favorable environmental conditions for the reef development (as increasing freshwater input or lack of accommodation space for reef vertical growing), and low within-habitat reworking, with little post-morten disturbance.

2. Mactridae dominated biogenic-sedimentologic concentrations consist of 0.02 to 0.2 m densely packed and good sorted deposits inside of cross-stratified fine to medium-grained sandstone of the FA-4 (Fig. 4f). Mactridae shells are mostly entire and low abraded, disposed concordant to bedding and mostly convex-up oriented. Scarce fragments and valves of other mollusks are present.

Interpretation. The preferred convex-up orientation of the Mactridae specimens, which have an infaunal life habit, indicates that the shells were uprooted and transported by currents. However, the delicate preservation of the specimens suggests that current action was of short duration and that residence time on the seafloor must have been short. These concentrations are interpreted as originated by sudden disruption and reworking of benthic communities by storms waves. This storm reworking is likely to occur in the terminal distributary channels within the delta front.

SPATIAL FACIES ASSOCIATION DISTRIBUTION

The strata studied in this work have a slight regional dip to the south. For this reason, the coastal cliff sections located in the northern part of the study area show the lowest stratigraphic horizons, whereas this is the opposite in the southern area.

The distribution of FAs is highlighted in five representative sedimentary sections (Fig. 5). From the larger scale perspective, the FAs defined in this work are vertically arranged from FA-1 in the lowest position to FA-6 in the uppermost position (Fig. 5). Only FA-4 and FA-5 show intercalations (Fig. 5). The combination of this stratigraphic order with the gentle dip to the south make the lower FAs to be better represented in the northern localities (Fig. 5). From Cañadón de La Chacra to Cañadón Jack locality, FA-1 shows an average of 15 m in thickness (Fig. 5). A few kilometers south of Cañadón Jack, FA-1 is no longer recognized and is assumed to lie below modern sea-level (Fig. 5). In all localities where FA-1 is observed it is covered by deposits of FA-2 (Figs. 5-6), either as a transitional passage or in some cases as a sharp contact. FA-2 is invariably covered in transition by FA-3 forming a coarsening- and thickening-upward succession between 20 and 30 m thick (Figs. 5-6). This passage is clearly visible from Cañadón de La Chacra to Cañadón Jack sections (Fig. 5). The upper reach of FA-3 is usually cut by the lenticular sandstone bodies of FA-4. Above, FA-4 intercalates with the fine-grained tabular deposits containing *Crassostrea orbignyi* reefs of FA-5, forming a complex stratigraphic package of about 40 m thick.

Up in the section, in the FA-6, the marine influence is reduced and a common element in the sections is composed of different types of concentrations of the oyster *Crassostrea orbignyi*, which represent the uppermost evidence of marine influence in the area, after the definitive passage to fully terrestrial environments of the Santa Cruz Formation.

DISCUSSION

Criteria for the recognition, and present delimitation and distribution of the Monte Observación Member

The MOM was ambiguously defined (Di Paola and Marchese, 1973; Bertels, 1980) and questioned by previous authors (*e.g.*, Riggi, 1978, 1979). Two confident facts about the original definition of the MOM are: 1) it is stratigraphically located between fully marine deposits below (namely the Punta Entrada Member of the Monte León Formation) and fully terrestrial deposits above (namely the Santa Cruz Formation); 2) its upper boundary was clearly defined as the uppermost record of oyster banks (Di Paola and Marchese, 1973; Bertels, 1980); that is, the uppermost evidence of marine influence that could be recognized in the Monte León area (Figs. 1, 5). On the contrary, the lower boundary, the lithological differences in relation to the adjacent lithostratigraphic units, the type locality, the area of distribution, and the higher rank lithostratigraphic unit to which it belongs, are not clear and deserve further discussion.

