Paleoenvironmental reconstruction of the coastal Monte Léon and Santa Cruz formations (Early Miocene) at Rincón del Buque, Southern Patagonia: A revisited locality

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ABSTRACT

Sedimentological, ichnological and paleontological analyses of the Early Miocene uppermost Monte León Formation and the lower part of the Santa Cruz Formation were carried out in Rincón del Buque (RDB), a fossiliferous locality north of Río Coyle in Santa Cruz Province, Patagonia, Argentina. This locality is of special importance because it contains the basal contact between the Monte Léon (MLF) and the Santa Cruz (SCF) formations and because it preserves a rich fossil assemblage of marine invertebrates and marine trace fossils, and terrestrial vertebrates and plants, which has not been extensively studied. A ~90 m-thick section of the MLF and the SCF that crops out at RDB was selected for this study. Eleven facies associations (FA) are described, which are, from base to top: subtidal−intertidal deposits with *Crassotrea orbignyi* and bioturbation of the *Skolithos-Cruziana* ichnofacies (FA1); tidal creek deposits with terrestrial fossil mammals and *Ophiomorpha* isp. burrows (FA2); tidal flat deposits with *Glossifungites* ichnofacies (FA3); deposits of tidal channels (FA4) and tidal sand flats (FA5) both with and impoverish *Skolithos* ichnofacies associated; marsh deposits (FA6); tidal point bar deposits recording a depauperate mixture of both the *Skolithos* and *Cruziana* ichnofacies (FA7); fluvial channel deposits (FA8); fluvial point bar deposits (FA9); floodplain deposits (FA10); and pyroclastic and volcaniclastic deposits of the flood-plain where terrestrial fossil mammal remains occur (FA11).

The transition of the MLF−SCF at RDB reflects a changing depositional environment from the outer part of an estuary (FA1) through the central (FA2−6) to inner part of a tide-dominated estuary (FA7). Finally a fluvial system occurs with single channels of relatively low energy and low sinuosity enclosed by a broad, low-energy floodplain dominated by partially edaphized ash-fall, sheet-flood, and overbank deposits (FA8−11). Pyroclastic and volcaniclastic materials throughout the succession must have been deposited as ash-fall distal facies in a fluvial setting and also were carried by fluvial streams and redeposited in both estuarine and fluvial settings. These materials preserve most of the analyzed terrestrial fossil mammals that characterize the Santacrucian age of the RDB's succession. Episodic sedimentation

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under volcanic influence, high sedimentation rates and a relatively warm and seasonal climate are inferred for the MLF and SCF section.

Lateral continuity of the marker horizons at RDB serve for correlation with other coastal localities such as the lower part of the coastal SCF south of Río Coyle (~17.6–17.4 Ma) belonging to the Estancia La Costa Member of the SCF.

1. Introduction

Early Miocene deposits of the Santa Cruz Formation (SCF), widely distributed in the Austral or Magallanes basin (Patagonia, Argentina) (Fig. 1A), contain a rich assemblage of fossil mammals, studied since the 19th Century (Vizcaíno et al., 2012a, and references therein). The best-known fossiliferous exposures of the SCF crop out along the Atlantic coastline of the Santa Cruz Province between Río Santa Cruz and Río Gallegos (Vizcaíno et al., 2012a, Fig. 1A) (Fig. 1B). The fossil content of these localities was placed in a stratigraphic sedimentological context by Tauber (1994; 1997a; 1997b). Since then, abundant new data on the sedimentology (Matheos et al., 2008, 2010; Matheos and Raigemborn, 2012; Raigemborn et al., 2012), geochronology (Fleagle et al., 2012; Perkins et al., 2012), ichnology (Krapovickas, 2012; Krapovickas et al., 2013; Zapata et al., 2013), paleosols (Raigemborn et al., 2012) and paleobotany (Brea et al., 2012) contributed to a revised understanding of the temporal succession and paleoenvironments of coastal exposure of the SCF between Río Coyle and Río Gallegos (Vizcaíno et al., 2012a).

Localities north to Río Coyle (Fig. 1A) have received less attention, although there are geological and paleontological studies for Cerro Observatorio at Cañadón de las Vacas (Bown and Fleagle, 1993) (referred to as Monte Observación by these authors), and Monte León and Monte Observación in the Monte León National Park (Bown and Fleagle, 1993; Matheos et al., 2008). A third largely undocumented area is Rincón del Buque (RDB), named as Media Luna, Wreck Flat or Smith's Rock Flat by Bordas (1941), Feruglio (1949), Marshall (1976), Marshall et al. (1986) and Vizcaíno et al. (2012b) (Fig. 1C). Literature about the geology and paleontology of RDB is scarce. Ameghino (1906) does not mention it but provides sections of outcrops of his *Superpatagoniense* (upper MLF) and *Santacrucense* (SCF) between Río Santa Cruz and Río Coyle that would have included the area. Describing the *Santacrucense* between Río Santa Cruz and Río Coyle, Feruglio (1949) mentioned that at RDB the *Santacrucense* is 250 m-thick with layers disposed practically horizontally, that it is composed of interbedded fine tuffaceous material and pebbly sandstones, and that an oyster bed and several levels of white tuff can be used as local guide layers. Marshall et al. (1986) described RDB as a large amphitheater opening towards the sea (Fig. 1C) and located about 23 km north of Coy Inlet; this amphitheater is depicted as about 4 km in N–S direction, and labeled Media Luna on recent maps (Marshall, 1976; Vizcaíno et al., 2012b). Marshall et al. (1986) dated a rock sample using the potassium–argon method from the NE side of the amphitheater about 20 m above the exposed base of the outcrops, obtaining an age of ~16 Ma. The Riggs Expedition from the Field Museum of Natural History of Chicago (USA) made a collection of fossil mammals from RDB in 1923. They referred to the area as Wreck Flat or Smith's Rock Flat (Marshall, 1976; Vizcaíno et al., 2012b). Rigg's expedition collected 282 specimens belonging to 32 mammals species and a few birds (according to field identifications; Riggs, 1928). Later, José Brandmayr, from the argentine national oil company YPF, collected 23 fossils from a white tuff 35 m above the upper oyster bed of the *Superpatagoniense* that were

briefly described by Bordas (1941). Consequently, from a stratigraphic point of view, RDB locality is highly interesting because it contains the contact between the Monte Léon and the Santa Cruz formations. It is also rich in fossil vertebrates and trace fossils that, together with a precise sedimentological analysis, allowed us to interpret the environmental conditions at the time of deposition.

The goals of this paper are 1) to provide a detailed stratigraphic, sedimentological and ichnological description of RDB; 2) to interpret depositional paleoenvironments of the uppermost MLF and the lower part of the SCF in this area, 3) to provide a preliminary list of the fossil mammals identified so far; 4) to integrate the former information to infer paleoenvironmental conditions of this locality, considering the effects of the volcanism on the sedimentary environments, and including a paleoclimatic reconstruction, and 5) discuss probable correlations with other known fossiliferous localities.

2. Geological setting and study area

2.1. Tectonic framework

The Austral basin is located in southernmost South America (Russo et al., 1980; Biddle et al., 1986; Olivero and Malumián, 2002, 2008; Menichetti et al., 2008). It follows mainly a NNW–SSE axis limited by the Southern Patagonian Andes mountain range towards the west, and by the Río Chico High to the east (Biddle et al., 1986; Corbella, 2002; Peroni et al., 2002) (Fig. 1A). The latter represents a southern extension of the Deseado Massif that served as the basement for the Cretaceous/Cenozoic sedimentation, separating the Austral basin from the Malvinas basin (Rossello et al., 2008).

The geological history of the Austral basin begins in the Triassic with the initiation of rifting between South America and Africa (Biddle et al., 1986). During the Late Jurassic–Early Cretaceous, the margin of the basin was formed by the uplift of the western arc (Arbe, 1987; Corbella, 2002). From the Early Cretaceous to the Miocene, the basin experienced episodes of marine and continental deposition accompanied by repeated transgressions and regressions. From the Late Oligocene to the Early Miocene, a widespread transgression occurred in Patagonian basins, covering most of southern Patagonia (Malumián, 1999). This transgression and the deposition of the overlaying continental series are the result of several factors including: 1) Miocene deformation and uplift of the cordillera in the west (Guillaume et al., 2009; Ramos and Ghiglione, 2008), 2) important climate changes related to an increase in the global temperature (Zachos et al., 2008) and 3) worldwide fluctuations in sea-level (Miller et al., 2005).

2.2. Sedimentological and paleontological framework

The pre-Cenozoic infill of the Austral basin contains deep marine to continental sedimentary units and volcaniclastic deposits of Late Jurassic to Late Cretaceous age as Complejo El Quemado, Springhill, Río Mayer, Kachaike, Piedra Clavada, Mata Amarilla, Alta Vista, Asunción, Cerro Fortaleza and Calafate formations and their equivalents (e.g. Sacomani and Panza, 2012). The
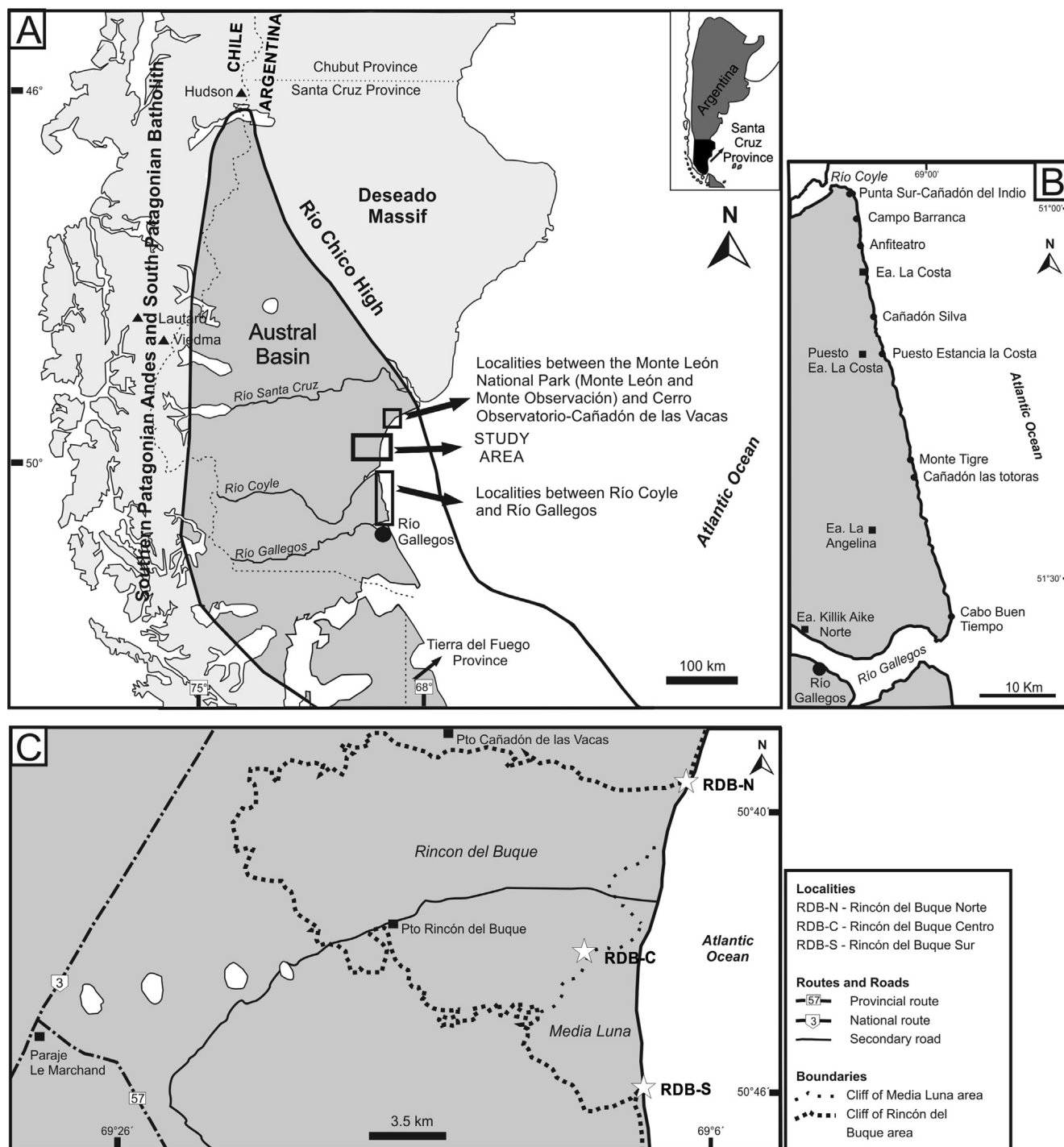
Fig. 1. A: Location of the Austral basin, the study area, and other well-known localities of the Santa Cruz Formation. B: Important Santacrucian localities south of Río Coyle. C: Simplified map of the Rincón del Buque area showing the position of the three analyzed sections.

Paleogene—Neogene infill of the basin is composed of marine units deposited during Atlantic transgressions intercalated with intervals of non-deposition, erosion and continental deposition (Malumián, 1999). The *Patagoniense* transgression occurred in three episodes named by Ameghino (1902) as *Juliense*, *Leonense* and *Super-patagónico*, the last of which is overlain by his *Formación Santacruceña*. The "Juliense" and "Leonense" are well exposed on the coastal parts of the Austral basin and were formally named as San Julián and Monte León formations, respectively (Bertels, 1970).

In this area the San Julián Formation onlaps felsic volcanic and siliciclastic rocks of the Jurassic Bahía Laura Group (Parras et al., 2012). The marine "Superpatagónico" stage, considered to be part of the upper MLF in the study area, is conformably overlain by the continental *Formación Santacruceña* of Ameghino (1902), now called the Santa Cruz Formation (see a review in Parras and Griffin, 2009; Griffin and Parras, 2012). Unconformably beneath the Monte León Formation lies the marine San Julián Formation (Parras et al., 2008). The MLF includes siltstones, mudstones, tuffs and

intercalated shell beds (Bertels, 1970), with frequent bioturbation, deposited in shallow seas, ranging from coastal plain (subtidal or intertidal environments) to shallow continental shelf systems (Parras and Griffin, 2009; Griffin and Parras, 2012). Bown and Fleagle (1993) mentioned that the uppermost 15 m of the MLF contains fluvial levels with paleosols, as well as thin intercalations of marine sediments with the oyster *Ostrea hatcheri*. On the basis of the invertebrates, palynomorphs (Barreda and Palamarczuk, 2000), and $^{87}Sr/^{86}Sr$ ages, the San Julián and the Monte León formations spanning the interval of ~25 to ~18 Ma (Late Oligocene–Early Miocene) (Parras et al., 2012).

In the coastal area of the basin, the marine MLF is succeeded transitionally by continental deposits of the SCF (Feruglio, 1949; Tauber, 1994; Barreda and Palamarczuk, 2000; Matheos et al., 2008; Matheos and Raigemborn, 2012) (Fig. 2). For the coastal zone the SCF is roughly 225 m thick mainly composed of mudstones, fine to medium sandstones of volcaniclastic origin, and tuffs with light colors, containing immature paleosols and laid down on a coastal plain incised by sand bodies representing river channels (Bown and Fleagle, 1993; Tauber, 1994, 1997a). In the coastal outcrops of the SCF south of Río Coyle (Fig. 1B), Tauber (1994, 1997a; 1997b) recognized two members separated by a locally erosional discontinuity: a lower unit, the Estancia La Costa Member, with a predominance of claystones and mudstones of pyroclastic origin; and an upper unit, the Estancia La Angelina Member, chiefly composed of pyroclastic claystones, mudstones, and sandstones
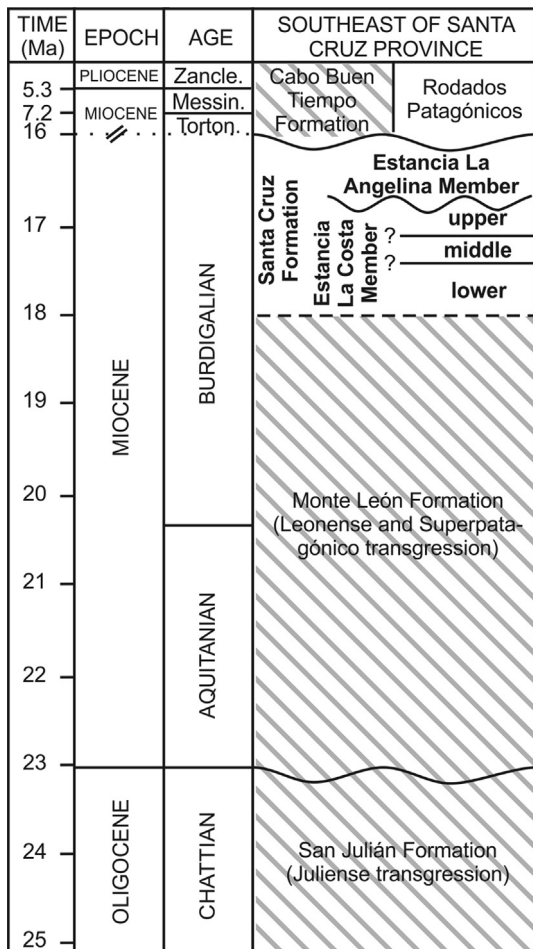
(Fig. 2). Recently, compositional and sedimentological analyses of the Estancia La Costa Member of the SCF south of Río Coyle, allowed Matheos and Raigemborn (2012) to differentiate three parts: lower, middle and upper. Throughout these three parts there is a decrease in pyroclastic materials (primary and reworked tuffs) and an increase in the participation of coarse facies and paleosols, which were interpreted as indicating an increase in the energy of the fluvial system.

