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Sr-stratigraphy and sedimentary evolution of early Miocene marine foreland deposits in the northern Austral (Magallanes) Basin, Argentina

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ABSTRACT. Early Miocene shallow marine deposits in the region of Lago Posadas-Meseta Belgrano (Argentina) represent part of the "Patagoniense" transgression, an Atlantic marine incursion that flooded large part of Patagonia, including the Austral (foreland) Basin (southern Patagonia). These deposits, referred as El Chacay (Argentina) or Guadal (Chile) formations, and the transition to the overlying Santa Cruz Formation were divided into six facies: subtidal sand-bars, shallow marine sandy deposits, muddy shelf deposits, estuarine complex deposits, fluvial channels and fluvial floodplains. These are arranged in a general transgressive-regressive cycle, subdivided into two stratigraphic sequences, separated by a major erosional surface. $^{87}Sr/^{86}Sr$ ages from shell carbonate in eight oysters yielded an age range of 20.3 to 18.1 Ma for these "Patagoniense" deposits. Correlation with other dated "Patagoniense" sections in southern Patagonia, like those at Lago Argentino or Comodoro Rivadavia, indicates that they belong to a single transgression that flooded several Patagonian basins approximately at the same time. Eustasy, flexural subsidence created by tectonic loading in the adjacent fold-and-thrust belt, and basin floor paleo-topography controlled the duration of the depositional event and the sedimentation style of these shallow marine deposits.

Keywords: Patagoniense, Patagonia, Sr-stratigraphy, Transgression, Sedimentology.

RESUMEN. Estratigrafía de Sr y evolución sedimentaria de los depósitos marinos del Mioceno temprano en el antepaís del norte de la Cuenca Austral (o Magallanes), Argentina. Los depósitos marino-someros del Mioceno temprano de la región del Lago Posadas-Meseta Belgano representan parte de la transgresión "Patagoniense", una incursión marina atlántica que invadió gran parte de la Patagonia, incluyendo la Cuenca de antepaís Austral (Patagonia austral). Estos depósitos, referidos como formaciones El Chacay (Argentina) y Guadal (Chile), y su transición a la suprayacente Formación Santa Cruz, fueron divididos en seis facies: barras submareales, depósitos arenosos marino-someros, depósitos fangosos de plataforma, complejo estuarino, canales fluviales y planicie de inundación. Estas facies muestran un arreglo general transgresivo-regresivo, el que puede ser subdividido en dos secuencias estratigráficas separadas por una superficie erosiva. Resultados de ocho edades $^{87}Sr/^{86}Sr$ de carbonato tomado de valvas de ostras dieron un rango entre 20,3 Ma y 18,1 Ma para estos depósitos Patagonienses. La correlación con sucesiones equivalentes de edad conocida en la Patagonia Austral, como las del Lago Argentino o Comodoro Rivadavia, indican que estas pertenecen a una misma transgresión que inundó gran parte de la Patagonia aproximadamente al mismo tiempo. La eustacia, la subsidencia flexural creada por carga tectónica en la faja corrida y plegada adyacente, y la paleotopografía del fondo de la cuenca, controlaron la duración del evento depositacional y el estilo de sedimentación estos depósitos marino-someros.

Palabras clave: Patagoniense, Patagonia, Estratigrafía de Sr, Transgresión, Sedimentología.

1. Introduction

The "Patagoniense" (or Patagoniano; or Patagonian), an informal chronostratigraphic unit that represents an event of regional marine transgression widely distributed over Patagonia, occurred during the late Oligocene to the early Miocene (Windhausen 1931; Feruglio, 1949; Camacho, 1967; Malumián *et al*., 1999; Parras *et al*., 2008; Cuitiño *et al*., 2012; Parras *et al*., 2012). In southern Patagonia, mainly in the Provincia de Santa Cruz (Santa Cruz province), its geographic distribution is approximately coincident with the Austral (or Magallanes) Basin borders (Malumián *et al*., 1999). In the northwestern extreme of this basin the "Patagoniense" sea formed an NNW-SSE elongated engulfment subparallel to the Andean belt (Ramos, 1982, Fig. 1A), whose northern extreme is located in the Aisén region of Chile (Niemeyer *et al*., 1984; Flint *et al*., 1994). The sedimentologic analysis of the sedimentary successions accumulated during the existence of this marine engulfment offers an opportunity to study ancient marine sedimentary dynamics and processes within a semi-enclosed basin. The association of the basin with an active Miocene orogenic belt (the Andes; Ramos, 1989; Fosdick *et al*., 2013) allows estimating the controls (*e.g*., subsidence, sedimentary supply; basin shape) that this major tectonic feature exerted on the adjacent foreland zone.

Despite the large areal distribution of the "Patagoniense" marine deposits, little is known about their sedimentology, stratigraphic evolution and controls over sedimentation. Most of the literature deals with the exposures located along the coastal cliffs in southeastern Provincia de Santa Cruz (Parras and Casadío, 2005; Parras *et al*., 2012; Dix and Parras, 2014), as well as in the northern San Jorge Gulf Basin (Bellosi, 1990, 1995; Carmona *et al*., 2008). The westernmost "Patagoniense" marine deposits occur in Andean positions within the Austral Basin, and this portion received less attention in comparison with eastern outcrops. General sedimentologic descriptions with limited paleoenvironmental interpretations arose as the result of geologic mapping in regions such as Lago Argentino (Furque, 1973), Lago Cardiel (Ramos, 1982) and Meseta Guadal in Aisén (Niemeyer *et al*., 1984). More recently some sedimentologic (Flint *et al*., 1994; Cuitiño and Scasso, 2010, 2013), chronostratigraphic (Cuitiño *et al*., 2012) and paleoecologic/isotopic (Cuitiño *et al*., 2013) information has been provided for this region. The Lago Posadas/Meseta Belgrano "Patagoniense" deposits are mainly known from a paleontologic perspective (Ortmann, 1902; Chiesa and Camacho, 1995; Parras *et al*., 2008) lacking detailed sedimentologic, stratigraphic and geochronologic analyses. Only south of Lago General Carrera in the Aisén region of Chile, a detailed sedimentologic analysis is available (Flint *et al*., 1994) which is useful for paleogeographic and paleoenvironmental comparisons with our study area. The ages of the western Patagoniense deposits and their correlation with the sections at the coastal cliffs have been the

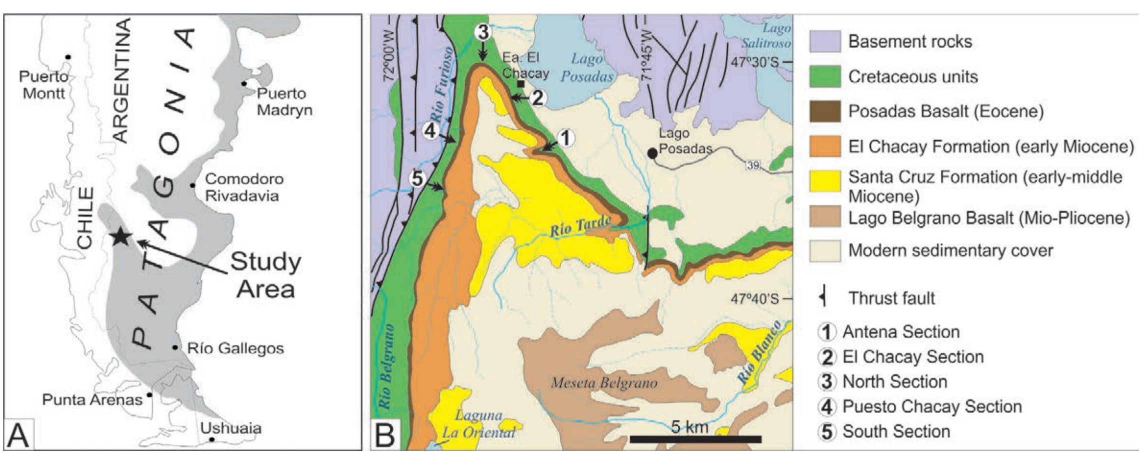

FIG. 1. Location maps of the study area in south-western Patagonia. **A.** Maximum area flooded by the "Patagoniense" transgression in gray (after Malumián *et al*., 1999). Note the location of the study area in a large engulfment; **B.** Simplified geologic map of the study area (modified from Giacosa and Franchi, 2001) showing the position of the studied sections.

subject of long-lived discussion (Hatcher, 1900; Ameghino, 1906; Feruglio, 1949; Camacho, 1967; Chiesa and Camacho, 1995; Frassineti and Covacevich, 1999; Casadío *et al*., 2000; Guerstein *et al*., 2004; Parras *et al*., 2008).

The objectives of this contribution are: **1)** to provide new $^{87}Sr/^{86}Sr$ ages for chronostratigraphic calibration of the stratigraphic column of the region and to establish regional correlations and; **2)** to present a facies analysis and paleoenvironmental reconstruction of sections located in the Lago Posadas (Argentina) area; **3)** to assess the controls (paleogeography, eustasy and tectonics) on the sedimentation in a foreland basin system.