After the observation and description of the Miocene strata cropping out along several localities between the Santa Cruz and Coyle rivers mouths (Figs. 1, 7), we are able to recognize three clearly defined, high-hierarchy lithological units. In the lower part, we recognize a relatively homogeneous thick succession composed of whitish fine-grained bioturbated tuffaceous sediments, rich in marine fossil invertebrates and representing shelf to lower shoreface deposits, whose upper part is here described as FA-1. These deposits are recognized in a wide region beyond our study area and are part of the Punta Entrada Member of the Monte León

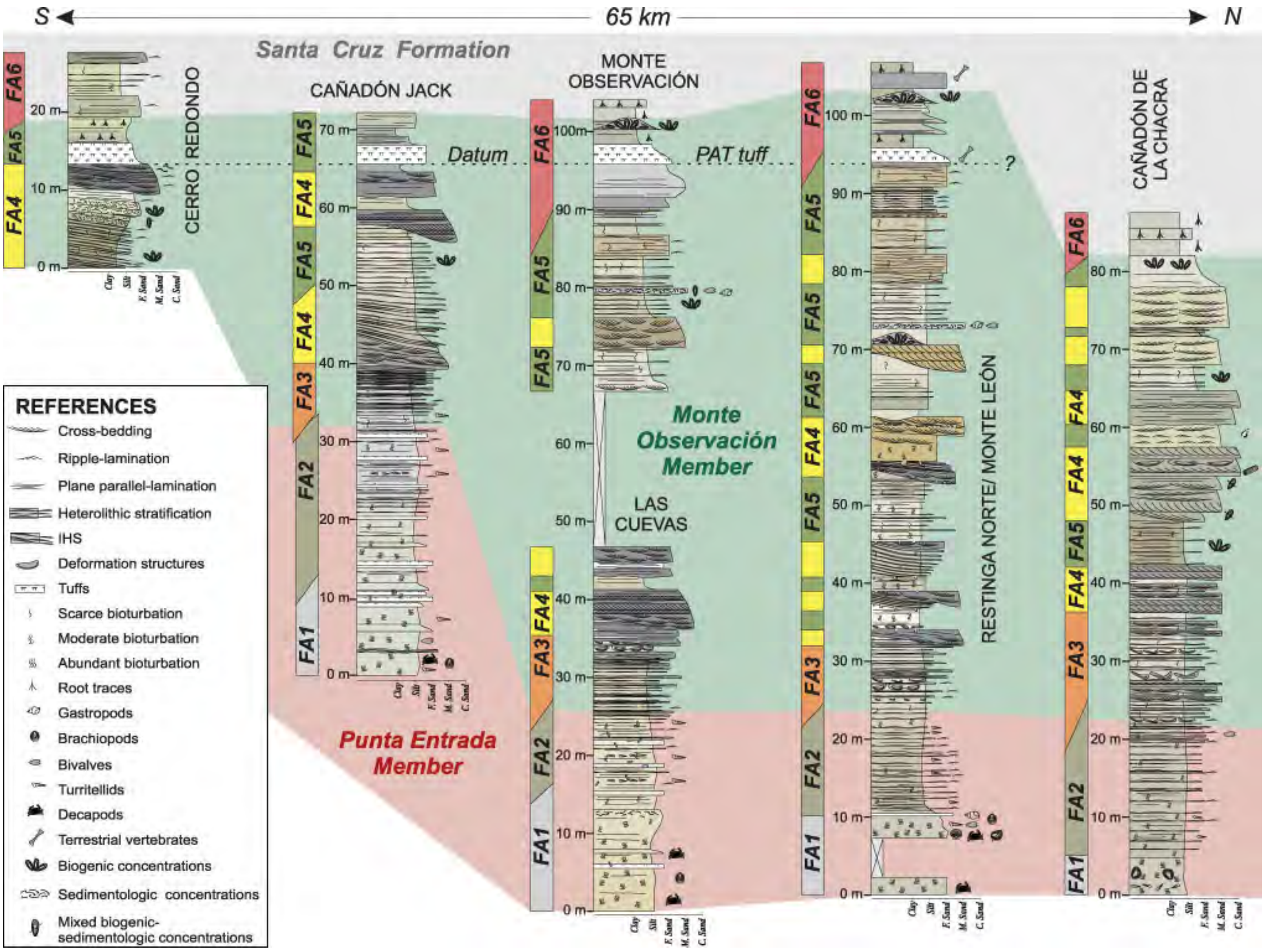

Figure 5. Representative five measured sections of the MOM, showing the distribution of the FAs. When possible, the sections are correlated using the tuff guide level "PAT" of Perkins *et al*. (2012).