Mammal faunas from the richly fossiliferous SCF were the basis for recognition of the Santacrucian Land Mammal Age of South America (Pascual et al., 1965). The Santacrucian is one of the most diverse taxonomically and better represented in terms of the preservation of specimens of all Cenozoic mammal faunas in South America before the Plio-Pleistocene closure of the Panamian isthmus (Marshall et al., 1986).

The absolute age of the SCF has been a subject of debate for more than a century (e.g. Marshall et al., 1986; Bown and Fleagle, 1993; Fleagle et al., 1995; Blisniuk et al., 2005). Recent radiometric dates of intercalated tuffs levels (Perkins et al., 2012; Fleagle et al., 2012) indicate that the coastal SCF spans the interval ~17.9–16.2 and a greater temporal interval, ~19–14 Ma, in the Andean foothills. During the period of deposition of the lower part of the SCF climate conditions in the south coastal Atlantic were extratropical and highly seasonal (see a review in Kay et al., 2012; Palazezzi et al., 2014).

Deposits of the SCF in the south Atlantic area are overlying disconformably by Late Miocene–Pleistocene marine and glacio-fluvial sediments, the Cape Fairweather beds of Hatcher (Cabo Buen Tiempo Formation) and the "Rodados Patagónicos" (Fig. 2).

2.3. The study area

The RDB area is located in the northeastern boundary of the Austral basin (southeast coast of the Santa Cruz Province), between Río Santa Cruz and Río Coyle (Fig. 1A). The area is within the boundaries of the Estancia Coy Inlet, Estancia Cañadón de las Vacas, and Estancia Ototel Aike. The exposures extend between 50°39′30″ and 50°46′10″S, and stretch as far west as 69°10′14″W from the Atlantic coast (Fig. 1C).

In the study area the outcrops of the uppermost MLF and of the lower part of the SCF are arrayed parallel to the Atlantic coastline, in active cliffs along the coast and nearby inland hills (Fig. 3). The transition between the MLF and the SCF appears conformable and gradual. The boundary between both units is placed subjectively in the top of the last oyster bed, similar to the criteria followed by Cuitiño et al. (2012). The contact between the two formations is exposed in the intertidal zone where the last oyster layer of the MLF with specimens in life position of *Crassostrea orbignyi* (Ihering, 1897) and other reworked marine mollusks (Griffin and Parras, 2012) take place (Fig. 3A). In this area the SCF is capped by the Pleistocene glacio-fluvial conglomerate of the Rodados Patagónicos (Fig. 2).

3. Material and methods

Three sedimentary sections exposed in the study area were measured. From north to south these are: Rincón del Buque Norte (RDB-N) (50°39′30″S; 69°06′38″W), Rincón del Buque Centro (RDB-C) (50°43′21″S; 69°10′14″W) and Rincón del Buque Sur (RDB-S) (50°46′10″S; 69°08′17″W) (Fig. 1C).

Facies and facies associations were described, following Miall (1996) and Bridge (2003) with modification for pyroclastic deposits (Smith, 1987). In the field, paleosols and rock colors were determined using the Geological Rock-color Chart (2009). The external shape of the sand bodies were described following the
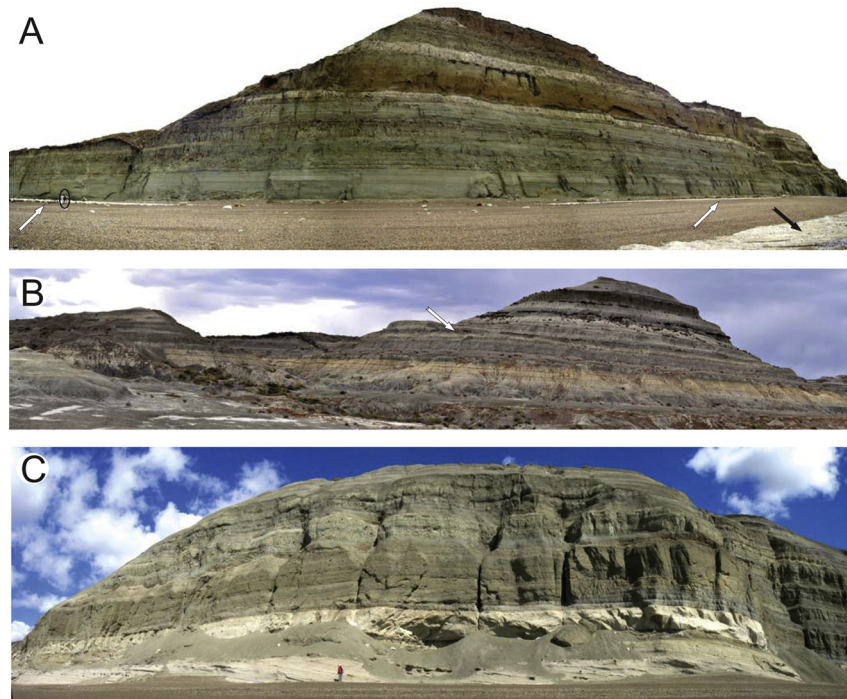

Fig. 2. Stratigraphic chart of the southeast Santa Cruz Province with timescale of Gradstein et al. (2012). The oblique stripes indicate marine deposits.

Fig. 3. Photomosaics of the coastal Santa Cruz Formation showing the general aspect in the study area. Note the lateral continuity of the outcrop exposures. A: Coastal outcrops at Rincón del Buque Norte at low tide. Black arrow marks the uppermost oyster layer of the Monte León Formation, and white arrows signal the fossiliferous tuff beds of the lower Santa Cruz Formation. See people in the circle for scale. B: Inland outcrops in Rincón del Buque Centro. White arrow indicates the ash bed "T-16" mentioned in the text. C: Coastal outcrops in Rincón del Buque Sur illustrating the lowermost part of the Santa Cruz Formation.

width/thickness (W/Th) criteria of Gibling (2006) as broad sheets (W/Th > 100), narrow sheets (W/Th > 15), broad ribbons (W/Th > 5) and narrow ribbons (W/Th < 5).

Trace fossils were studied and photographed *in situ* and left in the field. We use the preservational nomenclature of Seilacher (1964) and the Bioturbation Index (BI) of Droser and Bottjer (1986).

Preliminary collections of fossil vertebrates (birds and mammals) were made by some of the authors (SFV, MSB, RFK and JCF). The specimens are preserved and cataloged into the permanent collections to the Museo Regional Provincial Padre M.J. Molina of the Río Gallegos city (Santa Cruz Province). The coordinates of the fossils were recorded. Fossils were collected mainly from areas adjacent to where the sedimentary sections were measured. A record was made of whether the fossils were *in situ* or in lag deposits and they were referred to stratigraphic position relative to a marker horizon named arbitrary as "T-16", which is described below. This horizon is considered a local guide bed due to the fact that it is a fossil-rich pyroclastic level with a kilometer lateral continuity that takes place in the three measured sections at RDB.

4. Results

4.1. Sedimentology, trace-fossil distribution, and depositional environments

For this study we selected a ~90 m-thick section of the uppermost MLF and the lower part of the SCF that crops out in the analyzed area. It is composed of bioclastic, pyroclastic (tuffs), volcaniclastic (reworked tuffs and tuffaceous sandstones) and epiclastic (siltstones, sandstones and sporadic pebbly sandstones) deposits (Fig. 4). Sixteen sedimentary facies were defined on the basis of lithology, sedimentary structures, fossil content and trace fossils, and paleoedaphic features (Table 1). The succession starts

with volcaniclastic facies (Tw) that are overlaid by bioclastic facies (Sb) of the MLF. The last are covered by volcaniclastic (Tw, TS) and epiclastic facies (St, Sp, Sh, Sr, Sm, HS, IHS, Fm) (Table 1) of the SCF which arrange in a finning-upward succession grayish olive to light gray in color of ~10–20 m-thick. These facies arrange in seven facies associations (FA) (Table 2) which are: subtidal–intertidal deposits (FA1); tidal creek deposits (FA2); tidal flat deposits (FA3); tidal channel deposits (FA4); tidal sand flat deposits (FA5); marsh deposits (FA6); and tidal point bar deposits (FA7). Upward this succession is covered by fluvial deposits composed of epiclastic (Gm, Gt, St, Sp, Sm, Sl, Fm, Fl), pyroclastic (T) and volcaniclastic (Tw) facies (Figs. 3 and 4, Table 1) of four FA (Table 2) which are: fluvial channel deposits (FA8); fluvial point bar deposits (FA9); floodplain deposits (FA10); and pyroclastic and volcaniclastic deposits of the floodplain (FA11). Six trace fossil assemblages (TFA) related with the FA are shown in Table 3. Fluvial deposits of the SCF arrange in a ~18 to 34 m-thick succession, present in the three measured sections. Epiclastic facies are divided into fine- and coarse-grained. Bodies of fine-grained facies (Sm, Sl, Fm, Fl) are vertically stacked up to 30 m, and pyroclastic and volcaniclastic deposits (T and Tw) are interbedded within this stacking. Coarse-grained facies (Gm, Gt, St, Sp) are uncommon in the fluvial deposits in RDB, and they occur exclusively at middle–upper part of the analyzed succession (Fig. 4).

4.1.1. Facies association 1: subtidal–intertidal deposits

Description: FA1 of the uppermost MLF is composed of marine bioturbated Tw facies (Fig. 4) and broad massive bodies of Sb facies bearing oysters — *C. orbignyi* (Ihering, 1897) — in life position and a smaller number of reworked marine mollusks described by Griffin and Parras (2012) (Figs. 3A, 4 and 5D). Deposits of Tw facies crop out without an exposed base with irregular 0.5 m-thick top surfaces, which are covered by deposits of Sb facies. The latter presents
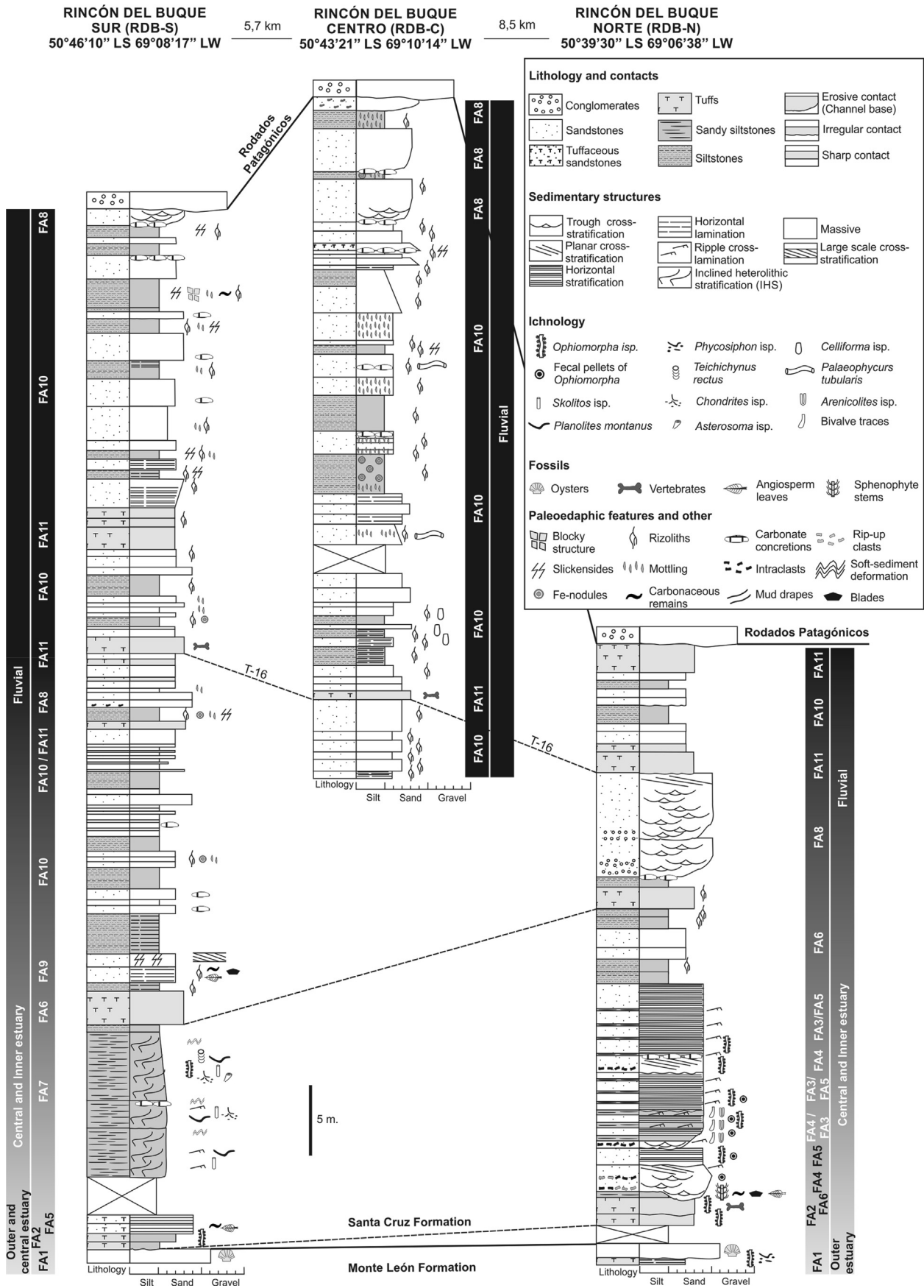
Fig. 4. Detailed sedimentary sections of the Rincón del Buque area.

Table 1
Description and interpretation of the sedimentary facies.