2. Geologic setting

2.1. Tectonic framework

The Austral Basin was formed on the foreland side of the Southern Patagonian Andes (Fig 1A), and two major phases of evolution are recognized (Biddle *et al*., 1986) a rift stage during the Early Cretaceous and a foreland stage during Late Cretaceous and Cenozoic times, when flexural subsidence was related to the development of a fold- and-thrust belt to the west. A major crustal block known as the Deseado Massif bordered the basin to the north east (Ramos, 1989). The Deseado Massif was relatively stable and rigid during the Mesozoic and Cenozoic and formed a positive topographic element, restricting sedimentation to a narrow, NNW-elongated engulfment at the northern tip of the basin, limited by the Andean Fold-and-thrust Belt to the west and the Deseado Massif to the east (Ramos, 1989; Ghiglione *et al*., 2015, Fig. 1A). At present, the sedimentary succession of this portion of the basin is part of the Southern Patagonian Andes Fold-and-thrust Belt and the associated frontal monocline (Ramos, 1989; Giacosa and Franchi, 2001). The development of these compressional structures started in the Late Cretaceous, although the maximum Andean uplift is recorded during the Miocene (Ramos, 1989; Blisniuk *et al*., 2005; Fosdick *et al*., 2013), partly in concomitance with the deposition of the Miocene foreland sediments studied here.

2.2. Stratigraphic framework

The sedimentary fill of the Austral Basin in the study area begins with the volcanic-volcaniclastic rocks of the Middle-Upper Jurassic El Quemado Complex, which makes up the technical basement of the basin (Biddle *et al*, 1986; Arbe, 2002). The Lower Cretaceous clastic succession begins with the transgressive sandstones of the Pueyrredón Group that includes the basal sandstones of the Springhill Formation, which are in turn overlain by the marine black shales of the Río Mayer Formation. A series of litoral and deltaic sandstones of the Río Belgrano Formation prograding to the south overlie the Río Mayer Formation and mark the beginning of the foreland stage of the basin (Giacosa and Franchi, 2001; Arbe, 2002; Ghiglione *et al*., 2015). These deposits are covered in turn by Aptian-Cenomanian fluvial tuffaceous sandstone and conglomerate beds of the Río Tarde Formation. The Upper Cretaceous and Paleogene record of this part of the Austral basin is reduced or absent, indicating a prolonged hiatus. The Río Tarde Formation is covered by the Eocene Posadas Basalt (Riggi, 1957; Ramos and Drake, 1987), a widespread basaltic volcanic event recorded in the northern part of the basin. In some areas, coal-bearing fluvial deposits assigned to the Río Lista Formation appear interbedded with the basalts (Giacosa and Franchi, 2001). The basalts are unconformably overlain by the lower Miocene marine "Patagoniense" deposits, the focus of this paper, named in the study area as the El Chacay Formation (Chiesa and Camacho, 1995), or the Guadal Formation (Niemeyer *et al*., 1984) in the Región de Aisén. In Meseta Belgrano, these deposits are in turn covered by nearly 500 m of fluvial strata assigned to the Santa Cruz Formation (Ramos, 1979; Blisniuk *et al*., 2005) or Río Zeballos Group (Ugarte, 1956; Giacosa and Franchi, 2001).The fluvial mudstone and sandstone deposits of the Santa Cruz Formation are the thickest unit in the area and represent the progradation of the terrestrial depositional systems concomitant with the uplift of the Andes to the west (Ramos, 1989; Blisniuk *et al*., 2005; Fosdick *et al*., 2013). The end of the deposition of the Santa Cruz Formation in Meseta Belgrano is dated at ~14 Ma (Blisniuk *et al*., 2005), or at about 15 Ma in the Meseta del Lago Buenos Aires (Boutonnet *et al*., 2010; Espinoza *et al*., 2010). Unconformably resting over the Santa Cruz Formation (or Río Zeballos Group) is a late Cenozoic succession of coarse glacio-fluvial deposits and back-arc volcanic products of middle Miocene-Pleistocene age (Giacosa and Franchi, 2001; Boutonnet *et al*., 2010; Espinoza *et al*., 2010).

The olivine basalts, extruded during late Miocene times, form large plateaus such as the Meseta Lago Buenos Aires and the Meseta Belgrano (Giacosa and Franchi, 2001), which are related to the late Miocene subduction of the South Chile Ridge and the creation of slab windows (Gorring *et al*., 2003; Boutonnet *et al*., 2010; Espinoza *et al*., 2010).

2.3. Patagoniense deposits south of Lago Posadas

The shallow marine to estuarine deposits known as the El Chacay Formation in the region of Lago Posadas-Meseta Belgrano (Chiesa and Camacho, 1995) were previously named as Patagonian Beds (Hatcher, 1900), Patagoniense (Feruglio, 1949; Riggi, 1957), Patagonia Formation (Ramos, 1979), Centinela Formation (Ricardi and Rolleri, 1980). An equivalent unit to the northwest in Aisén (Chile) was named as Guadal Formation (Niemeyer *et al*., 1984). Feruglio (1949) revised these deposits from a regional stratigraphic point of view, while Chiesa and Camacho (1995) provided information about their stratigraphic, paleontologic and lithologic features in order to formalize the name El Chacay Formation in the study area. Bande (2007) provided a general sedimentologic description that served as a field guide for this work while the contribution of Flint *et al*. (1994) represents a reference for stratigraphic and paleoenvironmental comparison. The "Patagoniense" marine deposits in the study area grades upward to the lower-middle Miocene fluvial deposits of the Santa Cruz Formation. Because the limit between both units is not clearly defined in the field, in this study we place it arbitrarily at the uppermost oyster bank present in the early Miocene marine-estuarine succession. This criterion was found useful to define the equivalent transitional passage in other regions of southern Patagonia (Cuitiño and Scasso, 2010; Cuitiño *et al*., 2012; Cuitiño *et al*., 2013; Raigemborn *et al*., 2015). This criterion for the position of the limit implies that the lowermost part of the Santa Cruz Formation may be composed of oyster-free estuarine deposits.

The "Patagoniense" deposits in the study area (Hatcher, 1900; Feruglio, 1949) can be correlated with other similar units in southern Patagonia such as the Guadal Formation in Aisén, Chile (Heim, 1940; Niemeyer *et al*., 1984; Flint *et al*., 1994; Frassinetti and Covacevich, 1999; De la Cruz and Suárez, 2006), Estancia 25 de Mayo Formation in Lago Argentino and Sierra Baguales (Cuitiño and Scasso, 2010; Cuitiño *et al*., 2012; Bostelmann *et al*., 2013) and Monte León Formation in southeast Provincia de Santa Cruz (Parras *et al*., 2008; Parras *et al*., 2012). All these units of the Austral Basin can be correlated with the Patagoniense deposits of the Golfo San Jorge Basin to the north (Feruglio, 1949; Malumián *et al*., 1999), grouped into the Chenque Formation (Bellosi, 1990, 1995) and recently dated between 19.3 Ma and 15.4 Ma in the Comodoro Rivadavia region (Cuitiño *et al*., in press).

3. Methodology

We use the term El Chacay Formation for the "Patagoniense" marine deposits of Lago Posadas-Meseta Belgrano, following the proposal of Chiesa and Camacho (1995), who described these deposits in the same area studied in this work. Other previous litostratigraphic proposals exist for adjacent regions (*e.g*., Guadal Formation, Niemeyer *et al*., 1984). However, it is not the objective of our work to discuss the validity of each of the abundant formal lithostratigraphic proposals available in the literature. Additional work on lithologic description and stratigraphic context is needed in some other regions of southern Patagonia in order to propose an integrated litostratigraphic scheme that may satisfy all cases. The reader is referred to Camacho (1967), Riggi (1979a, 1979b) and Malumián *et al*. (1999) for further discussion about this long-lived topic.

Field data were collected in five sections (Figs. 1B and 2) along the cliffs formed at the northern margin of Meseta Belgrano, south of Lago Posadas. The location of the studied sections coincides with part of those measured and described by Chiesa and Camacho (1995) between the Río Tarde valley and Veranada Cáramo. The studied sections are spatially arranged into two transects, a N-S transect (South-Puesto El Chacay-North sections) along the Río Furioso valley; and a NW-SE transect (North-El Chacay and Antena sections) along the southern border of the Posadas Lake valley (Figs. 1B and 2). Sedimentary rocks were described in detail in the field including grain size, texture, sedimentary structures, quantity and mode of preservation of the fossil content, trace fossils and bioturbation index (BI, following Taylor and Goldring, 1993), bed thickness and nature of limiting surfaces. This allowed us to define 16 lithofacies (Table 1). Bioclastic lithofacies are a subgroup of lithofacies