Formation, following the original description of Bertels (1980). One of the best exposures of these deposits can be observed in Punta Quilla (Fig. 1), near the mouth of the Santa Cruz River estuary (Parras and Griffin, 2009), although other exposures can also be observed north of the Santa Cruz River, up to the region surrounding the Puerto San Julián city. In the study area, these shelf deposits are covered by FA-2 (*e.g.*, Fig. 6), which is a whitish mud-dominated and variably bioturbated succession, with similar aspect to that of the underlying shelf deposits. Although the paleoenvironmental significance of FA-2 is somewhat different from that of FA-1 (*i.e.*, prodelta to distal delta front deposits), for practical reasons (see below), we include FA-2 within the Punta Entrada Member.

Above the former, we recognize an intermediate lithological unit about 70 m thick in the best exposed outcrops, which shows a characteristic alternation of different lithologies, providing a well-stratified aspect to the unit (*e.g.*, Fig. 6). It is composed of mudstones, grey sandstones, and tuffaceous sandstones, showing well-preserved primary sedimentary structures. These features are included in the FAs 3 to 6, and are interpreted to represent part of the regressive tract from the underlying shallow marine deposits. This sedimentary package is assigned to the MOM and is easily differentiated from the underlying fine-grained shelf and prodelta/distal delta-front deposits of the Punta Entrada Member because: 1) it shows null to very low bioturbation degrees; 2) it shows a reduced autochthonous invertebrate faunal content; 3) it shows a well stratified pattern given by the alternating lithologies; and 4) it shows abundant decimeter-to meter-scale intercalations of gray to greenish sandstone beds. The sandier lithology of