Facies code	Lithology	Sedimetary structures	Fossil content	Other features	Interpretation
Sb	Very fine bioclastic tuffaceous sandstones	Massive	Oysters (*Crassostrea orbigny*) and other marine mollusks	–	Oyster bioherms or reefs with oysters and in place reworked and redeposited mollusks in tide-influenced settings
Tw	Very fine- to medium-grained reworked tuffs	Massive or laminated	*Ophiomorpha* isp., c.f. *Phycosiphon*, *Skolithos* isp., *Palaeophycus tubularis*. Terrestrial mammals	Sporadic rhizoliths	Reworked ash-fall materials mixed with other sediments and deposited in tide-influenced settings with subsequent marine bioturbation, and in fluvial settings with sub-aereal exposure and pedogenetic modification
TS	Medium- to coarse-grained tuffaceous sandstones	Horizontal stratification	Leaves of Nothofagaceae	Carbonaceous remains	Reworking of pyroclastic material mixed with epiclastic materials with developed of upper-stage plane beds in tide-influenced settings
T	Fine- to medium-grained primary tuffs	Massive	Terrestrial mammals	–	Deposition of ash-fall in sub-aerial and subaqueous fluvial settings
Gm	Fine-grained conglomerates	Massive	–	–	Fluvial channel lag deposits
Gt	Fine-grained conglomerates	Trough-cross stratification	–	–	Migration of gravely 3-dimensional dunes in fluvial channels and bars
St	Medium- to very coarse-grained or pebbly sandstones	Trough-cross stratification	*Ophiomorpha* isp., fecal pellets	Mud drapes, muddy rip-up clasts	Migration of sandy 3-dimensional dunes in tidal settings with subsequent marine bioturbation, and in fluvial deposits
Sp	Medium- to coarse-grained sandstones	Planar-cross stratification	*Ophiomorpha* isp., fecal pellets	Mud drapes, muddy rip-up clasts	Migration of sandy 2-dimensional dunes in tidal settings with subsequent marine bioturbation, and in fluvial deposits
Sh	Medium- to coarse-grained sandstones	Horizontal stratification	*Ophiomorpha* isp., fecal pellets	Mud clasts, mud drapes	Upper-flow regime plane beds in tide-influenced settings with subsequent marine bioturbation
Sl	Very fine- to medium-grained sandstones	Horizontal lamination. Large scale- cross stratification	Leaves of angiosperms. *Celliforma* isp.	Carbonaceous remains, blades, slickensides, Rhizoliths, mottling	Upper stage plane-bed flow in fluvial settings. Sporadic sub-aereal exposure with incipient pedogenic modification and terrestrial bioturbation. Lateral accretion deposits
Sr	Fine-grained sandstones	Ripple-cross lamination	*Arenicolites* isp.	Mud drapes	Migration of ripples in tide-influenced settings with subsequent marine bioturbation
Sm	Very fine- to medium-grained sandstones	Massive	Angiosperm leaves. *Arenicolites* isp. *Palaeophycus tubularis*	Rhizoliths, mottling, Fe-nodules, slickensides, carbonaceous remains, calcareous concretions. Sporadic blocky structure	Stream-flow during high discharge conditions in tide-influenced settings with subsequent marine bioturbation, and in fluvial settings with sub-aereal exposure, pedogenic modification and terrestrial bioturbation
HS	Hetherolithic stratification: interbedded fine-grained sandstones and siltstones and mudstones; and very fine to medium-grained reworked tuffs	Horizontal lamination or ripple- cross lamination; and massive	Blades, angiosperm leaves, Sphenophytes stem	Carbonaceous remains, root traces	Deposition of epiclastic and reworked pyroclastic material with alternation in depositional conditions in tide-influenced settings. Subsequent sporadic sub-aereal exposure and pedogenic modification
IHS	Inclined hetherolithic stratification: interbedded very fine- to fine-grained sandstones and siltstones	Horizontal lamination or ripple cross lamination; and massive or laminated. Soft-sediment deformation	*Palaeophycus tubularis, Planolites montanus, Skolithos* isp, *Ophiomorpha* isp., *Asterosoma* isp., *Teichichynus rectus, Chondrites* isp	Mud drapes	Lateral meander migration in tide-influenced settings. Subsequent marine bioturbation
Fl	Siltstones	Horizontal lamination	*Celliforma* isp.	Carbonaceous remains, blades, slickensides, rhizoliths, mottling	Settling from suspension. Occasional sub-aereal exposure, incipient pedogenic modificaction and terrestrial bioturbation in fuvial settings
Fm	Siltstones	Massive to laminated	–	Rhizoliths, mottling, Fe-nodules, slickensides, carbonaceous remains	Settling from suspension with sub-aereal exposure and pedogenic modificaction in tide- and fluvial-influenced settings

Table 2
Synthesis of the facies associations.

Facies association (FA)	Sedimentologic features	Ichnofacies and paleontological contain	Interpretation and depositional setting
Subtidal–Intertidal deposits (FA1)	Marine bioturbated Tw deposit without an exposed base with irregular top surfaces and a minimum 0.5 m-thick, cover by lenticular deposits of Sb facies with variable thickness between 0.30 and 0.80 m and a lateral extension of several kilometres	*Skolithos-Cruziana* ichnofacies. Oysters (*Crassostrea orbigny*) and other marine mollusks	Bars and bioherms or reefs developed in the subtidal –intertidal setting of a coastal environment as the outer part of an estuary
Tidal creek deposits (FA2)	Vertically stacked (up to 3 m in thickness) ribbon-like bodies of marine bioturbated Tw deposits covered by HS facies giving a finning-upward trend. Individual bodies of Tw facies have thicknesses between 0.5 and 2 m with sharp, irregular and slightly erosive basal surfaces	Depauperate *Skolithos-Cruziana* ichnofacies. Terrestrial mammals	Volcaniclastic infill of small, low-hierarchy tidal channels (tidal creeks) developed in the intertidal zone of an estuarine environment
Tidal flat deposits (FA3)	Interbedded sheets with a maximum thickness of 2 m of centimeter-thick sheet-like bodies with flat-basal surfaces of Sm facies, broad centimeter-thick ribbon-like bodies with undulating basal surfaces of Sr facies and centimeter-thick of Fm facies. Mud drapes are present	*Glossifungites* ichnofacies	Alternation of bed load transport and deposition of sand and flocculated fluid muds with fluctuating tidal current energy in shallow flat areas as tidal flat settings that developed in the center of an estuary
Tidal channel deposits (FA4)	Channelized bodies composed of narrow sheets of St facies with thickness ranging from 0.3 to 1 m organized in finning-upward packages with slightly erosive concave-up basal surfaces, and narrow sheets or broad ribbons of Sp facies with thickness ranging from 0.3 to 2.5 m. Reactivation surfaces, mud drapes and muddy rip-up clasts are present	Depauperate *Skolithos* ichnofacies	Migration of subaqueous 3D- and 2D-dunes within channels formed in moderate to high energy environments with tidal influence as the subtidal part of the tidal channels in the central to inner part of an estuary
Tidal sand flat deposits (FA5)	Finning- and thinning-upward sheet bodies composed of marine bioturbated Sh facies limited by irregular to sharp basal surfaces with thickness ranging from 0.5 to 1.7 m. Muddy intraclasts and mud drapes are presents. Sheet bodies composed of TS facies have thicknesses between 0.8 and 1 m	Depauperate *Skolithos* ichnofacies. Leaves of Nothofagaceae	Deposits of high-energy that developed in shallow, tidally dominated systems, near to the "turbidity maximum" as tidal sand flats of the outer parts of the central estuary
Marsh deposits (FA6)	Sheet bodies of HS facies ranging in thickness from <0.5 m to 6 m and more than 900 m in length, and sheet bodies of Tw facies with up to 2.2 m-thick and with a lateral extension of kilometer-scale organized with a finning-upward trend. Root traces are present	Blades, angiosperm leaves, Sphenophytes stem	Depositional transition from peak to standstill flow of reworked pyroclastic material (Tw) and epiclastic material (HS) in a flat-lying area as salt marshes or marshes developed in an estuary. Subsequent pedogenesis
Tidal point bar deposits (FA7)	IHS facies 11 m in thickness and laterally continuous and ~0.4 m-thick sheets of Fm facies with an upward-finning trend. Mud drapes, bidirectional cross-stratification and soft-sediment deformation are present	Depauperate *Skolithos-Cruziana* ichnofacies	Tidal deposits as point bars developed in meandering channels in the fluvial-tidal zone of an estuary
Fluvial channel deposits (FA8)	Isolated bodies of Gm, Gt, St, Sp and Sm facies with narrow to broad sheet- to ribbon-like shapes, with irregular flat slightly erosive basal surfaces and internally with a finning-upward trend. The thickness ranges between 1.5 and 7 m. Intraclasts are observed	–	Infill of fluvial single, fixed and laterally stable channels
Fluvial point bar deposits (FA9)	Finning-upward packages of 2 m thick and less than 80 m wide unit composed of Sl facies with individual dipping beds with 0.4–0.5 m-thick. Paleoedaphic features are present	Blades, angiosperm leaves	Laterally accreting point bar deposits of fine-grained (counter point bars) in low-energy meandering channels in fluvial-dominated settings near the landward limit of the tidally influenced estuary. Subsequent pedogenesis
Floodplain deposits (FA10)	Stacks of narrow sheets of Sm and Fm facies with bases mainly planar and sharp and sporadically irregular and thickness between 0.3 and <2 m; and sheet bodies of 0.5 –< 2 m thick with planar and sharp contacts of Sl and Fl facies. Finning-upward trends and paleoedaphic features are observed	*Palaeophycus tubularis*, *Celliforma* isp.	Multiple flooding events of unconfined flows developed on a floodplain where the sediments were transported as bedload (sandy facies) and suspension components (muddy facies). Subsequent pedogenesis and bioturbation
Pyroclastic and volcaniclastic deposits of the floodplain (FA11)	Broad sheets of T and Tw facies with sharp nonerosional basal surfaces, ranging in thickness from 0.5 to 1.4 m and making up to ~13 km in lateral extension interbedded within FA10 deposits. Sporadic paleoedaphic features	Fossil mammals	T facies represent event of ash-fall in sub-aerial and subaqueous settings in floodplain environments. Tw represent unconfined sheet-flood episodes that remobilized pyroclastic materials in floodplain environments. Subsequent pedogenesis

Table 3
Summary of trace fossil assemblages and its environmental significance.

Unit	Trace fossil assemblages	Ichnofossils and bioturbation index	Ichnofacies and environmental significance	Facies	Facies association
Monte León Formation	TFA1	Moderately diverse, moderately highly bioturbated (BI 4). Dominated by *Ophiomorpha* isp. and cf. *Phycosiphon*	*Skolithos-Cruziana* ichnofacies. Impoverished marine communities. Soft substrates. Fresh water input, salinity fluctuations to more stable marine conditions.	Tw	FA-1
Santa Cruz Formation	TFA2	Scarcely diverse, scarcely bioturbated (BI 2). Dominated by *Ophiomorpha* isp. with subordinated elements of *Skolithos* isp. and *Palaeophycus tubularis*	Depauperate *Skolithos-Cruziana* ichnofacies. Impoverished marine communities. Soft substrates. Fresh water input with persistent salinity fluctuations.	Tw	FA-2
	TFA3	Scarcely diverse, intensity of bioturbation highly variable (BI 0–3), Dominated by bivalves vertical dwelling structure and *Arenicolites* isp.	*Glossifungites* ichnofacies. Impoverished marine communities Firm substrates.	Sm, Sr	FA-3
	TFA4	Scarcely diverse and scarcely bioturbated (BI 0–1). Composed by *Ophiomorpha* isp. and abundant isolated fecal pellets	Depauperate *Skolithos* ichnofacies. Impoverished marine communities. Soft substrates. Persistent salinity fluctuations. High-energy environment.	St, Sp Sh	FA-4 FA-5
	TFA5	Moderately diverse, locally moderately bioturbated (BI 3). Dominated *Palaeophycus tubularis*, *Planolites montanus*, and *Skolithos* isp., subordinate elements are *Ophiomorpha* isp. *Chondrites* isp. is locally abundant	Depauperate *Skolithos-Cruziana* ichnofacies. Soft substrates. Variation in the degree of bioturbation associated with changing salinity and elevations of the subtidal-intertidal zone	IHS	FA-7
	TFA6	Scarcely diverse and scarcely bioturbated (BI 0–1). Dominated by diverse ferric root traces, with subordinated *Palaeophycus tubularis* and *Celliforma* isp.	Continental environments. sub-aerial exposure, pedogenesis and bioturbation. Seasonality, well-drained paleosoils, occasionally waterlogged.	Sm, Fm, Fl	FA-10

lenticular shape with variable thickness between 0.30 and 0.80 m, and has an exposed lateral extension of several kilometres (Tables 1 and 2). Level of Tw is moderately highly bioturbated (BI 4) making it difficult to identify individual trace fossils, although some *Ophiomorpha* isp. and cf. *Phycosiphon* (TFA1) can be seen (Fig. 5A–C, Table 3). Other parts of this Tw bed are highly bioturbated by phycosiphoniform burrows creating a mottled fabric and obscuring other traces (Fig. 5A, Table 3). Burrows of *Ophiomorpha* isp. are filled by a massive reworked tuff that in turn is commonly reworked by cf. *Phycosiphon* (Figs. 5B–C, Table 3). However, beds of Sb have no trace fossils associated.

Interpretation: Bioturbated Tw facies of the MLF are interpreted as reworked ash-fall materials transported by the rivers to the tidal channels (e.g. Scasso and del Río, 1987) where they were mixed with other sediments and subject to marine bioturbation. This points to a transitional environment where energy from waves or tidal currents would have reworked the pyroclastic materials that came from contemporaneous explosive volcanism (e.g. Cuitiño and Scasso, 2013). The absence of mud drapes in these deposits suggests deposition by waters with low suspended sediment concentration in a seaward position of the system. Similarly, the record of a moderately diverse ichnofauna ascribed to the *Skolithos-Cruziana* ichnofacies (Table 3) in this facies with a higher degree of bioturbation than other assemblages studied, and including some elements typical of normal marine conditions such as cf. *Phycosiphon*, suggests possible increasing salinity in a seaward direction or periods of minor salinity fluctuations. On the other hand, oysters like those recorded at Sb facies of the FA1 can occur both, in shallow marine and estuarine environments (e.g. Kirby, 2001). In particular, the oyster *C. orbignyi* was adapted to inhabiting a hard or soft bottom, and tolerated a wide range of salinity and even subaerial exposure (Griffin and Parras, 2012), suggesting the presence of brackish water (Cuitiño et al., 2013). The prevalence of articulated shells in life position and its occurrence within a sedimentary rock with fine-grained matrix indicate little reworking. The tabular morphology, the lateral continuity and the internally massive bodies suggest colonization and growth of a community forming bioherms or reefs. The low diversity (mainly monospecific) shell

accumulations are related to environmental stress, commonly due to fresh-water input in a coastal setting (e.g. Cuitiño et al., 2013). Therefore, Sb facies of the MLF is interpreted as oyster bioherms or reefs developed in settings with shallow water, as in the subtidal to intertidal zone of an estuary. Thus, FA1 represents bars and bioherms or reefs developed in the subtidal–intertidal setting of a coastal environment as the outer part of an estuary (Table 2).

4.1.2. Facies association 2: tidal creek deposits

Description: The FA2 of the lowermost SCF is composed of Tw facies that frequently exhibit marine bioturbation (Fig. 4, Table 1). Upsection at both RDB-N and RDB-S, ribbon-like bodies of Tw facies mainly have thicknesses between 0.5 and 2 m (Figs. 3A, 4 and 5E–F). Basal surfaces of individual bodies are sharp, irregular and slightly erosive. In some cases two or more beds of Tw facies are vertically stacked forming successions up to 3 m in thickness (Table 2). These levels record trace fossil assemblages (TFA2) highly dominated by networks of *Ophiomorpha* isp. (Fig. 5E), and subordinated elements of *Skolithos* isp. and *Palaeophycus tubularis* (Fig. 4, Table 3). FA2 also contain terrestrial mammals (see below) which are well preserved, unweathered, and in some cases, partially articulated and associated to basal discontinuities of the bodies (Figs. 4 and 5F). These deposits are covered by HS facies (described below) giving a finning-upward trend (Fig. 4).

Interpretation: Tw facies of the lowermost SCF with slightly erosive basal surfaces and ribbon-like shapes are interpreted as the volcaniclastic infill of small channels. The record of extended decapods crustacean burrow systems such as *Ophiomorpha* isp., with constructional walls in this facies suggests the presence of soft substrates (Table 3). Low diversity of the ichnoassemblage points towards salinity-stressed environments (see below). Taphonomic details of fossil mammals in this facies suggest that the remains are autochthonous materials deposited in the intertidal zone. This facies association is interpreted as low-hierarchy tidal channels deposits. The finning-upward trend from Tw to HS facies also confirms such an interpretation. Thus, FA2 represents tidal creeks developed in lower tidal flats or marshes of an estuarine environment (Table 2).

4.1.3. Facies association 3: tidal flat deposits

Description: FA3 occur in the RDB-N section as: 1) centimeter-thick sheet-like bodies with flat-basal surfaces of Sm facies, 2) broad centimeter-thick ribbon-like bodies with undulating basal surfaces composed of Sr facies, and 3) centimeter-thick Fm facies (Table 1). These facies are arranged in interbedded sheets with a maximum thickness of 2 m (Figs. 4, 6A–B, Table 2). Individual beds show lateral thickness changes. Mud drapes are present in Sr facies (Fig. 6A). This FA is interbedded with Sh facies of the FA5. The same trace fossil assemblage (TFA3; Table 3) essentially occurs in both Sm and Sr facies. The intensity of bioturbation is highly variable (BI 0–3) with unbiorturbated beds interbedded with low to medium bioturbated ones (Fig. 6B). Trace fossils consist of vertical dwelling structures of stationary location of suspension feeders or surface-deposit feeding bivalves and of suspension- or filter-feeding polichaetes (*Arenicolites* isp.) of various sizes (Figs. 4 and 6A–B, Table 3).

Interpretation: Sm, Sr and Fm facies attest deposition in shallow flat areas with lower flow regime conditions. The interstratification between these facies indicates the persistent alternation of bed load transport and deposition of sand and flocculated fluid muds (Pearson et al., 2012). The occurrence of mud drapes suggests fluctuating current energy and the influence of tidal currents (Dalrymple and Choi, 2007). Sm facies record bivalve and polychaete burrows with sharp wall boundaries infilled by the overlaying sediments, suggesting that colonization occurred on firm substrates possibly exposed by tidal currents (Table 3). Thus, interbedded Sm, Sr and Fm facies of the FA3 are interpreted as deposits of tidal flat settings (e.g. Plink-Bjorklund, 2005) that developed in the center of an estuary (Fig. 4, Table 2).