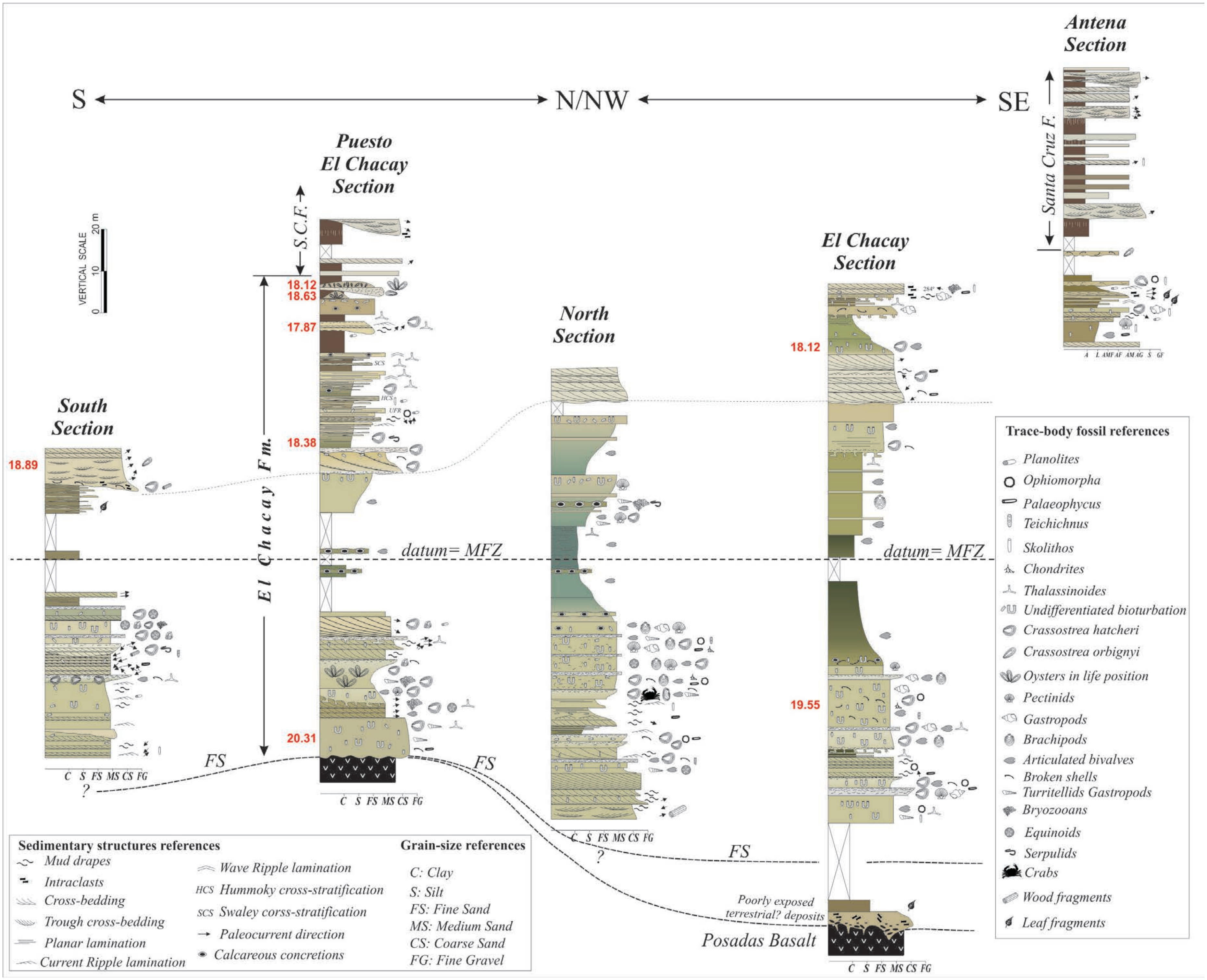

FIG. 2. Sedimentary sections and key stratigraphic surfaces for the El Chacay Formation and the lowermost part of the Santa Cruz Formation. The sections were correlated on the basis of the maximum flooding zone (MFZ, datum), except for the Antena Section, which was correlated with the closer section on the basis of facies characteristics and stratigraphic succession. **FS:** flooding surface. Numbers in red to the left of the columns are $^{87}Sr/^{86}Sr$ ages.

TABLE 1. LITHOFACIES CODE, DESCRIPTION AND INTERPRETATION.

Code	Texture	Sedimentary Structures	Bioturbation	Fossil content	Occurrence	Interpretation
Smb	From coarse siltstones to coarse sandstones. Dominance of fine to medium sandstones. Generally poorly sorted.	Structureless.	Bioturbation indexes (BI) between 4 and 6. Large diversity of trace fossils. *Planolites* isp., *Teichichnus* isp., *Skolithos* isp., *Thalassinoides* isp., *Ophiomorpha* isp., *Chondrites* isp., *Scolicia* isp.	Abundant and diverse marine macroinvertebrates. Oysters, pectinids and other epi and infaunal bivalves; gastropods; echinoderms and crustaceans. Variable degree of reworking.	Between 30 and 55% of the El Chacay Fm. Bed thickness from few cm to several m. Commonly grades vertically to bioclastic lithofacies.	The lack of tractive sedimentary structures is interpreted as the result of intense bioturbation in shallow marine environments with moderate energy and reduced rates of sedimentation.
Sm	Mainly medium sandstones.	Structureless.	-	Occasionally mammal remains.	Exclusive of the fluvial deposits of the Santa Cruz Fm. (20 %). It form tabular to domal beds 0,2 to 1,5 m thick.	The lack of tractive sedimentary structures is interpreted as the result of sudden sedimentation by fluid flows, or alternatively, as the result of secondary processes of alteration.
St	Medium to coarse sandstones.	Trough cross-bedding. Occasionally with mud drapes on the foresets.	Scarce or absent. Mainly *Skolithos* isp.	Scarce. Fragmented marine invertebrate remains.	4% of the whole succession although it is more abundant in the upper fluvial deposits. It forms tabular to lenticular decimetric sets in cosets up to 7m thick.	Migration of 3D subaqueous dunes.
Sp	Fine sandstones to very coarse sandstones. Medium sandstones dominate.	Tabular cross-bedding. Occasionally with mud drapes on the foresets.	Moderate to absent. *Skolithos*, isp., *Teichichnus* isp., *Paleophycus* isp., *Thalassinoides* isp., *Planolites* isp., *Ophiomorpha* isp.	From absent to abundant. Fragmentary marine invertebrate material predominates.	15% of the succession. Sets are a few cm up to 1 m thick.	Migration of subaqueous 2D dunes
Sp2	Coarse sandstone to granule conglomerate. Thick mud drapes on the foresets.	Giant tabular cross-bedding.	Scarce. Vertical burrows with thick lined wall. *Rosselia* isp.	Scarce marine invertebrate remains.	1-2%, restricted to the base of the El Chacay Fm. Tabular beds.	Migration of subaqueous bars of giant scale.
Sr	Very fine to medium sandstones. Fine sandstones dominate.	Current cross lamination.	-	-	3% of the succession, commonly associated to Sp sets.	Migration of current ripples.
Srw	Fine to medium sandstones.	Symmetric ripples. Form sets.	-	-	1%, restricted to the upper portion of the El Chacay Fm.	Wave reworking of a sandy substrate.
Sh	Siltstones to medium sandstones.	Horizontal lamination.	Scarce *Skolithos* isp. and *Thalassinoides* isp.	Vegetal remains, leave impressions. Others with marine invertebrates.	Less than 1% of the succession. Restricted to the upper part of the el Chacay Fm.	Deposition on a flat sandy bed under an upper flow regime condition
HCS	Fine sandstones	Hummocky cross-stratification (HCS) and swaley cross-stratification (SCS).	Absent or thick vertical burrows.	-	1%, exclusive of the upper part of the El Chacay Fm.	High amplitude waves (storms)
Gm	Granule to fine conglomerate.	Structureless or with normal grading.	Absent or thick vertical burrows.	Scarce marine invertebrate fragments.	Less than 1% of the succession. Restricted to the El Chacay Fm.	Lag deposits associated to erosional events
Fl	Siltstones and scarce claystones.	Parallel lamination.	Scarce.	-	Exclusive of the El Chacay Fm. (2%)	Decantation of fine grained material.
Fm1	Undifferentiated mudstones. Reddish.	Structureless. Clay cutans. Slickensides.	Root marks.	-	Exclusive of the upper fluvial deposits, making up a 60% of it. Tabular beds of up to 3 m thick.	Decantation of fine grained material in floodplains and subsequent modification by soil processes.
Fm2	Siltstones and scarce claystones. Brownish to greenish.	Structureless. Concretions or indurated levels common.	Abundant. Bioturbation Index between 4 and 6.	Scarce to abundant. Bivalves and articulated brachiopods. Some parts with vegetal remains.	Exclusive of the El Chacay Fm., making up 25% of it.	Decantation and traction of fine grained material in a low-energy marine setting. Primary sedimentary structures were destroyed by intense bioturbation or diagenetic processes.
Ht	Centimetric interbedding of sandstones and mudstones laminae.	Parallel lamination in mudstones and cross-lamination in sandstones. Structureless laminae are common.	Moderate to absent. *Thalassinoides* isp. is common.	Vegetal remains.	5% of the upper portion of the El Chacay Fm. Tabular beds from few cm up to several m thick.	Alternate events of decantation and traction produced by oscillatory or unidirectional currents.
Bb	Matrix or bioclastic supported. Bioclast commonly articulated, showing low degree of fragmentation.	Crude stratification. Normal gradding is common.	-	Reduced biodiversity. Oysters, panopeas, crustaceans, turritellids.	1% of the El Chacay Fm. Grades vertically with Sm or Bs.	In-situ biogenic concentrations or partially remobilized (parautochthonuos)
Bs	Bioclast supported. High degree of fragmentation.	Structureless, occasionally coarsening upward.	Moderate, dominated by large burrows such as Thallassinoides isp.	High degree of taxonomic mixing, although there are some monospecific.	4% of the El Chacay Fm. Vertical gradation with Sm o Bs. Erosive base for lag deposits.	Sedimentologic concentrations. Erosional lags or reduced clastic supply in high energy environments.

Bioturbation Index (BI) after Taylor and Goldring (1993).

defined when the bioclastic fraction exceeds 30% by volume of the rock.