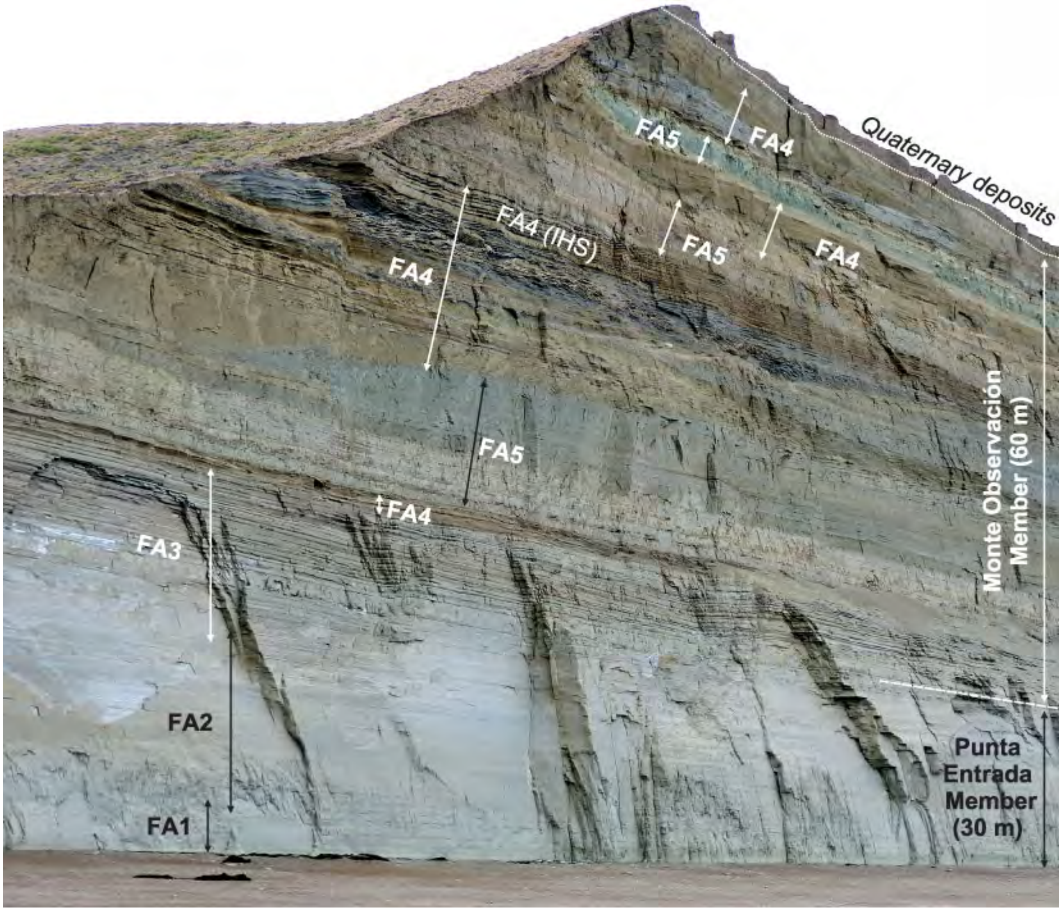

Figure 6. Cliff exposure of the upper Punta Entrada Member and the MOM at Restinga Norte. The cliff is about 90 m high and it is one of the best sites to see the vertical arrangement of FAs. Note the base of the MOM at the beginning of decimeter-thick dark gray sandstone beds. The upper part of this exposure is equivalent to the classic MOM localities Cerro Monte León and Cerro Monte Observación (=Cerro Observación).

the MOM respect to the upper tract of the Punta Entrada Member was noted by Russo *et al*. (1980), who indicated that although the passage from the marine beds of the *"Formación Patagonia"* to the Santa Cruz Formation was established at the higher bed with marine fossils, at the electric logs a very marked lithological change is observed at about 50 m below this bed. In addition to the aforementioned criteria for recognition of the MOM, fossils can be considered as lithological components when defining a lithostratigraphic unit (Art. 24.2.; CAE, 1992). In this sense, *Crassostrea orbigny* reefs are a distinctive feature of the MOM and its identification must be taken into account as criteria for the recognition of this member in the field.

Finally, the third uppermost high-hierarchy lithologic unit represents the bulk of the Santa Cruz Formation, which is composed of a ~150 m thick fine-grained, well stratified succession of greenish and yellowish claystones and siltstones, whitish tuffs, and scarce gray fine-sandstones, rich in paleosol horizons and terrestrial vertebrates (*e.g.*, Raigemborn *et al.*, in press). In this case, primary sedimentary structures are hardly recognized, excepting for some lenticular sandstone bodies with cross stratification.

As no further details were given about a type locality or a type section for the MOM, and considering that in the definition of a new lithostratigraphic unit the designation of a stratotype is essential, being recommendable to locate it in the geographic place from which the unit's name is derived (Art. 25; CAE, 1992), we propose the Cerro Monte Observación (=Cerro Observación)(S 50º 21' 44''; W 68º 57' 20'') as the type locality and the section there exposed as the Lectostratotype (Art. 15.5.; CAE, 1992; Figs. 1, 5). On the other hand, the section at Cañadón de La Chacra (Figs. 1, 5) in which the complete MOM and their boundaries are exposed, is designated as an auxiliary stratotype or Hipostratotype (Art. 15.7.; CAE, 1992).