4.1.4. Facies association 4: tidal channel deposits

Description: This FA is composed by St and Sp facies (Table 1). Individual bodies of St facies are narrow sheets with thickness ranging between 0.3 and 1 m. St facies are organized in finning-upward packages with slightly erosive concave-up basal surfaces (Figs. 6C and E, Table 2) and are concentrated at the base of channel bodies. Foresets are sometimes marked by mud drapes. Muddy rip-up clasts are observed at the base of the sets. The clasts are mostly platy shaped, but also can be rounded or angular (Fig. 6A), and (rarely) imbricated. Paleoflow directions are dominantly to the east-southeast. The bodies of the Sp facies (Figs. 4 and 6A, C and E) show slightly erosive bases, frequently covered by muddy rip-up clasts with similar characteristics to St facies (Figs. 6A and D). Foresets are tangential and are sometimes locally marked by mud drapes (Fig. 6A). Reactivation surfaces are also present. Individual bodies form narrow sheets or broad ribbons with thickness ranging from 0.3 to 2.5 m. This facies is the most common in channelized bodies. Paleoflow directions are dominantly to the southeast with minor south-southwest components; reverse paleocurrent directions are sometimes present. The only trace fossil in St and Sp facies are very fine specimens (BI 0–1) of *Ophiomorpha* isp. These consist of vertical components (Fig. 6E) with isolated fecal pellets of *Ophiomorpha* also being abundantly distributed (TFA4; Table 3).

Interpretation: St and Sp facies were formed in moderate to high energy environments, and are related to migration of subaqueous 3D- and 2D-dunes within channels, as indicated by the basal concave upward erosional bounding surfaces. Also, the internal organization of the succession suggests deposition during waning flow. Mud drapes within cross beds represent intervals of slack water during tidal cycles (Dalrymple and Choi, 2007). The occurrence of mud intraclast is common in the bottom of channel deposits in the middle reach of estuaries, in the vicinity of the "turbidity maximum" (Dalrymple and Choi, 2007) and indicates that the mud of underlying beds was still soft when eroded

(Mackay and Dalrymple, 2011). This is a typical feature of tidal influence (Dalrymple and Choi, 2007). The occurrence of mud drapes and reactivation surfaces in both facies reflect tidal influence (e.g. Dalrymple and Choi, 2007; Mackay and Dalrymple, 2011). The elevated energy of the channels generally reduces the preservation of trace fossils, even though facies-crossing biogenic structures are preserved, such as monospecific assemblages of *Ophiomorpha* isp. (Table 3). Thus, the features of St and Sp facies of the FA4 together with the presence of brackish ichnofauna allow us to distinguish these channels from a purely freshwater fluvial channel (e.g. Longhitano et al., 2012; Pearson et al., 2012), and allow us to interpret these deposits as the subtidal part of the tidal channels in the central to inner part of an estuary (Table 2).

4.1.5. Facies association 5: tidal sand flat deposits

Description: The FA5 is composed of Sh facies (Figs. 4 and 6A and E–F, Table 1), which is arranged in finning- and thinning-upward sheet bodies limited by irregular to sharp basal surfaces with thickness ranging from 0.5 to 1.7 m (Table 2). Muddy intraclasts and thick mud drapes are sometimes present (Figs. 6A and F). Bioturbation intensity is low (BI 1) with trace fossils occurring sporadically in low numbers. The trace fossil assemblage (TFA4; Table 3) is composed of the vertical components of decapod dwelling structures (*Ophiomorpha* isp.) and abundant fecal pellets, originally from the walls of the *Ophiomorpha* specimens (Figs. 4 and 6A and F, Table 3). In contrast, at RDB-S section are recorded sheet bodies composed of TS facies thickness ranging from 0.8 to 1 m (Tables 1 and 2). Carbonaceous remains and fossil leaves are recorded in TS facies (Fig. 4; Table 1). The leaves were assigned by Brea et al. (2012) to the Nothofagaceae and are generally undamaged. The TS facies contains no associated marine fossils or root traces.

Interpretation: Sh and TS facies indicate tractive currents and represent upper-flow-regime structures that developed in shallow, tidally dominated systems in the central parts of estuaries, where the "tidal maximum" occurs (Table 2). The presence of thick mud drapes indicates a seaward position respect to the peak of the "turbidity maximum" (Dalrymple and Choi, 2007). The *Ophiomorpha* traces and its fecal pellets ascrived to the depauperate *Skolithos* ichnofacies suggest energetic conditions, as does the presence of abundant isolated fecal pellets (Vilas et al., 2010) (Table 3). The low-diversity and preponderance of vertical traces in these facies suggests brackish-water conditions prevailed (Sisulack and Dashtgard, 2012) with the area being subject to periodic freshwater discharge (Pearson et al., 2012). Such biogenic reworking attests a high-energy environment in which sands were initially deposited and then colonized by different opportunistic invertebrates (Pearson et al., 2012). Similarly, the occurrence of fossil leaves of Nothofagaceae and carbonaceous remains suggests freshwater input and slack-water periods. Thus, FA5 is interpreted as tidal sand flats that developed in the outer parts of the central estuary (Table 2).

4.1.6. Facies association 6: marsh deposits

Description: FA6 of the SCF is composed of HS facies (Fig. 4, Table 1). It is arranged as sheet bodies ranging in thickness from <0.5 m to 6 m and more than 900 m in length (Table 2). HS facies records the finest deposits of the RDB-N. If so a finning-upward trend occurs; a change in thickness of sets success throughout the succession. Carbonaceous remains, blades, angiosperm leaves, and Sphenophytes stem compressions are present (Fig. 4, Table 1). This FA is also composed of sheet bodies of Tw facies (Table 1) with up to 2.2 m-thick and with a lateral extension of kilometer-scale (Table 2) which overlaid HS facies of this FA and IHS facies of the FA7 (Figs. 3C and 4). HS and Tw facies have no associated marine trace fossils; root traces occur in both RDB-N and RDB-S sections.
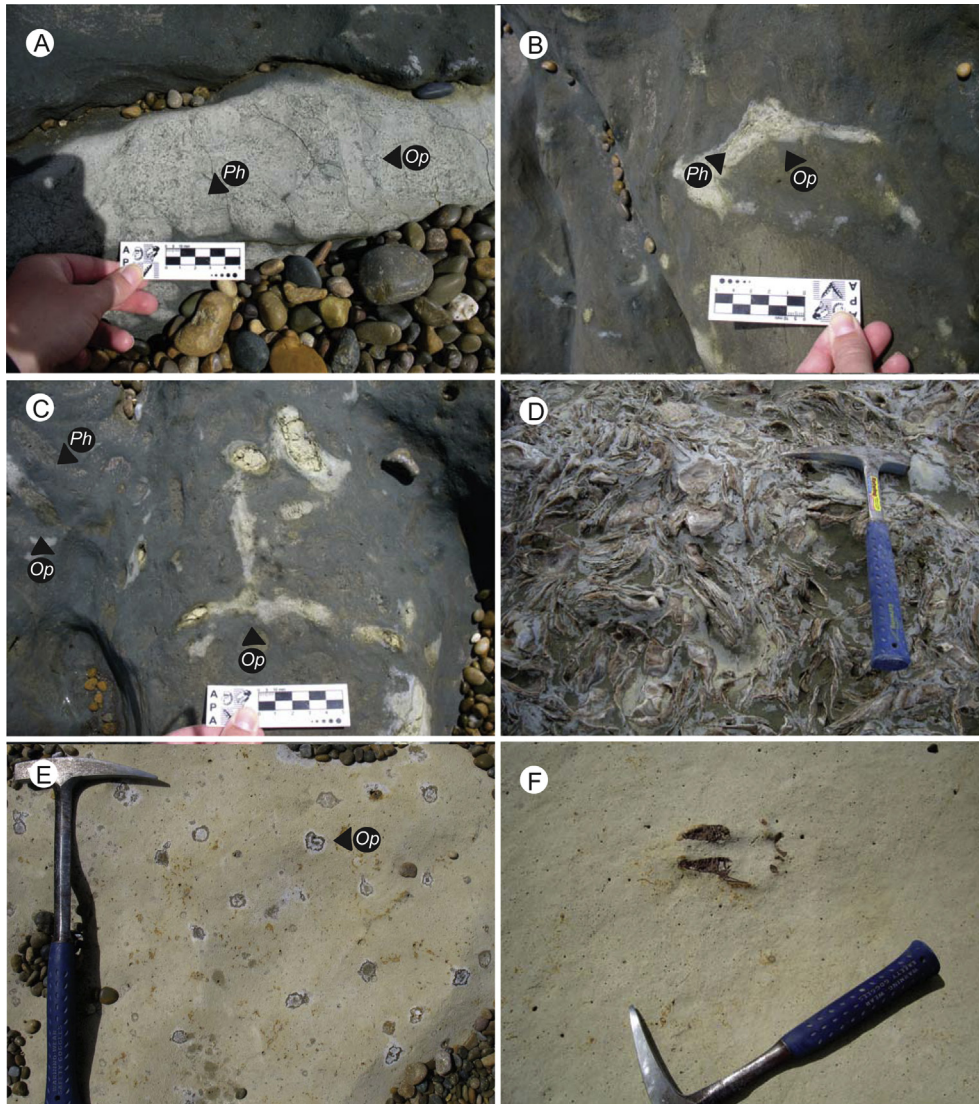
Fig. 5. Facies, ichnology and fossil record of the subtidal–intertidal deposits (FA1) and tidal creek deposits (FA2) of the outer and central estuary at Rincón del Buque Norte. A–D: Body and trace fossils within the volcaniclastic facies (Tw) of the lowermost analyzed levels (FA1). A: Highly bioturbated tuff (Tw) reworked by phycosiphoniform burrows (Ph), creating a mottled fabric, and individual *Ophiomorpha* isp. (Op) specimens. B–C: *Ophiomorpha* isp. (Op) filled by massive reworked tuffs and reworked by cf. *Phycosiphon* (Ph). D: Specimens of *Crassostrea orbignyi* in life position. E–F: View of the reworked tuffaceous level (Tw) of the lowermost part of the Santa Cruz Formation showing bioturbation by *Ophiomorpha* isp. (Op), and the presence of terrestrial mammal fossils (FA2).

Interpretation: Sheet morphology and lateral continuity of the bodies suggest deposition of reworked pyroclastic material (Tw) and epiclastic material (HS) in a flat-lying area. Rhythmic interbedding indicates a depositional transition from peak to standstill flow. Changes in the thickness of HS indicate that tidal currents are the main depositional process (e.g. Santos and Rosetti, 2006). The occurrence of root traces, blades, angiosperm leaf compressions and other carbonaceous remains suggest freshwater discharge, and the preservation of these is indicative of immature plain setting as brackish floodplain or immature-wetland deposition (e.g. Pearson et al., 2012). However, Sphenophytes stem compressions belong to the genus *Equisetum* (Page, 1972; Channing et al., 2011) (Iglesias, pers. com.) and show similar characteristics to the extant species *Equisetum giganteum*. The latter exhibits high salinity tolerance. It grows in coastal northern Chile (~18–20° LS) in saline soils and includes some of the few low elevation (3–90 m) populations known for this species (Husbi, 2009). Probably the lack of infaunal marine trace fossils in this FA could correspond to a system that

possessed a high ground-water table but still under tidal influence (e.g. Person et al., 2012). Root traces suggest reworking by vegetation and deposition in freshwater floodplains or salt marshes (e.g. Pearson et al., 2012). Thus, FA6 indicates the presence of a salt marsh developed in an estuary (Table 2). This environment might have been associated with marshes, especially upsection at RDB, where root marks were observed.

4.1.7. Facies association 7: tidal point bar deposits

Description: FA7 occur exclusively at RDB-S section and is composed of millimeter-to centimeter-thick interbedded Sh, Sr and Fm facies that form an inclined hetherolithic stratification 11 m in thickness (IHS facies) (Figs. 3C, 4 and 7, Tables 1 and 2). IHS facies are laterally continuous and have an upward-finning trend. IHS sets dip to the north-northeast with angles around 14°; up section there is a decrease in the dip to an average of 7° (Fig. 3C). Sedimentary structures are partially obliterated by bioturbation, and the walls of the burrows are oxidized and coated with dark yellowish orange
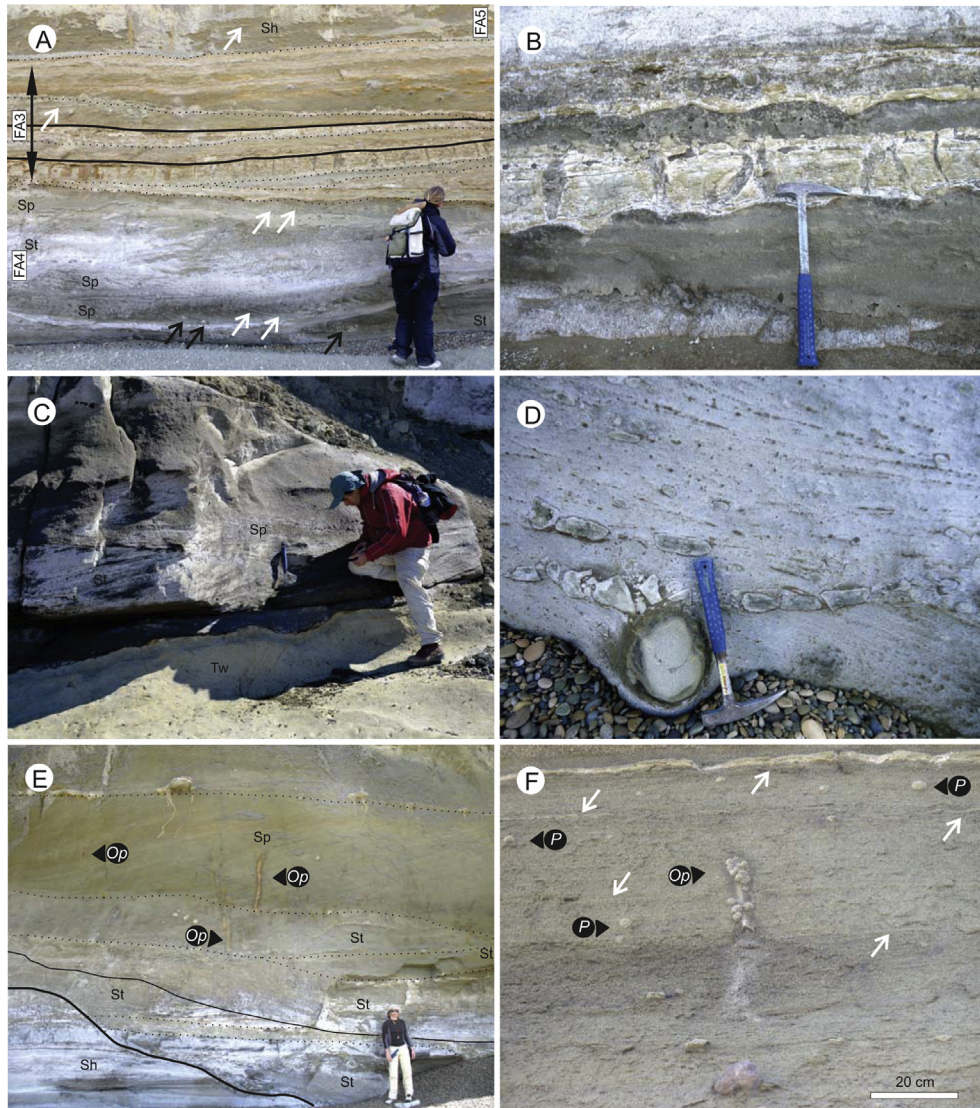
Fig. 6. Sedimentology and trace fossils of tidal flats (FA-3), tidal channels (FA4) and tidal sand flats (FA5) of the central to inner estuary environments at the Rincón del Buque Norte. A: General view of the FA3 in which firmground substrates containing the *Glossifungites* ichnofacies are developed. Thick full lines mark these surfaces, and dashed lines delineate bed boundaries. The interval of FA3 covers FA4 and it is covered by FA5. White arrows in Sr facies of the FA3 and in Sp facies of the FA4 identify mud drapes; black arrows denote muddy intraclasts in St and Sp facies. B: Detail of white silty levels of the FA3 shown in A, with vertical dwelling structures of bivalves and polichaetes (*Arenicolites* isp.) infilled by grey sands. C: A stack of coarse-grained cross-stratified sandstones (St, Sp) of the FA4 infilling a tidal channel that erodes the bioturbated and mammal-rich tuffaceous level (Tw) showed in Fig. 5. D: Details of Sp facies in tidal channels showing rounded and platy mud clasts as basal lags. E: Tidal channel infilled with St and Sp facies of the FA4 that erode levels of the FA5. Note vertical components of *Ophiomorpha* isp. (Op) in both facies. Thick and thin full lines mark the main discontinuity at the base of the channel, and a discontinuity of minor order, respectively. Dashed lines point internal discontinuities. F: Detail of *Ophiomorpha* isp. (Op) in Sh facies of the FA5 showing well developed pellets along the vertical shaft. Note the presence of dispersed fecal pellets (P). The arrows mark mud drape levels.

iron hydroxide (Fig. 7A–D). Mud drapes are in some cases rich in black organic material and in other cases are oxidized (orange) (Fig. 7F). Locally, the cross sets show bidirectional cross-stratification (Fig. 7F). Soft-sediment deformation occurs in the IHS facies (Figs. 4 and 7A–D and G–H): Convoluted bedding shows that the anticlinal folds are overturned in a downslope direction (Fig. 7G). Local increases in bioturbation intensity occur, especially upward. Bioturbation is mostly low but occasionally medium in intensity (BI 3). The trace fossil assemblage (TFA5; Table 3) is dominated by the polichaete dwelling and feeding structures *Palaeophycus tubularis*, *Planolites montanus*, and *Skolithos* isp. (Fig. 7A and D). Subordinate elements are decapod dwelling structures (*Ophiomorpha* isp.), and worm feeding structures such as those of *Asterosoma* isp. and *Teichichynus rectus* (Figs. 7A–C, Table 3). The latter one can also be interpreted as an equilibrium structure. On fine-grained sandstone and siltstone beds *Chondrites*

isp is locally abundant (Figs. 7B–C, Table 3). IHS sets are capped with ~0.4 m-thick sheets of Fm facies with no trace fossils.