We sampled unbroken, well-preserved oyster valves for Sr-stratigraphy. Samples come from the El Chacay Section, Puesto El Chacay Section and South Section (Fig. 2), and cover the whole stratigraphic interval of the El Chacay Formation from the basal contact with the Posadas Basalt up to the transition with the overlying Santa Cruz Formation. Each valve was cut and polished (Fig. 3) for microsampling following the criteria established by Cuitiño *et al*. (2012, 2013). Eight of the best-preserved valves were selected for microsampling. From each valve ~30 mg of calcite powder was obtained with a microdrill. Layers composed of light-colored, chalky microstructures were avoided because these were proved to be susceptible to diagenetic alteration. Instead, layers composed of dark, foliated and prismatic microstructures were selected (Fig. 3) because they preserve the original isotopic composition of the carbonate (Cuitiño *et al*., 2012; Cuitiño *et al*., 2013). From each microsample, a small aliquot of carbonate powder was used to perform $\delta^{18}O$ and $\delta^{13}C$ isotopic analyses, in order to check for diagenetic alterations or freshwater input into the environment. After separating Sr using Teflon columns filled with 0.5 ml of Eichrom Sr Resin/50-100 µm, the $^{87}Sr/^{86}Sr$ isotopic ratio of the samples was determined by a Neptune ICP Mass Spectrometer. The $\delta^{18}O$ and $\delta^{13}C$ isotopic composition of the carbonates were determined by a Thermo Fisher DELTA V Plus Isotope Ratio Mass Spectrometer attached to Gas Bench II analyzer. The associated errors are 0.1‰ for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$. Stable isotope results are expressed in the PDB notation. $^{87}Sr/^{86}Sr$, $\delta^{13}C$ and $\delta^{18}O$ methods were carried out at the Geochronos Laboratory of the University of Brasilia, Brazil. For $^{86}Sr/^{88}Sr$ the accuracy was estimated by the analysis of the NBS standard 987, which produced a mean value of 0.710243±0.0000102 (N=21). Age calculations from $^{87}Sr/^{86}Sr$ are based on the Look-Up Table Version 4B: 08/04 of McArthur *et al*. (2001) with an uncertainty of 0.07 Ma derived from the mean curve.

4. Depositional systems

Sedimentologic, paleontologic and ichnologic data were integrated into a facies analysis in order

FIG. 3. Cut and polished surfaces of three oysters. Cuts are aligned in a dorsal-ventral direction of entire valves showing no mechanical abrasion. PCH-10c is articulated and preserved the sedimentary infill, whereas Ostrea-1 and PCH-2 are disarticulated. The white boxes near the hinge zone correspond to the microsampled areas where coloration is darker (translucent microstructures) in relation to other zones with pale yellowish colors (chalky microstructure).

to define the paleoenvironmental setting. The nature and hierarchy of the bounding surfaces of the sedimentary bodies were also used for stratigraphic interpretation. The facies analysis was also based upon the definition of lithofacies (Table 1) characterized mainly by texture, sedimentary structures, bioturbation and nature of the fossil remains. Sixteen lithofacies were defined (Table 1), two of which consists of bioclastic accumulations of fossil invertebrates that are a noticeable feature in the studied succession. The comparison and spatial distribution of the lithofacies, together with paleocurrent data and nature of the bounding surfaces, allowed defining 6 facies, which represent similar conditions of sedimentation.

4.1. Facies A: Subtidal sandbars (Fig. 4A)

This facies is composed essentially of lithofacies Sp, Sp2 and St, with minor proportions of Sr, Smb, Bb and Bs. It appears as thick cross-bedded or massive strata with sharp and plane bases usually covered by a lag of bioclasts (Bs). Lithofacies Sp and Sp2 form tabular cosets of up to 15 m thick. Mud drapes are abundant within this facies and patterns of neap-spring tidal cycles can be recognized in large-scale cross-bedding (Fig 4A). Paleocurrent measurements derived from cross-strata show highly variable directions, and bipolar arrangement in adjacent sets. Body and trace fossil contents are irregularly distributed, while cross-bedded intervals show BI from 0 to 2, although some thin massive sandy levels show higher BI varying from 2-4. The trace fossil assemblage is dominated by vertical burrows such as *Ophiomorpha* isp. and *Skolithos* isp., together with *Thalassinoides* isp. Subordinate elements comprise monospecific associations of *Rosselia* isp. (Fig. 4A), sometimes associated with Fugichnia structures. This facies appears in the basal part of the El Chacay Formation and is well exposed in the North Section (Fig. 2). Scarce marine invertebrates preserved as disarticulated/fragmented skeletons are concentrated in thin layers (Bs) at the base of the cross-bedded sets.

The abundance of mud drapes, the neap-spring tidal cyclicity observed in some cross-bedded sets and the bipolar paleocurrent pattern suggest a strong tidal influence on the deposition of this facies. The sandy grain-size plus the scarcity of trace fossils dominated by vertical burrows, suggest a high-energy setting. Large-scale cross-bedded sets showing mud drapes and monospecific *Rosselia* isp suites, suggest alteration of periods of fast sedimentation with periods of paucity in sedimentation (*e.g.,* Desjardins *et al*., 2010). Facies A is interpreted as deposits of subtidal dunes (Sp, St and Sp2), under the influence of strong tidal currents (Dalrymple and Rhodes, 1995). The presence of large, simple cross-bedding sets of nearly 3 m thick suggest deposition by large dunes in water deeper than 15 m (Allen, 1980; Ashley, 1990), that together with the absence of channelized sedimentary bodies, suggests a tide-dominated shallow shelf to outer estuarine environment of deposition (Dalrymple, 2010).

4.2. Facies B: Shallow marine sandy deposits (Fig. 4B)

This facies is composed essentially of Smb intercalated with bioclastic levels of lithofacies Bs and Bb. Gradations to muddy lithofacies Fm2 are frequent. The grain size is finer than in Facies A. Lithofacies Smb shows a high degree of bioturbation with more or less uniform intensities that vary from BI4 to BI6 (Fig. 4B), developing a mottled structure. The trace fossil suite is dominated by the ichnogenera *Teichichnus* isp., *Ophiomorpha* isp., *Thalassinoides* isp., *Asterosoma* isp., *Paleophycus* isp., *Scolicia* isp., with subordinated *Chondrites* isp. Shelly marine fossils are abundant in this facies, forming sedimentologic (lithofacies Bs) and biogenic (lithofacies Bb) concentrations (Kidwell *et al*., 1986). Lithofacies Bs contain disarticulated and abraded remains of shells, especially oysters, turritellid gastropods, other bivalves such as pectinids and terebratullid brachiopods. Bb concentrations are dominated by the large oyster *Crassostrea* (?) *hatcheri*. The fossils mentioned for lithofacies Bs and Bb together with many other marine invertebrate fossils including echinoids, crustacean, bryozoan, barnacles and many forms of bivalves and gastropods typical of the El Chacay Formation (*e.g*., Chiesa and Camacho, 1995) also appear as dispersed specimens within lithofacies Smb.

The abundant invertebrate fossil concentrations and the abundance and high diversity of trace fossils, together with the sandy nature of the sediments, suggest that this facies accumulated in an open, shallow marine, well-oxygenated and agitated environment. The good sorting and tight packing of the shells plus the sandy nature of the intercalated beds suggest