As pointed out by Di Paola and Marchese (1973) and Bertels (1980), and confirmed by our own observations, the lower boundary of the MOM is

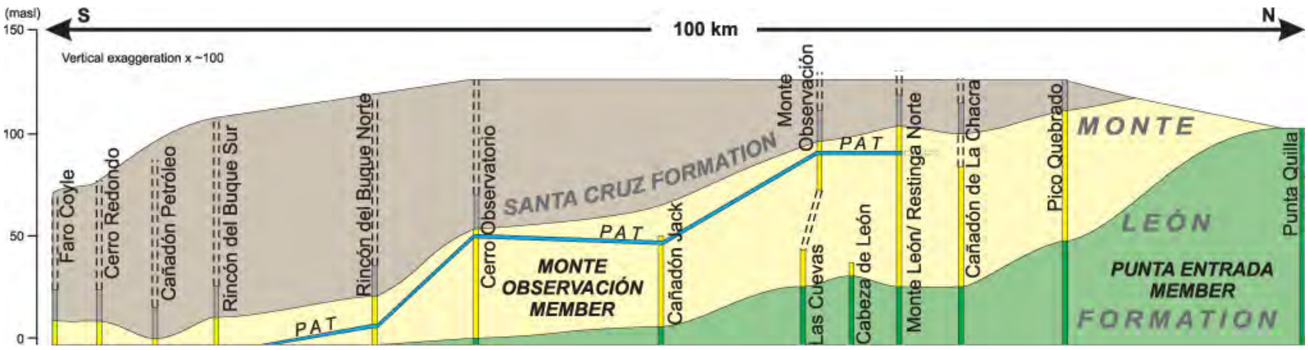

Figure 7. North-south correlation scheme showing the stratigraphic distribution of the early Miocene MOM and adjacent lithostratigraphic units along the studied localities in the southeastern Santa Cruz Province. From Cañadón de La Chacra southward, the full thickness of the Santa Cruz Formation is not shown.

gradual, so it is difficult to select a specific bed. As a practical guide, we propose to locate it at the lowermost record of a decimeter-thick, well sorted and structured gray sandstone bed occurring above the fine-grained bioturbated deposits of the Punta Entrada Member. According to our facies scheme, it would correspond to the lower part of the FA-3. In turn, for the upper boundary of the MOM there was coincidence between previous authors to establish it in the uppermost oyster bank and, consequently, we propose to maintain this criterion. However, the conformable or unconformable character in relation to the overlying Santa Cruz Formation had been long debated. On one hand, the gradual passage between the marine beds and the terrestrial beds of the Santa Cruz Formation has been signaled early by Ameghino (1906) and Feruglio (1938), who noted that along the coast, between the mouths of the Santa Cruz and Coyle Rivers, the transition between the "*Suprapatagoniano*" and "*Santacruciano*" was absolutely gradual and concordant. On the other hand, other authors (*e.g.*, Hatcher, 1897; Bown and Fleagle, 1993; Fleagle *et al.*, 1995; Perkins *et al.*, 2012; Sacomani *et al.*, 2012) considered an unconformable relationship and included a *hiatus* between both units. In concordance with Ameghino (1906), Feruglio (1938), Di Paola and Marchese (1973) and Bertels (1980), and based on our numerous sedimentological observations, the upper boundary of the MOM is also considered here as gradual (Fig. 2).

Regarding to the areal extension of the MOM, Bertels (1980) indicated that this unit is exposed typically in Monte León (=Cabeza de León), on the road that leads from Monte León to the National Road 3, on Las Cuevas, and on Monte Observación (Fig. 1). However, as was noted by Parras and Griffin (2009), Bertels (1980) included in the MOM the shell beds exposed at Cabeza de León and Las Cuevas localities. Based on our results and previous studies in the area (Parras and Griffin, 2009; Griffin and Parras, 2012; Sacomani *et al.*, 2012; Raigemborn *et al.*, 2015), we define the MOM in the region comprising the Pico Quebrado in the north to the mouth of the Coyle River in the south (Figs. 1, 7). Between both areas, excellent exposures can be observed in the coastal cliffs, whereas lower quality, partly covered outcrops appear inland along some creeks and small hills. Also, isolated expositions in the Santa Cruz River valley, such as that mentioned by Fernicola *et al.* (2014) about 60 km west of Piedrabuena town (Fig. 1), and others in the lower reach of the Chalía River valley (own observations), can be attributable to this member.