Interpretation: As with the HS facies of FA6, the interbedded sands and silts of FA7 are interpreted as tidal deposits (e.g. Johnson and Dashgard, 2014). Sisulak and Dashtgard (2012) point out that sands of IHS are deposited during the freshet whilst muds are deposited during waning freshet flow. The occurrence of mud drapes in Sr beds attest that mud was settling during of slack water. Reversing current directions on cross-laminated levels reflect tidal influences. Both features characterize fluvial-tidal transitions (e.g. Dalrymple and Choi, 2007) as are drapes rich in terrestrial organic material (Van den Berg et al., 2007). Similarly, oxidized drapes and wall of burrows are formed in the upper intertidal zone of the bars of a tidal-fluvial transition (Choi et al., 2004) and the observed convolute bedding may be triggered by waves and by gravity-driven downslope movement in tidal bars (Choi et al., 2004). The

almost exclusive record of infaunal trace fossils in the whole finning-upward succession denotes burrowing as a strategy for surviving in environments with salinity fluctuations. In addition, the small size of trace fossils suggests brackish water conditions. Variations in the degree of bioturbation throughout the deposit are associated with changing elevations in the subtidal to intertidal zone (Choi et al., 2004) and variable salinity (Johnson and Dashgard, 2014) (Table 3). IHS facies also are related to lateral accretion on tidally influenced points bars (tidal bars) (e.g. Choi et al., 2004; Dalrymple and Choi, 2007; Johnson and Dashgard, 2014), probably associated with and laterally infill in high-sinuosity channels (e.g. Plink-Bjorklund, 2005; Longhitano et al., 2012; Scasso et al., 2012). The scale of the IHS reinforces the interpretation that it corresponds to point bars developed in meandering channels in the fluvial-tidal zone of an estuary (Choi et al., 2004; Dalrymple and Choi, 2007) (Table 2). In this context, Fm facies in the upper part of the IHS are interpreted as fine deposits that finish with the upward-finning grain size trend (e.g. Choi et al., 2004), reflecting the decrease in flow velocity associated with decreasing water depths (Johnson and Dashgard, 2014).

4.1.8. Facies association 8: fluvial channel deposits

Description: This facies association is composed of coarse-grained deposits consisting of isolated bodies of sand and gravel with narrow to broad sheet-to ribbon-like shapes, which show irregular flat slightly erosive basal surfaces (Fig. 3A–B and 8A, Table 2). In some cases intraclasts are observed. The thickness of such deposits ranges between 1.5 and 7 m. The thicker bodies occur in RDB-N (Fig. 4). Internally the thicker bodies show a finning-upward trend from Gm, Gt or St to Sp facies (Table 1). Thinner beds are composed of St or Sm facies and fine upwards from coarse- to fine-grained sandstone. Such deposits are interbedded with floodplain deposits of FA10.

Interpretation: Taking in consideration the geometry, finning-upward trends, and slightly erosive character of the basal surfaces of these coarse-grained facies, these are likely single story fluvial channel deposits (e.g. Bridge, 2003; Gibling, 2006). The occurrence of Gt, St, and Sp facies suggests prevalence of tractive deposition from dilute flows (Umazano et al., 2012), which represent migration of gravely, and sandy three-dimensional dunes (Gt, St), and migration of sandy two-dimensional dunes (Sp). Gm facies at the base of the bodies are lag deposits (e.g. Miall, 1996). However, the lack of structures in some bodies may indicate that the channel flow was heavily laden with sediment relative to its competence, resulting in suppression of bedform development (Fisher et al., 2007), or even may indicate that sedimentary structures were lost by weathering/pedogenesis. The fining-upward nature and the lack of structures up section of some of these channels indicate a decrease in flow velocity and suggest that the mechanism of transport change from bedload to suspended load. The interbedded floodplain deposits suggest that during times of peak discharge, unconfined overbank flow was important. The absence of evidence for sub-aerial exposure and of internal surface (reactivation or lateral migration surfaces) suggests that the channels were fixed and laterally stable (Table 2). The record of channel margin vegetation in the basal levels of the SCF (Brea et al., 2012), may have stabilized the channel banks and inhibited channel avulsion or migration to different positions (Nichols and Fisher, 2007).

4.1.9. Facies association 9: fluvial point bar deposits

Description: Large scale cross-stratification was observed at basal–middle part of the RDB-S section (Figs. 3C, 4 and 7E). This FA is characterized by a 2 m thick and less than 80 m wide unit that is dominated by finning-upward packages composed of Sl facies (Table 1). Individual dipping beds are 0.4–0.5 m-thick. The

inclination of the large-scale strata varies from 6 to 11° and the dip direction is towards the south-southwest (Fig. 7E). Fossil leaves of angiosperms (Iglesias, pers. com.), carbonaceous remains, blades, and paleoedaphic features (slickensides and root traces) were recorded in large-scale cross-stratified bodies.

Interpretation: Large-scale cross-stratified bodies are interpreted as laterally accreting point bar deposits in meandering channels (Table 2). The fine grain size of the Sl facies of such deposits is related to fine-grained dominated counter point bars deposits that form by lateral accretion in low-energy meandering rivers under tidal influence (Fig. 9) (e.g. Smith et al., 2009). The occurrence of deposits assigned to point bars or counter point bars in the lower–middle part of the section of the SCF at RDB-S, implied that some channels migrated laterally to some degree (Glibbing, 2006). The absence of marine fossil traces in this deposit and its relation with deposits of FA6 (marsh deposits) and FA10 (floodplain deposits) attest fluvial-dominated settings near the landward limit of the tidally influenced estuary (see Fig. 9) (e.g. Johnson and Dashgard, 2014) (Table 2).

4.1.10. Facies association 10: floodplain deposits

Description: This FA is composed of fine epiclastic facies, which consist of narrow sheets of Sm and Fm facies (Fig. 4; Table 1). The base of the bodies is mainly planar and sharp; however, irregular bases were sporadically observed. The thickness of Sm and Fm bodies varied between 0.3 and <2 m (Table 2). Sm and Fm commonly have paleoedaphic features, which include vertical rhizoliths, simple dwelling trace fossils, mottling, Fe-nodules, slickensides, carbonaceous remains and carbonate concretions (Figs. 4 and 8B–F). In general these facies show absence of horizons and are apedal; however, blocky structure is present up section in the RDB-S profile (Fig. 8C). Rhizoliths are the most common paleoedaphic feature recorded at the three measured sections. They are mostly ferric having a reddish-brown to yellow-brown color within the root infill and/or on its margins, forming haloes (Fig. 8B). The complete extension of a single root is difficult to observe, although some are delicate and tapering downwards others have constant diameter subtly tapering downwards and with horizontally-inclined secondary root traces (Fig. 8E). Rhizoliths show different combinations of the root infills and haloes. A root trace can be: 1) a discolored, 1–2 mm in diameter with a continuous brownish yellow halo 4–5 mm diameter (Figs. 8B), 2) a reddish to dark brown root infill of 1–2 mm with the halo absent or only locally developed (Figs. 8D), 3) a dark reddish brown root infill 1–2 mm in diameter surrounded by a pale brown to yellow concentric halo 4–10 mm of diameter.

Trace fossils are scarce and localized in some horizons. Mostly they consist of simple dwelling structures as in *Palaeophycus tubularis* (TFA6; Table 3). Carbonate concretions are abundant as isolated features or as rods and consolidated horizons frequently in the contacts between sandy and silty beds (Fig. 4). They appear in fine-grained facies and less commonly in Fl facies and in Sl facies. In both cases the latter have paleoedaphic features (Fig. 4). Sl and Fl facies occur in sheet bodies of 0.5 to <2 m thick with planar and sharp contacts (Table 2). Finning-upward trends are observed in the interbedded sandstones and siltstones associations. Paleoedaphic features of Sl and Fl facies include vertical rhizoliths, simple dwelling and nesting trace fossils, and sporadic mottling, slickensides, and carbonaceous remains. The pedogenic features are highly comparable with those described above and, in addition, contain records of small cells of solitary digging bees, 3–5 mm wide and 8–10 mm long, assigned to *Celliforma* isp. (Figs. 4 and 8F, Table 3), with the same characteristics as those found in the SCF south of Río Coyle at Cañadón las Totoras (Krapovickas, 2012; Raigemborn et al., 2012).
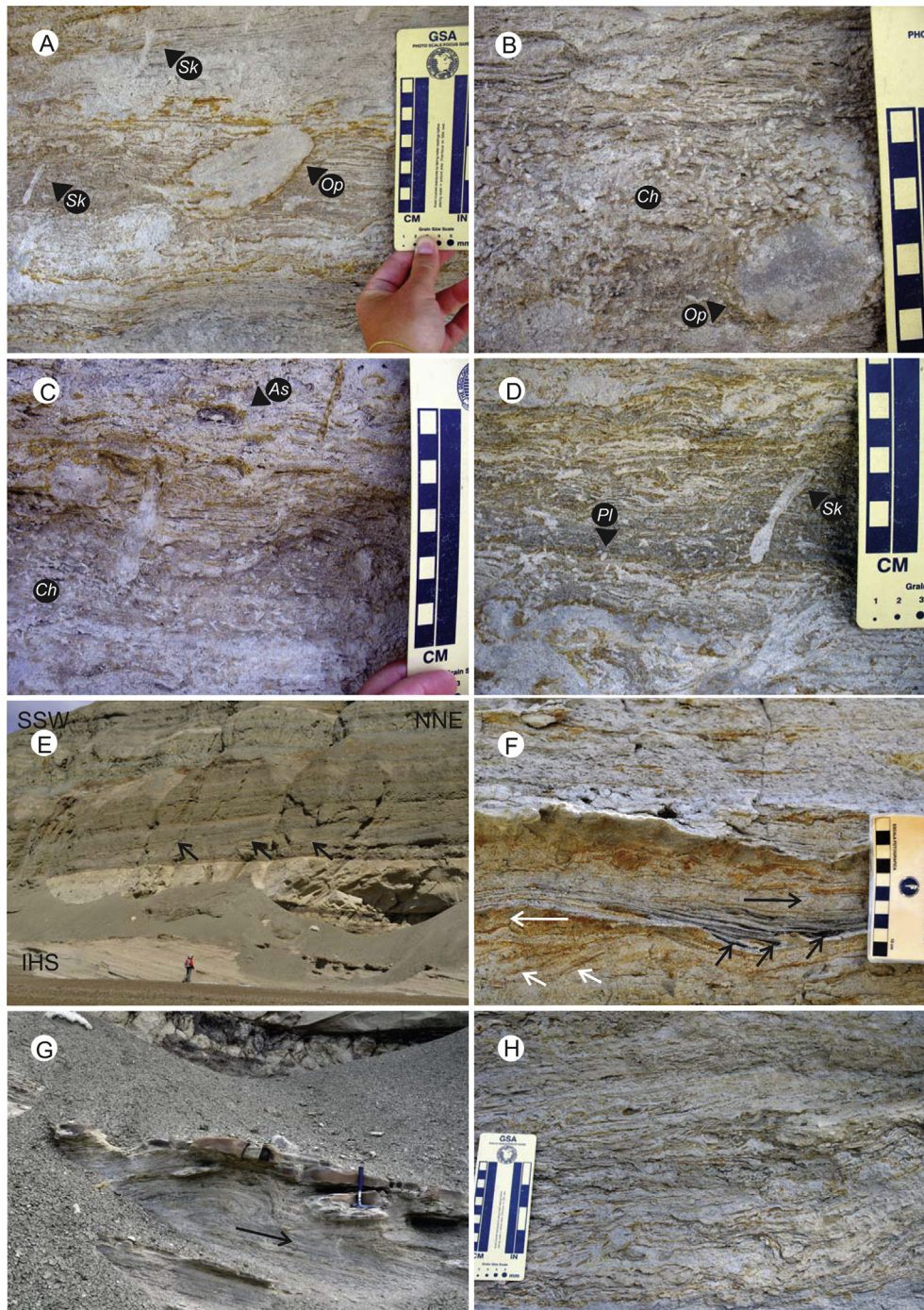
Fig. 7. Facies and ichnology of the central—inner estuary to fluvial settings at Rincón del Buque Sur. A—D: Cross-sections of thinly interbedded sand-silt that display different trace fossils in the IHS facies (FA7). A: Detail of *Ophiomorpha* isp. (Op) and *Skolithos* isp. (Sk). B: Detail of locally abundant *Chondrites* isp. (Ch) and *Ophiomorpha* isp. (Op). C: Detail of locally abundant *Chondrites* isp. (Ch) and *Asterosoma* isp. (As). D: Detail of abundant *Planolites montanus* (Pl) and *Skolithos* isp. (Sk). E: General view of the transition from estuarine to fluvial facies. Note that IHS facies dip to the right of the photographs (NNE), whilst the large-scale cross stratification (marked with arrows) of the FA9 dips to the left (SSW). F: Detail of IHS facies showing rhythmic cross-and plane-parallel lamination. Black arrows indicate mud drapes rich in organic matter; white arrows mark oxidizing mud drapes. Note that mud drapes (short arrows) dip in opposite directions (marked with large arrows). G: Convoluted bedding in IHS facies showing that folds are overturned in the down slope direction marked with an arrow. H: Structures of soft-sediment deformation in an interval within IHS facies.

Interpretation: The sheet-like geometry of the sandy bodies of the fine-grained facies together with the lack of structures of low-flow regime suggests unconfined flows developed on a floodplain (Table 2). This interpretation is reinforced by the dominance of massive and laminated sheet-flood deposits (facies Sm and Sl), which occur during periods of high discharge when large quantities of sediment was transported in turbulent and unconfined sub-

aerial flow (Fisher et al., 2007). The sediments loads of these flows were transported as bedload (sandy facies) and suspension components (muddy facies). A change from massive to laminated facies could be in response to the wane of flow velocity. The finest facies (Fm, Fl) with sheet-like shapes and non-erosive bottoms attest deposition under predominantly low energy, sub-aerial conditions from an unconfined flow (Tunbridge, 1981). Finning-

upward trends are interpreted as an increase in the distance from source or to the gradual reduction of the discharge from tractive conditions (Sm, Sl) to settling ones (Fm, Fl). The planar-base nature of the deposits suggests that the flow surface was relatively competent, possibly being stabilized by surface vegetation, as the described by Brea et al. (2012) for the SCF to the south of the Río Coyle area; or indurated after a period of sustained sub-aerial exposure (Fisher et al., 2007), as the edaphized and bioturbated facies described by Krapovickas (2012) and Raigemborn et al.