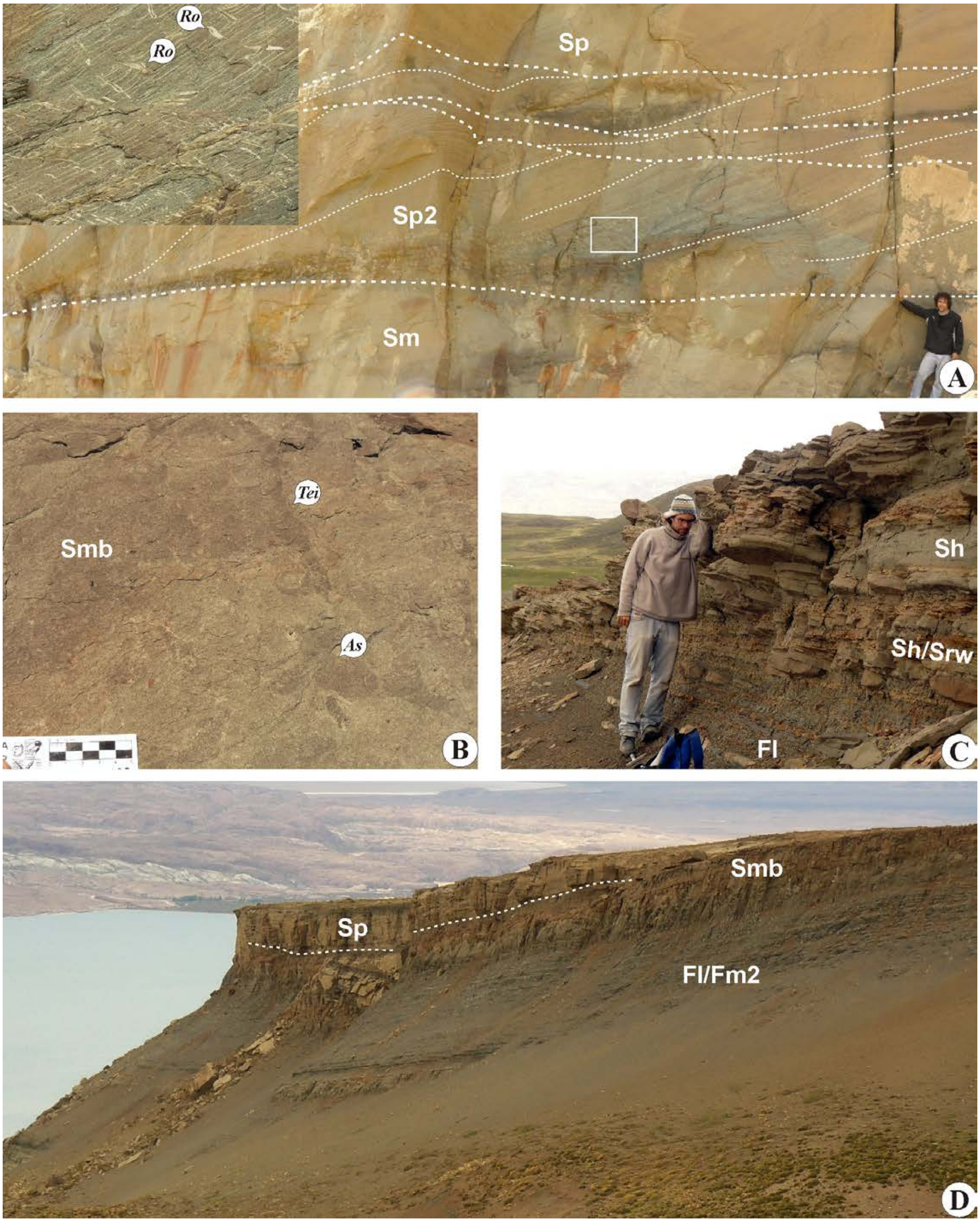

FIG. 4. Lithofacies and facies of the El Chacay Formation. **A.** Medium and large-scale cross-bedded strata composing the Facies A, interpreted as subtidal sand-bars. Neap-spring tidal cyclicity is observable in the large scale set (Sp2). Inset at the upper left correspond to the white box and shows details of the cross-bedded structure with abundant mud drapes and a monospecific association of the ichnogenus *Rosselia* isp. (Ro); **B.** Typical fully bioturbated sandstones (Smb) of Facies B; deep tiers such as *Teichichnus* isp. (Tei) and *Asterosoma* isp. (As) traces can be recognized; **C.** Coarsening up succession of Facies D1, dominated by parallel-laminated sandstones and wave-generated structures; **D.** General view of the shelf fine-grained deposits (Fl/Fm2) that grade upward to lower shoreface bioturbated sandstones (Smb). A sharp contact (dashed line) separates this succession from the overlying cross-bedded sandstones (Sp).

deposition under the action of tractive processes. Commonly, these types of facies were interpreted as lower shoreface deposits (*e.g.*, Carmona *et al.*, 2008) although it cannot be stated whether the currents are tidal- or wave-induced, since bioturbation obliterated any mechanic sedimentary structure. Coarse bioclastic accumulations suggest winnowing events over the sea bottom such as storm events and migration of sandbars. They might constitute parasequences formed as a result of high-frequency sea-level fluctuations.

4.3. Facies C: Shelf deposits

The exposure of this facies is generally poor and it was observed in few, isolated places (Fig. 4D) close to the El Chacay and North Sections (Fig. 2). It is dominated by laminated shales or massive mudstones (lithofacies Fl and Fm2 respectively) with subordinate massive fine sandstones (lithofacies Smb). It grades vertically into Facies B. The fossil content is sparse, and forms little-transported, high-diversity autochtonous to parautochtonous associations. Oysters, different forms of bivalves, turritellids and brachiopods are commonly observed in this facies. Carbonate concretions present in isolated beds show well preserved associations of oysters, pectinids, bryozoans, gastropods and encrusting serpulids. The BI is difficult to measure due to poor exposure, although the degree of bioturbation seems to be lower than that of Facies B.

The presence of fine-grained deposits suggests environments dominated by settling processes below storm wave base or at depths where the tidal action was not effective. Thin sandy layers or fossil concentrations suggest local events of high energy (storms?) that supplied sand to deeper environments. Shelly fossils commonly appear entire and articulated, with their ornamentation well preserved, suggesting preservation in life position or slight transport (parautochthonuos preservation). This facies represents the maximum depth that the “Patagoniense” sea achieved in this region, and reflects the maximum flooding stage.

4.4. Facies D: estuarine complex

This facies comprises the uppermost third of the El Chacay Formation and shows the highest lateral and vertical heterogeneity. Considering that the limit between the El Chacay and Santa Cruz formations is placed arbitrarily in the uppermost oyster bank present in the estuarine part of the succession, it is possible that part of the Facies D may belong to the lowermost beds of the Santa Cruz Formation. However, within the study area, oyster banks were found in all the cases where the transitional deposits crop-out. Facies D includes a variety of sandy, muddy and heterolithic lithofacies included in an estuarine complex with varying degrees of wave and tidal action. According to the lithofacies distribution it can be subdivided into four subfacies:

Subfacies D1is well exposed in the Puesto el Chacay Section. It is composed of coarsening-upward cycles averaging 5 m thick (Fig. 4C) which display a gradation from Fl and Ht to Sh. They culminate in sandy lithofacies with common wave structures such as HCS and Srw. Tidal structures such as mud drapes and herringbone cross-stratification are subordinate. Bioturbation is confined to discrete layers, with intensities ranging from BI0 to BI3. The trace fossil assemblage is dominated by isolated burrows of *Skolithos* isp. and *Thalassinoides* isp.

Subfacies D2 is well exposed in the Antena Section. It is composed of thin, coarsening-upward cycles of Fl and Ht that grade to centimetric tabular beds of Sr and Sp (Fig. 5A). Wave ripples are present and no tidal structures were found. Paleocurrents show a unidirectional pattern (Fig. 6B). Bioturbation intensities vary from BI1 to BI3 and the ichnoassemblage is dominated by *Skolithos* isp., *Ophiomorpha* isp., and *Planolites* isp. Scattered, disarticulated oysters (*C. hatcheri* and *C. orbignyi*) together with common, fine carbonaceous detritus or less frequently leaf impressions are the main fossil remains.

Subfacies D3 is dominated by fine-grained lithofacies such as Fl and Ht. It grades upward into D1 and D2. The exposure of this subfacies is poor although in some concretionary levels it shows delicate heterolithic lamination with minute *Teichichuns* isp. and *Planolites* isp. (Fig. 5B).

Subfacies D4 interfingers laterally with the other subfacies. It is composed of tabular, muddy and heterolithic bodies that are truncated by lenticular sandstone bodies with erosional bases. Muddy strata are scarce or not bioturbated, lacking marine or estuarine fossils except for oysters. The oyster *Crassostrea orbignyi* forms small-mounded accumulations (Bb) within the muddy deposits. The oyster specimens show their commisures in vertical position and are