Due to the gentle regional dip towards the south and the flat erosion surface produced by Quaternary terrace conglomerates especially to the north, the thickness of the MOM varies according to the location (Fig. 7). The maximum thickness corresponds to the classic localities Cerro Monte León and Cerro Monte Observación (Fig. 7) within the Monte León National Park (Fig. 1). However, in these localities the MOM is partly covered by recent sediments and vegetation and only the upper ~30 m bearing the *Crassostrea orbignyi* reefs can be observed, which probably corresponds to the descriptions provided by Di Paola and Marchese (1973). Field observations let us know that this covered tract is exposed along the upper part of the coastal cliffs of Restinga Norte and Las Cuevas, and also in some coastal creeks located inside of the MLNP, being the most complete section that exposed in Cañadón de La Chacra (Figs. 1, 5, 7).

Finally, up to now, it is not clear whether the MOM should be part of the Monte León Formation or the Santa Cruz Formation. Di Paola and Marchese (1973) separated the MOM from the Santa Cruz Formation, although recognized it shares lithological features with both the underlying and overlying units. Based on the supposedly similar sandier lithology and reworked character of the marine mollusk content (other than *Crassostrea orbignyi*), Parras and Griffin (2009) considered the MOM as a member at the base of Santa Cruz Formation, whereas Griffin and Parras (2012) included in the last unit some *C. orbignyi* concentrations. However, these observations were based on the 20-30 m thick exposures visible at the base of Cerro Monte León and Cerro Monte Observación, as well as the base of the cliff in Cerro Redondo. The findings of new outcrops, the detailed lithological descriptions, the paleoenvironmental interpretations, and the increased stratigraphic and geographic extension of the MOM proposed in this work, allow us to highlight lithological and paleontological differences with that of the Santa Cruz Formation. For this reason, we propose to include the MOM as part of the regressive phase of the Monte León Formation (Fig. 7). It is worth noting that, although forming part of the Monte León Formation, the MOM shows an upper transitional part that shares some similarities with the overlying unit.

The stratigraphic significance of the Monte Observación Member

The MOM represents part of an overall regressive stratigraphic package comprising from the prodelta/delta front deposits of FA-2 at the lower part to the upper coastal plain deposits of FA-6, which finally grade upward to the fully terrestrial deposits of the Santa Cruz Formation. The vertical coarsening and thickening upward succession, represented by FA-2, FA-3 and FA-4, represents a classic progradation of prodelta to delta front/delta plain deposits (Bhattacharya, 2010) that migrated eastward over the Patagonian shelf. The instauration of sandy or heterolithic channel deposits of FA-4 represent deltaic distributary channels feeding the delta front system (Martini and Sandrelli, 2015), showing variable influence of marine processes such as the tides. The complex intercalation of different types of channel bodies of FA-4 with the fine-grained interdistributary deposits of FA-5, plus the variability of the fossil invertebrate concentrations, marks the development of a thick delta plain complex (Bhattacharya, 2010). The delta plain deposits represent at least twice the thickness of the prograding prodelta to delta front deposits, suggesting an aggradational tract where sediment supply keeps pace with a continuous creation of accommodation space. The facies and architectural complexity of FA-4 and FA-5 is interpreted as the consequence of both the interaction of marine and fluvial processes (*e.g.*, Dalrymple *et al.*, 2003), as well as the high frequency relative sea level fluctuations that would have had strong facies control in these shallow marine-transitional sedimentary settings. Evidence of this are fossil invertebrate concentrations showing signs of reworking and mixing of specimens with different taphonomic signatures, which are interpreted to correspond to transgressive lags limiting small-scale individual prograding sedimentary bodies. Monospecific oyster reefs of *Crassostrea orbignyi*, more frequent toward the top of the unit, suggest the onset of brackish water in the system, ideal for a prolific growth of these organisms. Environmental conditions became progressively shallower, ending with the deposition of fluvial deposits of the overlying frankly continental Santa Cruz Formation. In the study area, the latter is composed of about 150 m of aggradational fine-grained fluvial deposits (Raigemborn *et al.*, 2015, in press), suggesting that subsidence continued to create accommodation space at least until 16 Ma.