(2012) for the SCF to the south of the Río Coyle area. The large number of individual deposits that stack to form deposits of the fine-grained facies indicates deposition from multiple flooding events (Table 2). The relationship between these facies and the coarse-grained facies supports this interpretation of multiple sheet-flood events having occurred. Paleoedaphic features and burrows in the finest facies attest intervals of insignificant or absent deposition in which sub-aerial exposure gave place to pedogenesis and bioturbation. Thus, massive appearance of some levels of the
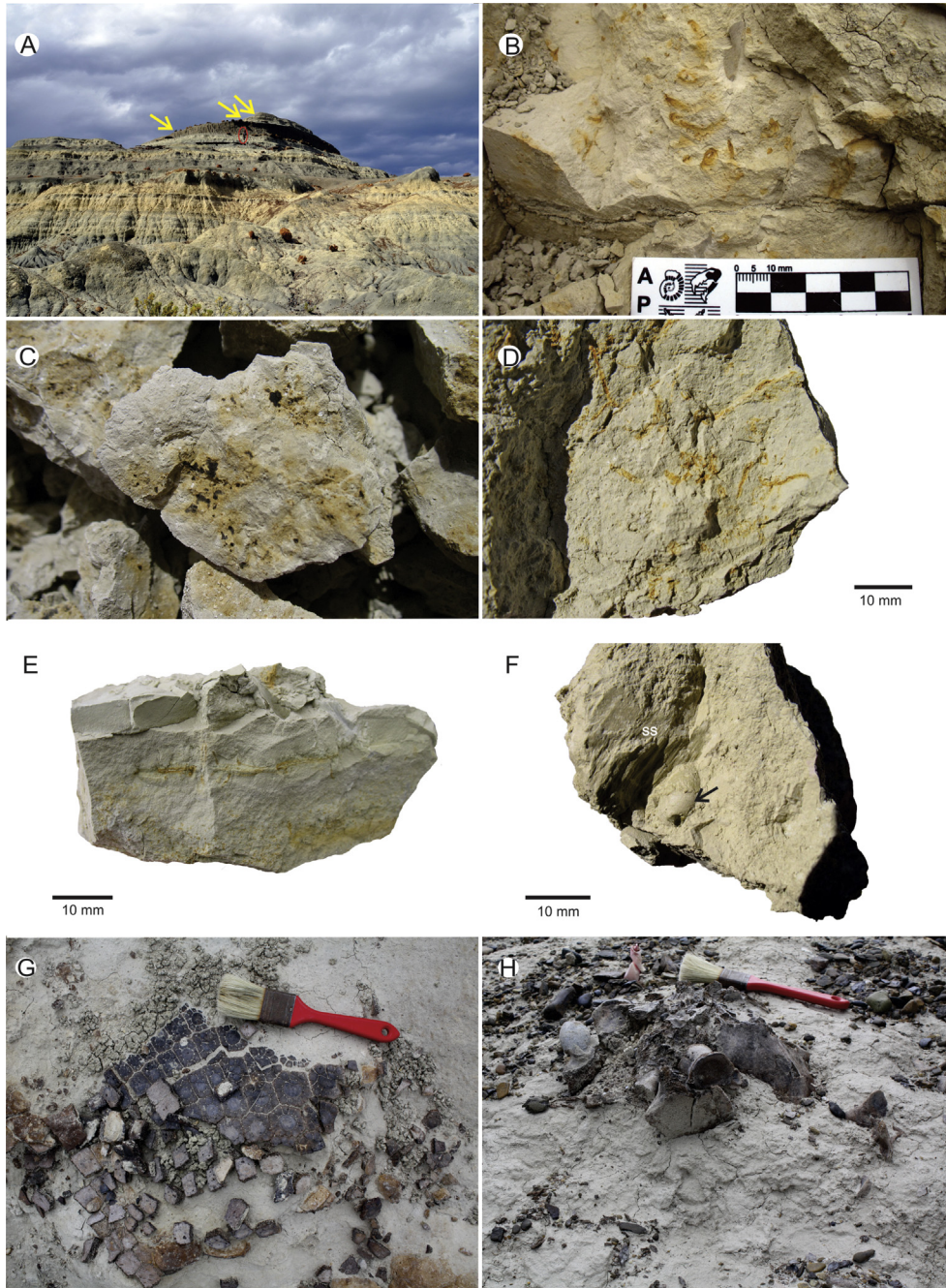

Fig. 8. A: General aspect of the fluvial facies at Rincón del Buque Centro (middle and upper part of the analyzed succession). The arrows indicate channel deposits enclosed in floddplain deposits. B–F: Detail of rhizoliths showing different combination of the root infill and halo and other paleoedaphic features present in FA10. B: Decolored root trace and a continuous brownish yellow halo. C: Detail of a slickenside surface of a paleosol with blocky structure. Note the presence of carbonaceous remains (black in color), mottling and thin root traces. D: Inclined reddish to dark brown root traces with the halo absent or locally developed. E: Lateral view of vertical rhizoliths with secondary horizontal root traces. F: Detail of a slickenside surface (ss) and a specimen of *Celliforma* isp (arrow) in a paleosol. G–H. Fossil mammals found *in situ* in the "T-16" level (FA11): a fragment of a glyptodont carapace (G) and a partial skull of a large notoungulate (H). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

finest facies of this FA may indicate reworking by biota and pedogenesis following deposition. In this sense, the abundance of carbonate concretions indicates an excess of alkaline solutes and precipitation in a well-drained floodplain (Retallack, 2001). In addition, burrowing bees generally nidify in arid conditions or in soils with only moderate plant growth, good drainage, and limited exposure to the sun (Ratcliffe and Fagerstron, 1980; Genise and Bown, 1994). Mottling and slickensides suggest periodic waterlogging, with alternating humid and dry stages or seasons. Moreover, the presence of ferric root traces and Fe-nodules implies that the B-horizons of the soil were moderately well drained (Kraus and Hasiotis, 2006). Iron is reduced and mobilized when the soil is water-saturated, and oxidized and immobilized when the soil dries, precipitating in places open to oxygen circulation (Duchaufour, 1987; Kraus and Aslan, 1993; PiPujol and Buurman, 1994). All these processes took place in a setting with a certain degree of seasonality as waterlogged paleosols with hydromorphic features vertically stacked with relatively dry, well-drained paleosoils were carbonate concretions and cells of solitary bees occur.

4.1.11. Facies association 11: pyroclastic and volcaniclastic deposits of the floodplain

Description: Pyroclastic and volcaniclastic facies of the FA11 are characterized by the occurrence of T and Tw facies (Table 1). Both facies have sharp nonerosional basal surfaces. They occur as broad sheets ranging in thickness from 0.5 to 1.4 m interbedded within floodplain deposits (Table 2). Sporadically, paleoedaphic features such as vertical rhizoliths are found at the top of Tw bodies (Fig. 4). One level of yellowish gray T facies occurs in the middle part of three measured sections of the Rincón del Buque area, making it ~13 km in lateral extension and 0.7–1.3 m thick (Figs. 3B, 4 and 11, Table 2). Fossil mammals were recorded in this lateral continuous tuff bed, which we call "T-16" (Figs. 3B, 4 and 8G–H).

Interpretation: Primary tuff beds occurring as sheets lack evidence of erosion at their bases and do not have cross bedding. These deposits derived from settling of volcanic ash (e.g. Cas and Wright, 1987). Thus, each primary tuff of FA11 represents a single event of ash-fall in sub-aerial and subaqueous settings. The presence of in general well preserved, unweathered and, in some cases, partially articulated fossil mammals in these primary tuff deposits, especially in the case of "T-16", attests deposition in floodplain environments (Smith, 1987) (Table 2). In contrast, volcaniclastic facies suggest reworking of ash-fall materials by surface processes and admixture with epiclastic materials (e.g. Smith, 1991; Orton, 1996). The sheet-like shape and the dominance of massive bodies points to unconfined sheet-flood episodes that remobilized pyroclastic materials (Cas and Wright, 1987; Umazano et al., 2012) (Table 2). Incipient paleoedaphic features to the tops of these deposits indicate subaerial exposure, and development of incipient paleosols with very low net sedimentation rates (Smith, 1987), indicating short periods of landscape stability. Humid conditions would have hastened the development of these incipient paleosols.

4.2. Paleontology

During three short visits to RDB, mainly devoted to the geological work, some fossil vertebrates were collected. In all, there are ~200 taxonomically identifiable specimens, mainly of mammals. As the samples are still in preparation, the real number is unknown. Most of the specimens (~80%) were recovered from tuff beds, about 75% from "T-16" (FA11), and 5% from the fossil-rich facies Tw (FA2) near the base of the SCF (Fig. 4); the rest were mostly recovered from surface prospecting at various levels between Tw and "T-16", or above the latter. Specimens collected in Tw

and "T-16" are in general well preserved, unweathered and, in some cases, partially articulated.

A preliminary faunal list based on our collections is summarized in Appendix 1. This list will be refined and expanded with future preparation and collecting. All the genera and species identified have been previously recorded in the SCF (Marshall et al., 1983; Abello et al., 2012; Bargo et al., 2012; Candela et al., 2012; Cassini et al., 2012; Vizcaíno et al., 2012c). The assemblage is typical of the Early Miocene Santacrucian South American Land Mammal Age (Patterson and Pascual, 1972).

5. Discussion

5.1. Paleoenvironmental reconstruction

5.1.1. The transition of the Monte León–Santa Cruz Formation at Rincón del Buque

Overwhelming evidence indicates that the uppermost part of the MLF as it appears along the Atlantic coast and inland along the eastern parts of Río Santa Cruz was deposited in a tide-dominated shallow marine to estuarine environments (e.g. Bande et al., 2008; Griffin and Parras, 2009; Cuitiño and Scasso, 2008, 2010; Fernicola et al., 2014). Matheos and Raigemborn (2012) also report a fluvial-marine transitional environment in the lowest parts of the coastal SCF.

The evidence reported here further supports the conclusion that the uppermost part of the MLF and the lower part of the SCF at RDB are transitionally fluvial-marine: there was tidal influence as indicated by: 1) mud drapes covering ripples and dune foresets; 2) muddy rip-up clasts; 3) hetherolithic intervals composed of interbedded sand, silt and mud; and 4) oposite dipping cross lamination/stratification, and reactivation surfaces. Evidence of wave influence is indicated by symmetrical ripples, and by the reworking of primary pyroclastic materials (soft-sediment deformation structures in IHS facies can be trigged by waves) (Choi et al., 2004; Santos and Rossetti, 2006; Dalrymple and Choi, 2007; Van der Berg et al., 2007; Scasso et al., 2012, among others).

The mixture of land-vertebrate remains with shallow marine invertebrates, leaves of Nothofagaceae and other angiosperm leaves, unidentified carbonaceous remains, blades (common in freshwater fluvial settings), Sphenophytes (characteristic of salt-marshes), and root traces (characteristic of marshes) point to terrestrial and freshwater input from rivers. These are classical features of estuarine environments where small shifts of the coastline leads to rapid changes from shallow marine to terrestrial environments, and/or the organic remains are transported to seaward or landward by alternating tidal currents (Scasso et al., 2012). Also, the coexistence of tidal-influenced deposits with deposits that evidence the action of freshwater is consistent with an estuarine setting.

The ichnological evidence of the uppermost part of the MLF and the lower part of the SCF at RDB supports the above sedimentology-based interpretation. The dominance of brackish water estuarine communities into the analyzed succession is consistent with trace fossil assemblages of low diversity (Buatois et al., 2005; MacEachern and Gingras, 2007). Ichnogenera with a limited saline tolerance are absent but euryhaline marine organisms are present. Trace fossil records indicate the preponderance of trophic generalist organisms, in agreement with modern brackish water communities. Similarly, the relatively small size of trace fossils in relation of their marine counterparts is a brackish-water indicator because ionic and osmotic regulation is difficult in such settings. Nevertheless, as their modern counterparts, Miocene brackish-water deposits do not necessary exhibit size reduction in burrows produced by such crustacean as *Thalassinoides*, *Ophiomorpha* and *Psilonichnus* (e.g. Rosseti, 2000; Gingras et al., 2002; Carmona et al.,
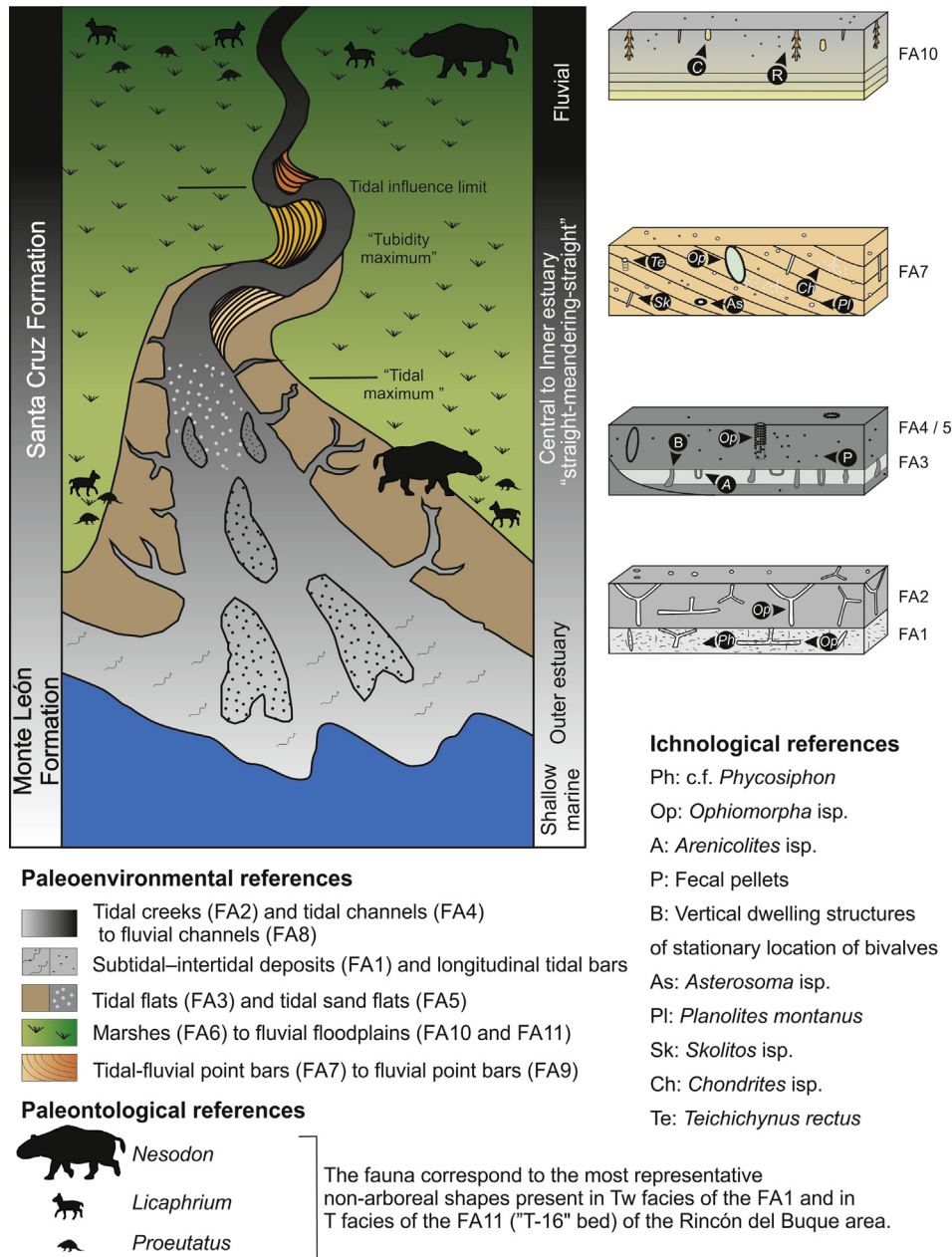
Fig. 9. Paleoenvironmental model for the coastal uppermost part of the Monte Léon Formation and the Santa Cruz Formation deposits at Rincón del Buque area and ichnologic assemblages. The schematic tide-dominated estuary is modified from Darlrymple and Choi (2007) and Scasso et al. (2012).

2009). Crustacean dwelling structures at RDB (*Ophiomorpha* isp.) agree with other Miocene recorded cases in having only a small reduction in size (e.g. Carmona et al., 2008). In brackish water environments, salinity fluctuations mostly affect the water column, but a few centimeters into the substrate, the sediment is barely affected because the presence of impermeable fine sediments slows down the exchange of pore water allowing it to be inhabited by a wider variety of endobenthic organism. This results in the dominance of vertical subsurface trace fossils produced by infaunal organisms rather than surface epifaunal trails.

Brackish water conditions are also suggested by the occurrence of monospecific accumulation of *C. orbignyi*, a brackish water tolerant organism (Griffin and Parras, 2012; Cuitiño et al., 2013), in the top of the MLF (FA1). Stressed conditions due to dilution of normal marine waters take place in a setting where freshwater

discharge contributes. Brackish water ichnofaunas and a brackish water tolerant *C. orbignyi* also attest an estuarine environment for the uppermost MLF.