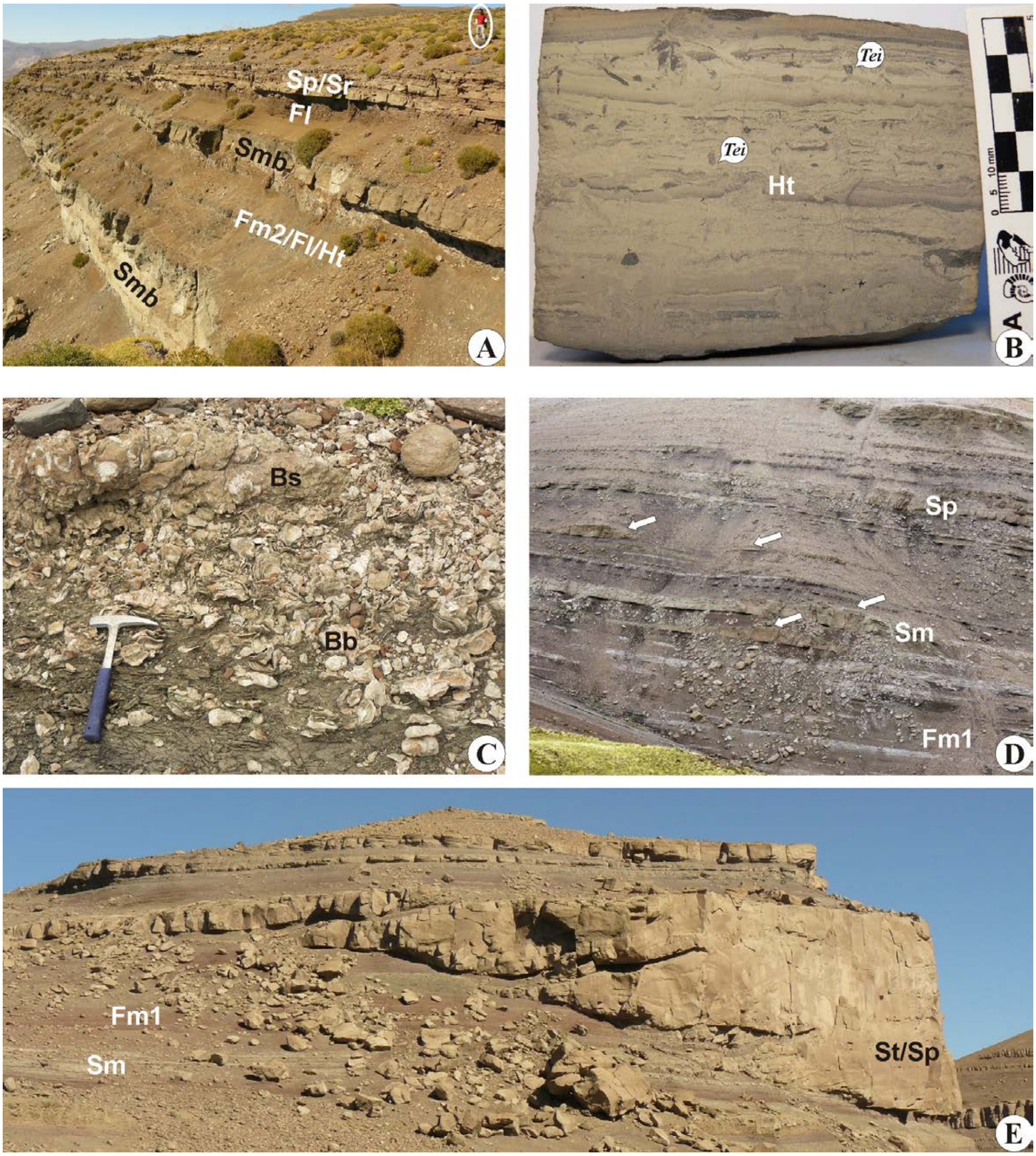

FIG. 5. Lithofacies and facies of the El Chacay Formation and the lower part of the Santa Cruz Formation. **A.** Interbedded sandstone and mudstone/heterolithic beds of Facies D2 and D4. Bioturbated sandstones (Smb) indicate marine influence whereas cross-bedded sandstones (Sp/Sr) with plant remains indicate fluvial influence. Fm2, Fl and Ht lithofacies compose the central estuarine basin deposits (facies D3); **B.** Polished hand sample showing finely laminated heterolithic deposits (Facies D3) with minute *Teichichnus* isp. and mottling from other trace fossils; **C.** Monospecific, biogenic accumulation of *Crassostrea orbignyi* (Bb) in life position. The upper part is a reworked accumulation (Bs) of the underlying fossils; **D.** General view of the lowermost portion of the Santa Cruz Formation. Typical brown-reddish beds are floodplain mudstones (Fm1) whereas sandstone beds (Sm, Sp) are overbank deposits (Facies F). Note the dome shape of some sandstones bodies (arrows); **E.** Lenticular sandstone body composed of St/Sp lithofacies interpreted as a fluvial channel (Facies E) interbedded within floodplain deposits of lithofacies Sm and Fm1.

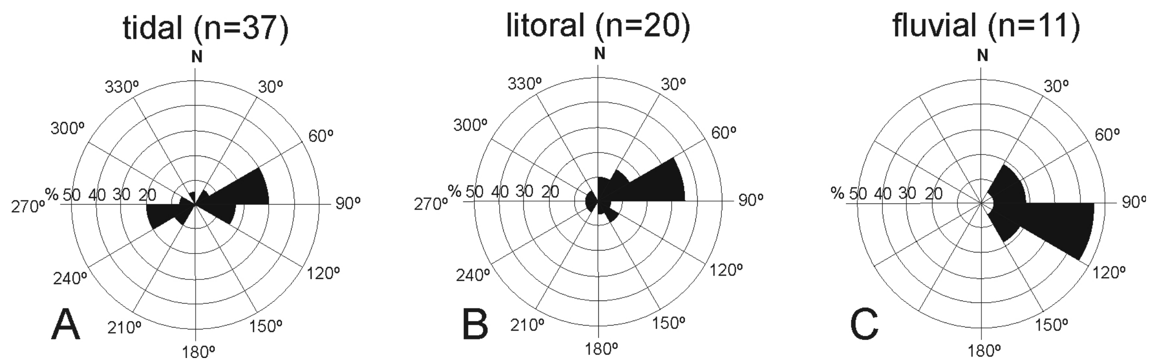

FIG. 6. Paleocurrent measurements separated by paleoenvironments. **A.** Bimodal pattern typical of tidal deposits of the lowermost part of the El Chacay Formation; **B.** Widely dispersed, plurimodal pattern from shoreface plus estuarine complex deposits of the upper part of the El Chacay Formation; **C.** Unidirectional paleocurrent pattern of the fluvial (mainly channel) deposits of the lowermost part of the Santa Cruz Formation.

cemented one to each other (Fig. 5C). The lenticular sandstone bodies are massive or cross-bedded (Sp, St). The bases show bioturbation characterized by the presence of *Thalassinoides* isp. burrows that penetrate downward into the underlying strata. Usually they bear reworked fragments of oysters, and in some cases are entirely formed by fragments of *Crassostrea orbignyi* (lithofacies Bs; Fig. 5C).

On the basis of the impoverished fossil and trace-fossil associations, the plant remains, the abundant brackish water oyster *Crassostrea orbignyi* (Cuitiño *et al*., 2013), and the evidence of tidal and wave action, we interpret Facies D as deposited in an estuarine complex. Subfacies D1 shows wave influence in the form of HCS and wave ripples, and can be related to the progradation of sandy lobes in the most seaward part of the estuarine system, possibly related to flood tidal deltas. The coarsening-upward cycles of Subfacies D2, with unidirectional seaward paleocurrent patterns and abundant plant remains can be interpreted as bay-head delta lobes that prograded into the low energy, brackish central estuarine basin of subfacies D3. The impoverished association and reduced-size of the trace fossils from deposit feeder organisms in subfacies D3 is a common feature in wave-dominated central estuarine basins (Buatois *et al*., 2002; Savrda and Nanson, 2003; Buatois and Mángano, 2011).

Subfacies D4 are interpreted as the deposits of tidal flats fringing small tidal channels in an estuarine system, with minor influence of fluvial or wave processes.

4.5. Facies E: fluvial channels

This facies appears at the top of the Antena and Puesto el Chacay Sections and correspond to the base of the Santa Cruz Formation (Fig. 5E). It is composed of sedimentary bodies formed by Sm, Sp and St that show sharp erosive bases and planar tops. Their geometry is usually tabular to lenticular at outcrop scale and they have an average thickness of 3 m, being always less than 5 m thick. Lateral extension is limited to 50 m. Trace fossils in the sandstone bodies are *Skolithos* isp. and *Taenidium* isp. The paleocurrent vectors show a unimodal distribution and E orientation (Fig. 6C).

This facies is interpreted as fluvial channels. The width-to-thickness ratio of the channels of about 10-20 (broad ribbons), together with the low dispersion of the paleocurrents suggest low lateral mobility and high sedimentation rates (Miall, 1996; Gibling, 2006), typical of anastomosed fluvial systems (Makaske, 2001).

4.6. Facies F: fluvial floodplains

This facies composes a high proportion of the lowermost part of the Santa Cruz Formation (Fig. 5D). It is interbedded with Facies E, and is mainly formed by Fm1 showing evidence of pedogenesis such as slickensides, cutans, granular peds and root traces, with intercalations of thin layers of fine to medium sandstone beds (Sm). The sandstone bodies are normally less than 1 m thick and tabular, although some lenticular bodies, with convex-up tops are recognized (Fig. 5D). They are laterally more extended than the sandstone beds of the channels. Terrestrial vertebrate fossil remains are abundant in these deposits, especially those of mammals.

These deposits are interpreted as floodplains in a fluvial environment. Reddish and structureless mudstones are interpreted as having been deposited in the flood basin during the flooding stage of the river, later modified by pedogenetic processes. Mound-shaped, structureless sandstones are interpreted as quickly accumulated crevasse splay deposits formed during channel bank breakout and quick deposition on the flood plain.

4.7. Paleocurrents

Paleocurrents for the lower third of El Chacay Formation (mainly Facies A) show a predominant eastward direction, although reversals to the west are also recorded (Fig. 6A). The f1ne-grained intermediate section (Facies C) lacks measurable structures. A complex pattern is observed in the upper third of the El Chacay Formation (Facies D), with dominant directions pointing northeast, east and southward (Fig. 6B) and some local reversals (Fig. 2). The uppermost fluvial section (mainly Facies E) shows consistent eastward dispersion (Fig. 6C).

These three paleocurrent associations are coherent with a coastline broadly oriented north-south, with tidal currents perpendicular to it (nearly east-west) for the El Chacay Formation. The subsequent fluvial system that corresponds to the Santa Cruz Formation prograded to the east, reflecting the Andean (western) source of the sediment.

5. $^{87}Sr/^{86}Sr$ Chronostratigraphy

The eight $^{87}Sr/^{86}Sr$ ages range from 20.31 to 17.87 Ma (Table 2) and span the entire thickness of the El Chacay Formation (ages indicated with red numbers in Fig. 2). Ages cluster into two intervals separated by another interval corresponding to the maximum flooding zone, which lacks datable oysters. The stratigraphically lower interval yielded ages of 20.31Ma and 19.55 Ma, whereas the upper interval yielded ages from 18.89 Ma to 17.87 Ma. The six dates in the upper interval span little more than 1 Ma and four of them belong to the Puesto el Chacay Section (Fig. 2). There, some calculated ages reverse the stratigraphic order of the samples and indicate that errors in the age calculation are significant in relation to the time involved in the accumulation of the interval. Errors in age calculations arise from the method itself (analytical error ±0.2 Ma for the look-up table) but also may arise from local modifications of the isotopic composition of the seawater at the time the oysters were formed, or from diagenetic changes in the oyster shells.

The C and O stable isotope composition of the biogenic carbonate helps to understand the possible sources of $^{87}Sr/^{86}Sr$ age deviation, because they may drastically change during diagenesis or due to extreme environmental modifications such as large freshwater input into the environment (see discussion by Bryant *et al*. (1995), Surge *et al*. (2001) and

TABLE 2. $^{87}Sr/^{86}Sr$, $\delta^{18}O$ AND $\delta^{13}C$ RESULTS FOR THE EIGHT ANALYZED OYSTERS.