From a regional perspective, the early Miocene Monte León and Santa Cruz formations represent a transgressive-regressive cycle (second order sequence) that comprise a time interval of nearly 6 My (Aquitanian-Burdigalian). Considering their lateral equivalent deposits, this cycle accumulated a thick sediment succession in nearly the entire area of the Austral-Magallanes Basin. The cycle begins with a fast transgression that, in the southeastern part of the Santa Cruz Province, accumulated nearly 200 m of shelf sediments of the Punta Entrada Member of the Monte León Formation. The available ages for this member (22–18 Ma; Parras *et al.*, 2012) suggest an average sedimentation rate of about 50 m/Myr. The Punta Entrada Member grades upward to the MOM, represented by about 70 m of regressive shallow marine to deltaic deposits. For this member the available ages indicate it accumulated in only 0.3

My (~18–17.7 Ma; Parras *et al*., 2012; Perkins *et al*., 2012), with an average sedimentation rate of 230 m/Myr, more than four times the rate of the underlying member. Transitional marine sedimentation culminates with the terrestrial deposits of the Santa Cruz Formation, which in southeast of Santa Cruz Province range in age from 17.7 to ~16 Ma (Perkins *et al*., 2012; Cuitiño *et al*., 2016).

The accumulation of the entire Miocene depositional cycle is synchronous with the onset of a rapid period of exhumation of the Southern Patagonian Andes (Cuitiño *et al*., 2012; Fosdick *et al*., 2013; Ghiglione *et al*., 2016; Aramendía *et al*., in press). Increased denudation in the western part of the Southern Patagonian Andes started at about 30–23 (Ma Thomson *et al*., 2001) and migrated eastward towards the retroforeland thrust belt where thermochronology data document exhumation at 22–18 Ma (Fosdick *et al*., 2013). Regional orogenic exhumation peaks can be associated to increase uplifting and subsequent foreland basin subsidence by means of lithospheric flexure, which is thought to be responsible for the regional marine transgression that reached the foot of the Andes in the western Austral Basin (Cuitiño *et al*., 2012, 2015). In this context, we hypothesize that after the initial Miocene transgression the fast accumulation of the regressive deposits of the MOM could be in part the response to a peak of retroforeland thrust belt deformation. The MOM roughly occurred at the end of the thrust belt exhumation period (18 Ma) which, as suggested by Fosdick *et al*. (2013), exposed easily eroded cretaceous sedimentary rocks of the Austral-Magallanes Basin depocenter. This tectonic process, together to the increased explosive volcanic activity along the arc at this latitude (Hervé *et al*., 2007), dramatically increased the fluxes of sediment to the foreland basin producing a fast eastward regression in the adjacent shallow marine Patagonian shelf.

CONCLUSIONS

Based on facies and invertebrate fossil concentrations analyses, we defined the boundaries, distribution, type section, as well as the paleoenvironmental and stratigraphic significance of the Monte Observación Member of the Monte León Formation. The main conclusions of our work are:

The upper and lower boundaries of the MOM are transitional. For the lower boundary, we mark the first appearance of decimeter-thick gray sandstone layers above the shelf and prodelta/distal delta front deposits of the Punta Entrada Member. For the upper boundary, we maintain the original definition as the uppermost *Crassostrea orbignyi* bed, prior to the definite passage to the terrestrial deposits of the Santa Cruz Formation.

The MOM displays a maximum thickness of about 70 m and is typically distributed along the coastal zone between few kilometers south of the Santa Cruz River mouth in the north and the Coyle River mouth, in the south.

The MOM is composed of a well stratified succession of gray sandstones, whitish mudstones and some tuffs with intercalated concentrations of fossil invertebrates, especially of *Crassostrea orbignyi*. These beds were deposited in a prograding deltaic system with tidal influence that gradually passes upward to terrestrial deposits.

The MOM is part of a regressive high-hierarchy sequence that is probably related to an episode of Andean retroforeland uplift.

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