The transition of the MLF–SCF at RDB area reflects a changing depositional environment (Figs. 4 and 9). Volcaniclastic deposits at the base of the profile at RDB-N (FA1) record a *Skolithos-Cruziana* ichnofacies (TFA1) with higher BI suggesting minor periods of salinity fluctuation due to fresh water input. Consequently, FA1 of the uppermost MLF possibly represent the subtidal–intertidal deposits of the outer estuary (Figs. 4 and 9). The vertical relationship of the FA1 (MLF) with the overlying mammal-rich reworked pyroclastic deposits (FA2; SCF) of a freshwater and continental origin suggests that the most basal levels of SCF was deposited very close to the coastline. This FA is interpreted as tidal creeks that scour tidal flats and marshes (FA3 and FA6, respectively) in the central part of
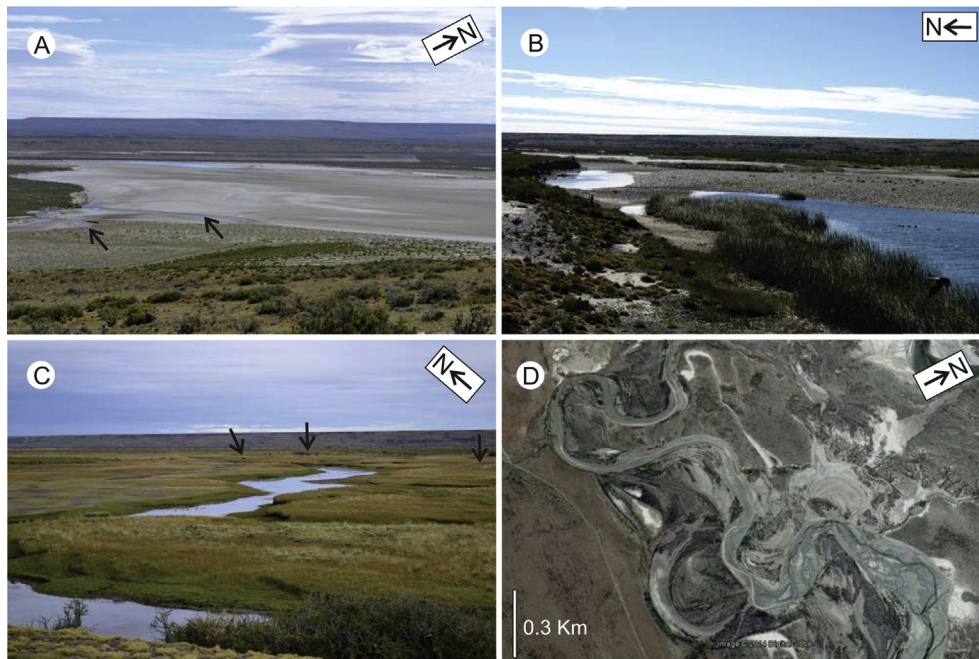
Fig. 10. Modern tide-dominated environemnets analog for the estuarine deposits of the lowermost SCF. A: Tidal sand flats, tidal creeks (arrows) crossing the tidal flat, and marshes of the central estuary in the Coyle estuary. Marshes are covered by halophyte-grass. This photograph was taken during the low tides. B: Freshwater ponds adjoin to the tidal flat (sand flat) and marshes beside the tidal channels in the central estuary in the Coyle estuary. C: Tidal channels of the Coyle estuary and marshes in the floodplain (central to inner estuary) cover by grass where animals graze. Arrows indicate the Patagonian cattle (sheep and cows). The photographs were taken during high tide. D: Satellite image of Google Earth showing meandering tidal channels and tidal point bars developed in the meandering area (inner estuary) of the Coyle estuary.

an estuary (Figs. 4 and 9). The taphonomic features of the verte-brate fossils of the FA2 suggest that the remains were transported only for short distances or not at all. Therefore, the terrestrial fossils probably correspond to animals that inhabited freshwater areas where ponds and marshes adjoin to the tidal flats and channels (Fig. 9). Similarly, Brea et al. (2012) point out that the features of the preserved leaves at RDB-S locality, within the TS facies (FA2), sug-gest that transportation of the leaves could only have been over a short distances from their source, up to a few kilometres, or dispersed short distances by wind. Thus, it is probably that fossil leaves suggest that the coastal region was forested, as was also suggested from palynological records by Barreda and Palazzesi (2007). The occurrence of *Ophiomorpha* isp. burrows (TFA2) within the mammal-rich Tw facies of FA2 is distinct from purely freshwater fluvial channels of the FA8. However, the mix of leaf debris, fossil mammals, and marine fossil traces of low diversity suggest that channels of the FA2 were periodically influenced by fluvial discharge.

This basal succession of the SCF is succeeded by infills of sandy tidal channels (FA4) developed in the central part of an estuary (Figs. 4 and 9). The presence of mud clast within these channels indicates deposition in the vicinity of the "turbidity maximum" (Fig. 9). Paleocurrent directions were predominantly east-southeast with a smaller component running south-southwest with large-scale subaqueous dunes migrating in the same directions as the current. Similarly, the FA5 represent tidal sand flats of the central estuary, in a seaward position respect to the tidal channel deposits, and located beneath the peak of the "turbidity maximum" and near to the "tidal maximum" (Fig. 9). All these sandy facies tend to lack biogenic structures, excepting for monospecific suites of *Ophio-morpha* isp. (TFA4) in soft ground indicating an impoverish *Skoli-thos* ichnofacies in brackish conditions.

Sandy deposits of tidal channels (FA4) and tidal sand flats (FA5) are laterally and vertically associated with tidal flats (FA3), salt

marsh (FA6) and tidal-fluvial point bars (FA7); these are deposits of the central and inner parts of an estuary (Fig. 9). Sandy-muddy facies in hetherolithic intervals of the FA3, are interpreted as tidal flat deposits closely associated with tidal sand flats deposits (FA5) (Fig. 9). Some colonization of firm ground substrates by bivalves and polichaetes (TFA3) is observed within this facies indicating pauses in deposition (e.g. Pearson et al., 2012). The tracemaking organisms initially colonized muds that had been exhumed by erosion; subsequently the traces were passively infilled. These correspond to autogenic examples of the *Glossifungites* ichnofacies denoting minor erosional surfaces within the tidal flat. The colo-nization of autogenic firmgrounds implies significantly shorter time of exposure after exhumation than in allogenic firmgrounds that have a basinwide scale (Pearson et al. 2012).

IHS facies of the FA7, recorded only at RDB-S, represent tidal-fluvial point bars. Seaward-dipping IHS present in the north-northeast represents deposition beneath the "turbidity maximum" in the central to inner estuary (Fig. 9). IHS facies record a depauperate mixture of both the *Skolithos* and *Cruziana* ichnof-acies (TFA5), the alternation corresponding to fluctuations in en-ergy inputs typical of estuarine environments, but also influenced by the abundant nutrient availability in the water column and the substrate (MacEachern and Gingras, 2007). The abundance of simple structures of trophic generalists is possibly related to these rich food resources. Upward in the succession a gradual transition to the fluvial environment (FA8–11) occurred (Figs. 4 and 9).

Modern day analogs for the depositional environment of the lowermost part of the coastal SCF can be found in several estuaries of the Patagonia region on the southeastern Atlantic coast as those of the Río Santa Cruz, Río Coyle, and Río Gallegos, each of which opens directly to the South Atlantic. For instance, the Coyle estuary (Fig. 10) is hypertidal with less extensive longitudinal bars near the sea in the outer estuary, whilst being dominated by extensive tidal sand flats in the central estuary (Figs. 10A and B) and fluvio esturine
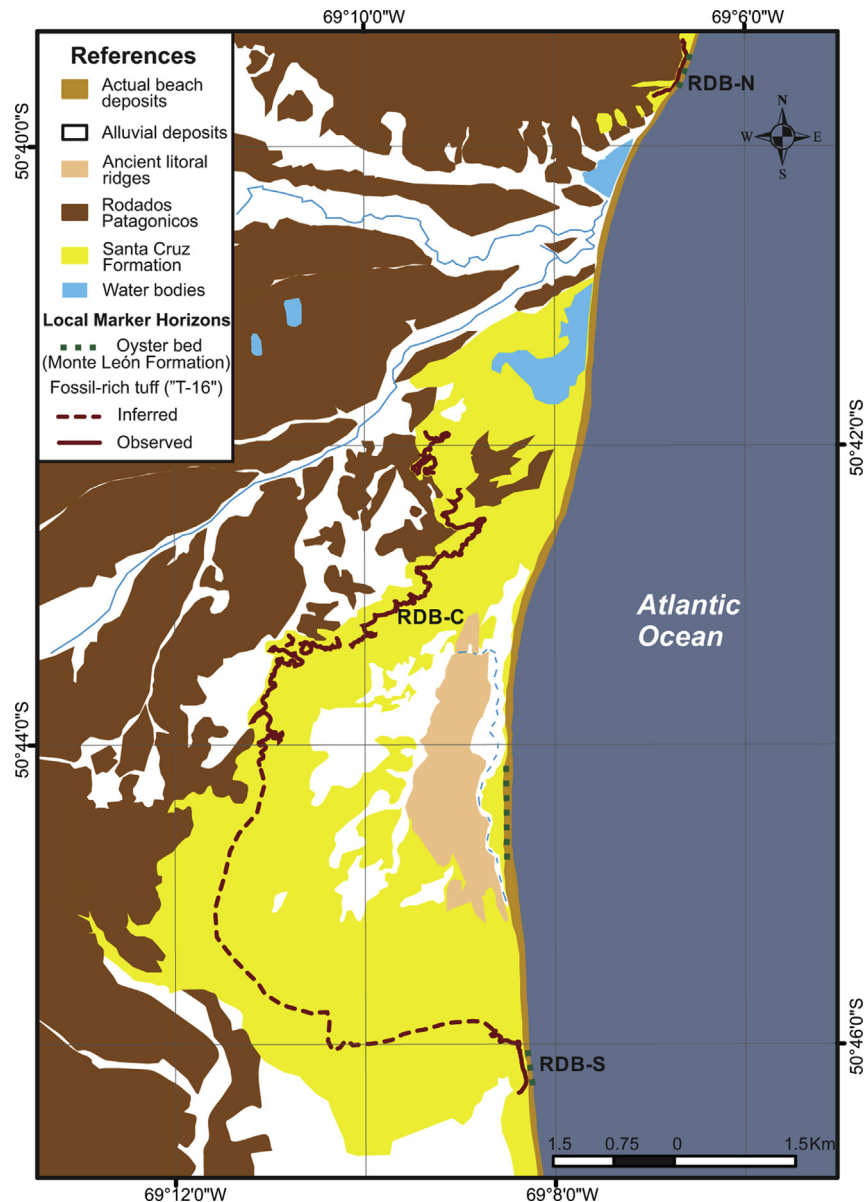
Fig. 11. Geological map of the study area showing position and distribution of the main marker horizons.

channels with large fluvio-estuarine point bars in the inner estuary (Figs. 10C and D) (Archer, 2013). In addition these modern Patagonian estuaries also resemble those of the Early Miocene in that there is influence of the Andean volcanic activity, for example with volcanic ash being deposited on the tidal sand flats (Archer, 2013). However, unlike the Early Miocene estuary that developed in an actively subsiding basin and with large river systems that fed a coastal zone prograding seaward, the Coyle estuary has minimum fluvial connection with limited/absence of freshwater flux that may allow an influx of marine-derived sediments (Archer, 2013), and it is characterized as a flooded river valley (Piccolo and Perillo, 1999) developed in an erosion dominated region.

5.1.2. The middle and upper section of the Santa Cruz formation at Rincón del Buque

At RDB, continental influence comes to dominate upsection. The transition from FA1–7 (estuarine deposits) to FA8–11 (fluvial deposits) can be recognized in the shifting lithofacies, the fossil content, and the shapes of the beds distinguishing estuarine (tidal channels/creeks, tidal sand flats, tidal point bars and tidal flat/marshes) from riverine conditions (fluvial channels, fluvial bars and fluvial floodplain). The overall decrease in marine influence is evidenced by the decline in marine fossils and their traces. Paleoedaphic features and exclusively remains of continental vertebrates as well as leaf compressions appear as tidal influences disappear (Fig. 4).

FA8–11 are interpreted as being produced by a fluvial system with single channels of relatively low energy and low sinuosity (FA8) similar to those described by Matheos and Raigemborn (2012), enclosed in a broad floodplain dominated by sheet-flood, overbank and ash-fall deposits (FA10 and FA11). Large-scale cross bedding of the FA9 indicating the presence of sinuosity in the fluvial system is seen exclusively in the middle part of the analyzed RDB-S section (Figs. 3C and 4) superimposed upon inner estuary deposits without cross-bedding. The lack of marine trace fossils and the presence of continental remains (leaves and blades) at RDB-S signifies a fluvial-dominated depositional regime. Such deposits

represent fluvial point bars (e.g. Johnson and Dashgard, 2014), probably positioned in the fluvially dominated setting of the transitional tidal-to-fluvial part of the estuary (Fig. 9). Fine-grained fluvial point bars or counter point bars are characteristic of the lowermost reaches of low-energy meandering rivers in tidal estuaries (Fig. 9) (e.g. Smith et al., 2009).

5.1.3. Pyroclastic and volcaniclastic sedimentation at Rincón del Buque

Ash-fall deposits (T facies), reworked tuffs (Tw facies), and tuffaceous sandstones (TS facies) of both MLF and SCF attest to a supply of sub-aerial eruptions from an active volcanic source area. Moreover, the decrease of pyroclastic deposits up section of the analyzed SCF at RDB (Fig. 4) probably indicates a diminution in explosive volcanic activity. The tabular shape and the lateral extension of the primary tuff as the "T-16" level, in the study area suggest that pyroclastic materials mantled a flat paleosurface. The relatively fine grain size of the primary tuff in the study area must have been deposited as ash-falls that affected the Austral basin as a whole. Reworked tuffs of the middle and upper sections of the analyzed SCF (Fig. 4) reveal a fluvial environment influenced by an active volcanic source area where a large amount of fine-grained pyroclastic particles were mixed with epiclastic particles. Similarly, reworked tuff and tuffaceous sandstones of the uppermost MLF and the lower part of the SCF at RDB (Fig. 4) indicate pyroclastic materials, which reached the marginal estuarine environment by freshwater input and then were reworked and mixed with other materials (e.g. Cuitiño and Scasso, 2013). Subsequently these materials were bioturbated by marine organisms. The presence of carbonaceous material, leaves, and mammal bones in pyroclastic and volcaniclastic facies reinforce the interpretation that the pyroclastic material was supplied from the land. In the same way, the salinity-stressed conditions suggested by fossil traces are related to fluvial input into the coastal system. An additional source of stress, together with the elevated sedimentation rates during explosive volcanism, may be due to the acidification of the flowing waters interacting with volcanic particles (Cuitiño and Scasso, 2013). The alternation of ash-fall deposits with reworked tuffs and non-pyroclastic deposits through the succession suggests episodic sedimentation in which the volcanic influence was important. Major sedimentation would have taken place during episodes of intense volcanism (syn-eruptive periods); when volcanism decreased or ceased (inter-eruptive period), erosion and reworking dominate the system (Smith, 1991).

The initial influx of volcaniclastic sediments in the coastal Atlantic region began at ~22 Ma (age of the base of the coastal pyroclastic-rich MLF; Parras et al., 2012) and continued uninterrupted until at least 16 Ma, the age of the youngest strata of the SCF in the Atlantic coastal plain. However, in the Andean foothill it occurred somewhat earlier at ~19 Ma, and finished at ~14 Ma (Blisniuk et al., 2005; Fleagle et al., 2012; Perkins et al., 2012). The mentioned oldest ages represent the beginning of the continental synorogenic sedimentation immediately after the eastward withdrawal of the "Patagonian" sea, which westward started one million years earlier (Cuitiño et al., 2012; Bostelmann et al., 2013). The source area of these pyroclastic materials probably was located ~300–400 km to the west in the Andean range (Matheos and Raigemborn, 2012; Cuitiño and Scasso, 2013), where the South Patagonian Batholith is currently located (Fig. 1A) (Hervé et al., 2007). This is a similar setting as now occurs in the dispersal of ash deriving from highly explosive eruptions in the southernmost Southern Volcanic Zone and Austral Volcanic Zone of the Andean Range hundreds of kilometres from the source (Ramos and Kay, 1992) where ash is distributed east and south-eastward over Austral Patagonia (e.g. Hudson eruptions in the last ~10.000 years

[see Stern, 1991; Scasso et al., 1994]; the eruptions of the Lautaro and Viedma volcanoes in the past two centuries [see Martinic, 2008 http://www.segemar.gov.ar/]) (see position of these volcanoes in Fig. 1A), and the recent eruptions of the Chaitén and Puyehue volcanoes (e.g. Lara, 2009; Mulena et al., 2012).