Sample	$^{87}Sr/^{86}Sr$	Age (Ma)	error±(Ma)	$\delta^{18}O$	$\delta^{13}C$
PCH-1	0.70842±1	20.31	0.2	-2.7862	-0.2358
CH-5	0.70847±1	19.55	0.2	-0.8562	0.9446
Ostrea 1	0.70852±1	18.89	0.2	-4.8564	-0.8726
PCH-9a	0.70854±1	18.63	0.2	-5.1373	-4.0835
PCH-2	0.70856±1	18.38	0.2	-1.6224	0.823
PCH-10c	0.70858±1	18.12	0.2	-2.7868	-0.2049
CH-7 bis	0.70858±1	18.12	0.2	-0.9314	0.4596
PCH-8	0.70860±1	17.87	0.2	-3.8319	-1.3228

The ages are derived from the Lookup Table of McArthur *et al*. (2001). The error is the sum of the instrumental isotopic measurement error and the mean curve error.

Cuitiño *et al*. (2013)). The expected values for $\delta^{18}O$ and $\delta^{13}C$ seawater of Patagonia during the early Miocene are from 1 to -1‰ (Zachos *et al*., 2001). In the samples of Lago Posadas, $\delta^{18}O$ values are in the range of -0.8‰ to -5‰ whereas $\delta^{13}C$ are in the range of 0.9‰ to -4‰ (Table 2). $\delta^{18}O$ and $\delta^{13}C$ are in the same range of variation of those obtained by Cuitiño *et al*. (2013) for equally well-preserved oysters of the an equivalent unit in the Lago Argentino region. Values close to -4‰ and -5‰ were interpreted as the result of freshwater input into the basin and subsequent modifications of the seawater composition. Mixing of marine and freshwater can produce noticeable changes in $\delta^{18}O$ and $\delta^{13}C$ (see discussions by Cuitiño *et al*., 2012, 2013) but still keep the $^{87}Sr/^{86}Sr$ seawater signal relatively unchanged, since the amount of Sr contained in freshwater is commonly orders of magnitude lower than that of seawater (Bryant *et al*., 1995). By means of multiple Sr-age measurements in a single shell, Cuitiño *et al*. (2012, 2013) interpreted that major changes in the stable isotope composition can be assigned to post-depositional alteration. However this process only results in subtle alteration of the $^{87}Sr/^{86}Sr$ ratio of shells and therefore calculated ages are still reliable.

Sources of confidence for the Sr-derived ages are **1)** the narrow age dispersal (2.44 my for the whole section), specially for those ages around 18-19 Ma located in the upper part of the section; **2)** the stratigraphic coherence of the results, in which samples near the base of the sections yielded older ages than those in the upper portion of the sections; and **3)** the good correlation with other Sr-dated "Patagoniense" sections elsewhere in Southern Patagonia such as the Monte León Formation (22.12-17.91 Ma; Parras *et al*., 2012), the Estancia 25 de Mayo Formation (20.05-18.96 Ma; Cuitiño *et al*. 2012), and the Chenque Formation (19.6-15.4 Ma, Cuitiño *et al*., in press).

Age data immediately above the Posadas Basalt yielded 20.31 Ma and represent the beginning of deposition for the El Chacay Formation. The age results of the uppermost beds of the El Chacay Formation vary between 18.89 Ma and 17.87 Ma (Fig. 2). From this subset of ages, the two older ones (18.89 Ma and 18.63 Ma) have the most negative values for the $\delta^{18}O$ composition (Table 2), suggesting possible contamination of the original isotopic composition, and for this reason they are less reliable. Considering the remaining four ages as the most reliable, an average age of 18.1 Ma is for the upper part of the unit (all lying above an erosion surface, Fig. 2), and this age is assumed to be the age of the marine-fluvial transition at the study area.

6. Discussion

6.1. Evolution of the Sedimentary Systems and Sequence Stratigraphy

Based on facies distribution, key stratigraphic surfaces and correlation among the sedimentary sections of the El Chacay Formation and the base of the Santa Cruz Formation, a general transgressive-regressive (T-R) cycle can be recognized throughout the succession. Its base lies above an unconformity eroded on the Eocene Posadas Basalt (Figs. 2 and 7), which involves a hiatus of about 25 my. An irregular relief on top of the basalt is evidenced by the 35 m of thickness variation of the lower part of the El Chacay Formation (Fig. 2). A bed about 5 m thick of poorly exposed, possibly terrestrial deposits, whose age and stratigraphic affinity are uncertain, is preserved between the Posadas Basalt and the early Miocene marine deposits in the basal portion of the El Chacay Section (Fig. 2). It was not included in our facies analysis because exposure is poor and the paleoenvironmental/stratigraphic interpretation that could be extracted from would be highly hypothetical. This basal bed and the overlying thick deposits of El Chacay Formation in the El Chacay Section (Fig. 2) are indicative of paleo-lowlands with increased accommodation space. Paleohighs of the Posadas Basalts are associated with thinner and higher-energy shallow marine deposits of the El Chacay Formation, such as those deposited on the flooding surface observed in the Puesto El Chacay Section (Fig. 2). No coastal or estuarine deposits are present immediately below the flooding surface especially in areas interpreted as paleohighs (*e.g*., the Puesto El Chacay Section), possibly due to erosion caused by the strong tidal currents that also shaped the overlying subtidal sandbars (Facies A) as the sea level rose during the initial transgression (tidal ravinement). As the sea level rose, tidal and wave action on the sea bottom diminished thus reducing local energy and the grain-size of the sediments being deposited. The increase in water depth also meant that organisms had enough time to colonize and rework the substrate that became

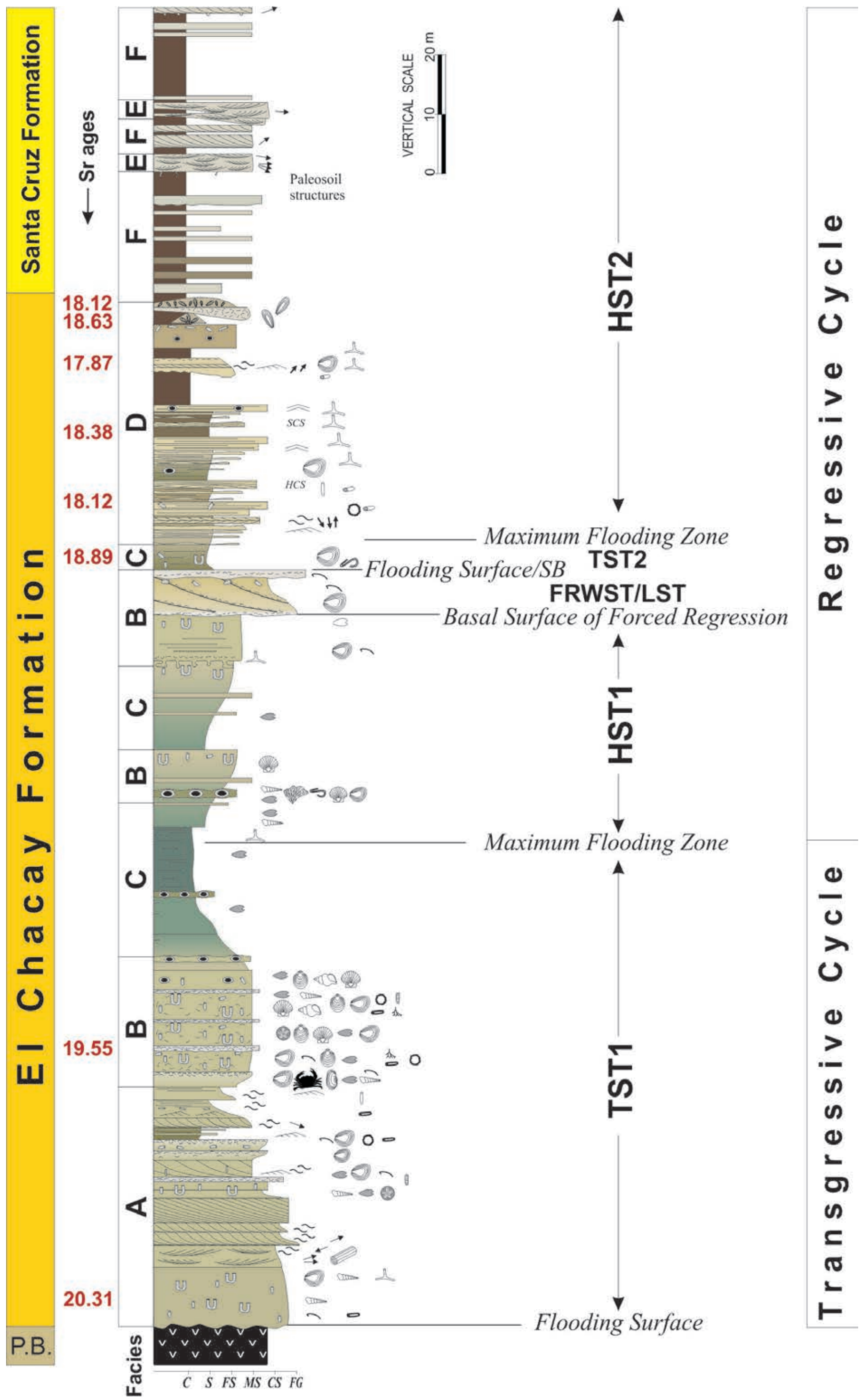

FIG. 7. Integrated column of the studied interval showing the main observed cycles, and the position of significant discontinuities and their sequence stratigraphic meaning. $^{87}Sr/^{86}Sr$ ages are given in red to the left of the column. TST stands for Transgressive Systems Tract; HST for Highstand Systems Tract; FRWST for Forced Regressive Wedge Systems Tract and LST for Lowstand Systems Tract. References for the sedimentary column as in figure 2.

highly bioturbated (Facies B). When sea level was at its maximum, the sedimentary system reached its lowest energy thus allowing the deposition of mud on the sea bottom (Facies C, shelf deposits). The recognition of the Maximum Flooding Surface (MFS) is not straightforward because the muddy interval is homogeneous and locally not exposed. Hence, a Maximum Flooding Zone (MFZ) is defined instead of the MFS, associated with the finest deposits within this muddy horizon. In general, the fining-upward vertical succession of facies A, B and C defines a first Transgressive Systems Tract (TST1, Fig. 7).