Vertebrate bones in tuff beds Tw and "T-16", although deposited in different environments (one estuarine and another continental), each show very little reworking indicating short or no transport before deposition, and rapid burial without exhumation (e.g. de Valais et al., 2012; Rogers and Kidwell, 2000). Considering that volcanic activity causes high mortality rates (e.g. Guo et al., 2007) and that sedimentation rates were high (100–200 m/Ma on average; Perkins et al., 2012) for the SCF (see below), specially during ash-bed deposition where sedimentation rate is instantaneous, it is probable that the vertebrate remains represent a community living very close to the setting of accumulation (in the tidal flat or marshes for Tw of the FA2, and in the floodplain for "T-16" of the FA11). Similar catastrophic ash-fall events from Miocene Andean volcanism account for the death and entombment of crabs were registered in the MLF (Crawford et al., 2008).

5.1.4. Paleoclimatic reconstruction at Rincón del Buque

Several taxa recovered south of Río Coyle in penecontemporaneous levels to those of RDB (e.g. palm trees, the frog *Calyptocephalella*, the lizard *Tupinambis*, the anteater *Protamandua*, and the primate *Homunculus*) strongly indicate that the climate was much warmer and wetter than today. The overall mammalian species richness and niche composition, expressed as percentages of arboreal or scansorial, frugivorous, and grazing species, suggest that overall rainfall was in the range of 1000–1500 mm per annum (Kay et al., 2012b) just to the south of RDB. Similarly, the occurrence at RDB of trees and forest-dwelling birds and mammals (spiny rats, sloths and scansorial marsupials) supports this conclusion. Although the fauna recorded in RDB so far does not allow the same specificity, what we know so far is consistent with the same paleoclimatic and paleoecologic interpretation. Based on plant macro- and microfossils, the vegetation of the lower part of the SCF section indicates estuarine and fluvial environments with the ground covered by warm–temperate semi-arid to humid forests, with seasonally low precipitation limiting for plant growth (Brea et al., 2012). Isotopic data of *C. orbignyi* from the top of the MLF at southwestern Patagonia suggest the presence of warm oceanic currents affecting the Early Miocene Patagonia shelf (Cuitiño et al., 2013).

Evidence of seasonal climatic conditions came also from the sedimentological and ichnological features. For example, the occurrence of cells of solitary bees (*Celliforma* isp.) and the presence of pedogenic carbonate (carbonate concretions) in well-drained paleosols suggest drier climatic condicions, meanwhile the alternation of waterlogged-paleosols and well-drained paleosols throughout the middle-upper section of the analyzed succession, indicate a certain degree of seasonality.

5.2. Correlation and age of the Rincón del Buque vertebrate fossil levels with previously described Santacrucian localities

The oyster bed of the uppermost part of the MLF (Sb; FA1) which demarcates the top of the MLF, is recognized in the sections of RDB-N and RDB-S (Fig. 3A, C and 4), and also at the base of the middle sector of RDB area (Fig. 11), making it a good local marker horizon in the study area. Likewise, several representative tuff beds are also useful guide beds in the study area (Fig. 4), such as, ribbon-like bodies of reworked tuffs (Tw; FA2), belong to the lowermost part of the analyzed SCF above the oyster bed where the fossil mammals take place, and sheet-like bodies of reworked tuffs (Tw; FA6). Finally, tuff "T-16" (T; FA11) is exposed in all sections within the

study area and makes another good marker horizon (Fig. 4). Thus, the three stratigraphic marker horizons allow us to establish correlations within the RDB area. The areal distributions of these guide horizons are shown in Fig. 11.

As mentioned above, using a relatively inaccurate K–Ar method, Marshall et al. (1986) reported a date of ~16 ± 0.8 Ma for a tuffaceous sample that came from the NE side of the amphitheater of RDB area, about 20 m above the base of the outcrops. Earlier, Bordas (1941) mentioned a fossiliferous tuff 35 m above the oyster bed of the *Superpatagoniense*. Our "T-16" level is located between ~32 and ~41 m above the last oyster bed of the MLF (Fig. 4). Considering that "T-16" is the most conspicuous mammal-rich tuff level, in the absence of other information we propose that Bordas' and Marshall's tuffs are equivalent to our "T-16".

South of RDB Santacrucian coastal localities occur along the 70 km beach strand from the inlet of Río Coyle south to the inlet of Río Gallegos (Figs. 1A and B). These southern localities were interpreted by Tauber (1994, 1997a) as a stratigraphic succession on account of an estimated regional 3° average dip to the southeast of the SCF. Three tuff horizons that crop out to the top of the exposures in Cañadón del Indio (Fig. 1B) were used by Tauber (1994, 1997a) and Kay et al. (2008) as levels to establish correlations among the localities between Cañadon del Indio and Puesto Estancia La Costa (Fig. 1B). Perkins' et al. (2012) work with tephrostratigraphy suggest that localities between Estancia La Costa and Puesto Estancia La Costa (including Cañadon Silva) (Fig. 1B), are more horizontally disposed and penecontemporaneous. Tauber and later Kay et al. (2008), suggest that the fossiliferous localitites south of Puesto Estancia La Costa (including Cabo Buen Tiempo, Cañadón Las Totoras and Monte Tigre) (Fig. 1B) are younger than the northerly localities, owing to the SE regional dip, a finding confirmed by the work of Perkins et al. (2012).

North of RDB at Monte León, where the contact MLF-SCF is observed, and at Cerro Observatorio-Cañadón de las Vacas (Fig. 1A), a sequence of tuffaceous horizons that crops out low in the section (~20 m from the base) had been dated at 16.3 Ma (Fleagle et al., 1995). This sequence was correlated with the marker horizons of Cañadón del Indio by Kay et al. (2008). More recently, Perkins et al. (2012) and Fleagle et al. (2012) showed an updated scheme of correlation between southern Río Coyle and Cerro Observatorio–Monte León National Park areas (Fig. 12). An interval of closely spaced tuffs near to the base of the SCF was designated by Perkins et al. (2012) as "L1-3". The base of this interval, just below the last oyster bed, was dated at 17.7 Ma ("PAT" tuff). The top of "L1-3" was dated on 17.4 Ma ("CO" tuff) (see Fig. 2.2 of Perkins et al., 2012; and Fig. 12). The L1-3 interval includes the three tephra of Cañadón del Indio ("<CI, CI and CO" tuffs).

Tentatively then, the RDB composite section overlaps the lower part of the southern region (Cañadon del Indio to Puesto Estancia La Costa and the middle part of the section at Monte León) (Fig. 1A) it is plausible to correlate the oyster bed and the tuffaceous levels of RDB with the previously described localities. Considering that the "L1-3" interval begin with a tuff level ("PAT") close to the last oyster bed, this could be represented in our area, at least in RDB-N and RDB-S (Fig. 4), by the lower tuff levels immediately above the oyster bed. Upsection, the fossil-rich tuff "T-16" could be correlated with the "CO" of Cañadón del Indio. As we understand it, the "L1-3" interval (~17.7–17.4 Ma) is recorded in the basal 30 m of the SCF at RDB area (Fig. 12), which represents an accumulation rate of ~100 m/Ma. This high sedimentation rate is consistent with the low degree of bioturbation (BI variable between 0 and 3) in the lower section of the analyzed SCF (estuarine deposits) and with other indicators of a high sedimentation rate such as the preservation of thick packages of floodplain deposits, the isolation and the low connectivity of the channels upsection, and the immaturity of the

paleosols. Cuitiño et al. (2012) mentioned high sedimentation rates (~170 m/Ma) for the upper member of the Estancia 25 de Mayo Formation (=MLF) in the Andean region of the Santa Cruz Province. Similarly, high sedimentation rates (100–200 m/Ma on average) were estimated by Perkins et al. (2012) based on radiometric age determinations for the coastal SCF.

Although the SCF at RDB is fossiliferous throughout, the richest and best-preserved specimens so far come from "T-16". On present evidence, "T-16" correlates with to the "L1-3" interval south of Río Coyle in the lower part of the coastal SCF (Fleagle et al., 2012; Perkins et al., 2012), and the section as a whole is equivalent to Estancia La Costa Member. Therefore, RDB is broadly correlated with the Santacrucian localities of Estancia La Costa, Cañadon Silva and Puesto Estancia La Costa, south of Río Coyle (Fig. 1B) (Kay et al., 2008; Vizcaíno et al., 2010). Furthermore, based on the proposed correlations (Fig. 12), it is probable that the RDB's fauna are slightly younger than the Anfiteatro–Campo Barranca's fauna (Fig. 1B) due to the fact that the fossil-rich tuffs of these localities are correlated with "<CI and CI" tuffs, whereas the mammal-bearing tuff of RDB would correlate with the overlying "CO" tephra (Fig. 12).

To the north, the correlation between "T-16" and localities in Cerro Observatorio–Cañadón de la Vacas and Monte León National Park (Figs. 1A and 12) would indicate that the first is contemporary with the fossil-rich level of the Stake (staca) #64 of the Cerro Observatorio-Cañadón de las Vacas described by Bown and Fleagle (1993).

6. Conclusions

The uppermost levels of the Monte León Formation (MLF) and the deposits of lower part of the Santa Cruz Formation (SCF), both of Early Miocene age, crop out along the Atlantic coastline of the Santa Cruz Province in the Rincón del Buque area (north to Río Coyle; Patagonian Argentina) as a conformable succession rich in
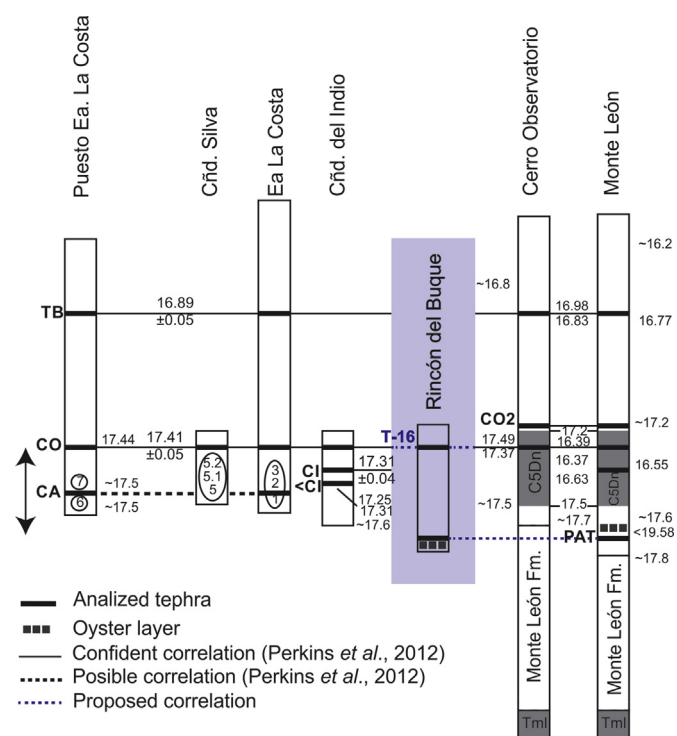

Fig. 12. Correlation diagram between Rincón del Buque and other coastal Santacrucian localities. Modified from Fleagle et al. (2012) and Perkins et al. (2012).

terrestrial vertebrate fossils and marine trace fossils. The sedimentological, ichnological and paleontological analysis of the succession shows that the settings of deposition vary from estuarine to fluvial, and attest a progradation with continentalization upsection. The uppermost levels of the MLF and the lowermost beds of the SCF contain subtidal to intertidal deposits with *C. orbignyi* specimens and bioturbation of the *Skolithos-Cruziana* ichnofacies (FA1), tidal creek deposits with terrestrial fossil mammal remains and *Ophiomorpha* isp. burrows (FA2), and tidal flat deposits with *Glossifungites* ichnofacies (FA3). These three facies associations represent the more seaward part of an estuary (outer and central estuary). Upsection, the levels of the SCF represent the infill of tidal channels (FA4) and tidal sand flat deposits (FA5) with associated impoverished *Skolithos* ichnofacies, marsh deposits (FA6), and tidal point-bar deposits (FA7) recording a depauperate mixture of both the *Skolithos* and *Cruziana* ichnofacies. This interval of the SCF was deposited in the central and inner parts of a tide-dominated estuary. These tide-influenced deposits are transitionally covered by continental facies of fluvial channels deposits (FA8), fluvial point bars deposits (FA9), and edaphized, bioturbated and mammal-rich floodplain deposits (FA10 and FA11), which represent a low energy and low sinuosity fluvial system.

Pyroclastic and volcaniclastic materials are present in the analysed succession sourced by sub-aerial eruptions from an active volcanic source area located in the Andean range that affected the Austral Basin. These materials must have been deposited as sub-aerial distal facies in a fluvial setting and also were carried by fluvial streams and redeposited in both estuarine and fluvial settings. Volcanic materials preserve most of the terrestrial fossil mammals distinctive of the Santacrucian Land Mammal age of the RDB succession.

The alternation of pyroclastic material with volcaniclastic and epiclastic material throughout the RDB area suggests episodic sedimentation with volcanic influence, and could represent the alternation of syn-eruptive and inter-eruptive periods, respectively. In addition, high sedimentation rates are assumed for the analyzed section of the SCF on the basis of the low degree of marine bioturbation (BI 0–3), the preservation of thick packages of floodplain deposits, the isolation and low connectivity of channel deposits upsection, the immaturity of the paleosols, and for the interpreted geochronological data that indicate an accumulation rate of ~100 m/Ma, on average, for the basal 30 m of the SCF at RDB area.

Paleoclimatic inferences from sedimentological, paleontological and ichnological analyses indicate a relatively warm and seasonal climate for the Early Miocene in the coastal area of the Santa Cruz Province, in agreement with previous paleoclimate reconstructions.

The wide lateral extension of both the oyster-rich bed demarcating the top of the MLF, and the tuffaceous levels of SCF especially the highly fossiliferous "T-16" tuff level, are useful stratigraphic marker horizons for correlation with other fossil-bearing localities. We correlate the basal 30 m of the SCF at RDB area with the lower part of the coastal SCF south of Río Coyle —Estancia La Costa, Cañadon Silva and Puesto Estancia La Costa— (~17.7–17.4 Ma), equivalent to the Estancia La Costa Member. Moreover, the RDB's principal faunal level is slightly younger than the Anfiteatro–Campo Barranca's fauna.

Acknowledgements

Appendix 1. Preliminary faunal list of Rincón del Buque locality.

AVES
  Phorusrhacidae
    Phorusrhacus longissimus

MARSUPIALIA
Paucituberculata
  Caenolestidae indet.
  Palaeothentidae
    Palaeothentes intermedius
    Palaeothentes lemoinei
    Palaeothentes minutus
    Palaeothentes cf. *aratae*
    Acdestis lemairei
    Acdestis owenii
  Microbiotheriidae
    Microbiotherium tehuelchum
Sparassodonta
  Hathlyacynidae indet.

XENARTHRA
Cingulata
  Peltephilidae
    Peltephilus
  Dasypodidae
    Proeutatus
    Prozaedyus
    Stenotatus
  Propalaehoplophoridae
    Propalaehoplophoridae indet
    Cochlops
Pilosa
Megatherioidea
    cf. *Pelecyodon*
    cf. *Hapalops*

RODENTIA
Chinchilloidea
  Neoepiblemidae
    Perimys sp
  Dinomyidae
    cf. *Scleromys*
Cavioidea
  "Eocardiidae"
    Phanomys sp

"Eocardia" sp
Dasyproctidae
   Neoreomys sp
Octodontoidea
   Acarechimys minutus
   Acarechimys minutissimus
   Spaniomys sp
   Spaniomys riparius
  Acaremyidae
   Acaremys sp
   Sciamys principalis

NOTOUNGULATA
Toxodontia
  Toxodontidae
   Nesodon
   Adinotherium
  Homalodotheriidae
   Homalodotherium
Typotheria
  Interatheriidae
   Interatherium
   Protypotherium
  Hegetotheriidae
   Hegetotherium

LITOPTERNA
Proterotheriidae
   Tetramerorhinus
   cf. *Diadiaphorus*
Macraucheniidae
   Theosodon

ASTRAPOTHERIA
Astrapotheriidae
   Astrapotherium

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