After the MFZ there is a general coarsening upward of the succession in which bioturbated deposits of facies B are observed. This trend defines a thin (20 to 40 m) Highstand Systems Tract (HST1, Fig. 7), which is truncated by a laterally extensive surface that marks a change in sedimentation style. Sediments above this surface are everywhere coarser than the underlying deposits (Fig. 2) and characterized by different types of shallow marine, sharp-based sandstone deposits. They can show tabular cosets of cross-bedded sandstones (El Chacay Section, North Section, Figs. 2, 4D), inclined master bedding surfaces (Puesto El Chacay Section, Fig. 2), or channelized trough cross-bedded sandstones (South Section, Fig. 2). The sandstone bodies indicate an abrupt fall in the sea-level allowing a variable degree of erosion of the underlying beds (Figs. 2, 7). These deposits may be assigned to a Forced Regressive Wedge Systems Tract (FRWST, Hunt and Tucker, 1992), or as a Lowstand Systems Tract (Posamentier and Allen, 1999). The deposition of these sharp-based sandstones may also be produced during the initial phase of subsequent transgression, and in this case no FRWST or LST is preserved in this part of the basin.

The sharp-based sandstone bodies are overlain by a thin interval of bioturbated marine mudstones and fine sandstones (Fig. 7), interpreted as a renewed deepening of the sedimentary system. In the Puesto El Chacay Section, the sandstone body is separated from the overlying marine mudstones by a thin, hardened lag of shell fragments and rounded pebbles colonized by encrusting serpulids (Fig. 2). The bedding plane at the base of this layer is interpreted as a ravinement-omission surface and the fine-grained sediments above it as marine sediments from a thin Transgressive Systems Tract (TST2, Fig 7).

The TST2 is covered by deposits of the estuarine complex (Facies D), which in turn grades upward into the low-energy fluvial beds of Facies E and F. Altogether they form a upward shallowing succession included in a Highstand Systems Tract (HST2, Fig. 7) that grades upward into the fluvial beds of the Santa Cruz Formation that are nearly 500 m thick (Ramos, 1979; Blisniuk *et al*., 2005). The lowermost 30 m analyzed here are composed of sandy bedload fluvial deposits accumulated in an anastomosed system. However, a detailed description and discussion of the sedimentary evolution of the entire Santa Cruz Formation is beyond the objective of this paper.

6.2. Age and Correlations

Biostratigraphic analyses of the "Patagoniense" beds historically concentrated on the exposures along the coastal cliffs of eastern Patagonia (Ameghino, 1906; Windhausen, 1931; Feruglio, 1949; Camacho, 1967; Malumián *et al*., 1999; del Río, 2004). For those deposits, palynologic (Barreda and Palamarczuk, 2000), foraminifer (Malumián and Náñez, 1988) and molluscan (del Río, 2004) studies allowed a tentative regional chronostratigraphic correlation, although some contradictions persisted. On the contrary, the exposures along the Andean foothills received little attention and few biostratigraphic studies are available (Chiesa and Camacho, 1995; Frassinetti and Covacevich, 1999; Guerstein *et al*., 2004; Parras *et al*., 2008).

Recently published isotopic ages for some localities of southern Patagonia provide good resolution for stratigraphic correlation. To the southeast of the Austral Basin, Parras *et al*. (2012) obtained $^{87}Sr/^{86}Sr$ ages and placed the marine to estuarine Monte León Formation in the early Miocene (22.12 to 17.91 Ma). The Sr ages of the Monte León Formation match well with younger $^{40}Ar/^{39}Ar$ ages obtained in the overlying fluvial Santa Cruz Formation by Perkins *et al*. (2012) (17.7 Ma to 16.1 Ma) in the same region (Fig. 8). To the west, in the Lago Argentino region, Cuitiño *et al*. (2012) proposed a Burdigalian (20-18.8 Ma) age of deposition for the marine Estancia 25 de Mayo Formation by means of $^{87}Sr/^{86}Sr$ and U-Pb data, in agreement with the Burdigalian U-Pb age proposed by Bostelmann *et al*. (2013) for the overlying Santa Cruz Formation in Sierra Baguales (Chile). In the Comodoro Rivadavia region (San Jorge Gulf Basin) the Chenque Formation was dated in

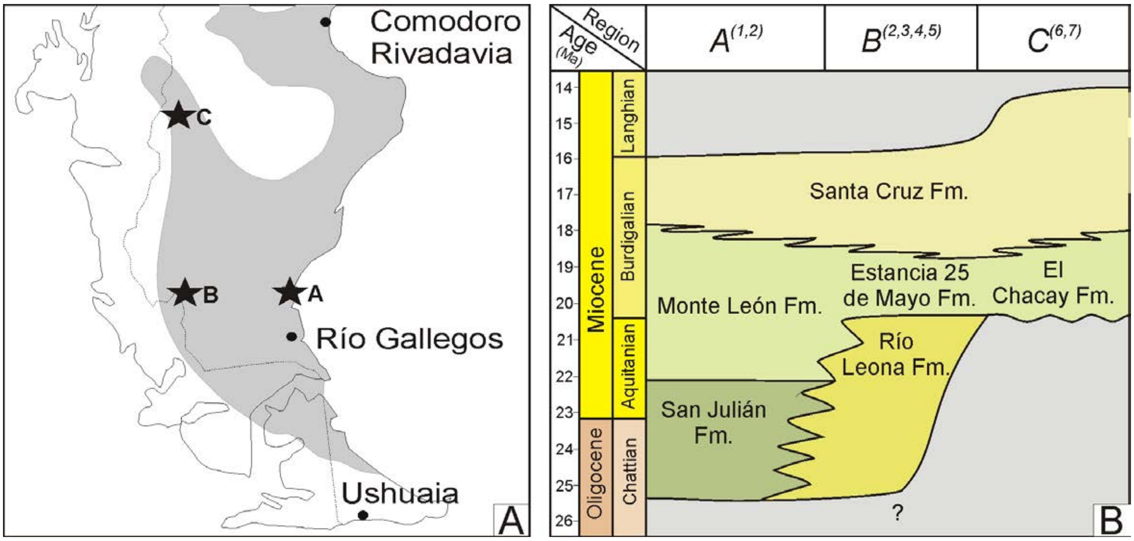

FIG. 8. Chronostratigraphic chart. **A.** Location of the sections where dates are available; **B.** Chronostratigraphic chart for the three well-dated regions figured in A. Numbers indicate the reference from which the ages were taken: 1) Parras *et al*. (2012); 2) Perkins *et al*. (2012); 3) Cuitiño *et al*. (2012); 4) Fosdick *et al*. (2011); 5) Bostelmann *et al*. (2013); 6) Blisniuk *et al*. (2005); 7) this study.

the interval between 19.3 Ma and 15.4 Ma (Cuitiño *et al*., in press). These Miocene marine units are equivalent strata belonging to the “Patagoniense” transgression (Fig. 8).

Blisniuk *et al*. (2005) provided numerous $^{40}Ar/^{39}Ar$ ages ranging from 22.36 to 14.24 Ma for tuffs intercalated in the 500 m thick fluvial deposits of the Santa Cruz Formation in the study area. These data restrain the age of the El Chacay Formation to the late Oligocene (Chattian) or earliest Miocene (early Aquitanian). Parras *et al*. (2008) obtained an $^{87}Sr/^{86}Sr$ age of 25 Ma (Chattian) from an oyster shell of the El Chacay Formation. Results in both papers seem to indicate that the El Chacay Formation is older than proposed in our paper. However, the age of Parras *et al*. (2008) was obtained from a single oyster and no other correlative ages are offered for the rest of the section in order to check the validity of the result. On the other hand, Perkins *et al*. (2012) questioned the validity of the age calculated by Blisniuk *et al*. (2005) for the lowermost beds of the Santa Cruz Formation at Lago Posadas (22.51 Ma), because it would require a very low sedimentation rate in comparison to overlying sedimentary deposits, and there is no evidence of such a change across the sedimentary column. Perkins *et al*. (2012) estimated that the sedimentation of the Santa Cruz Formation at the Lago Posadas region started around 19 Ma. This estimation agrees better with our results for the El Chacay Formation, which range from 20.3 Ma at the base, to 18.1 Ma at the transition to the Santa Cruz Formation (Fig. 8).

The new ages provided here allow the temporal correlation of similar deposits in southern Patagonia, suggesting that the marine “Patagoniense” beds resulted from a huge transgression that flooded the Austral and San Jorge Gulf basins. A maximum time-span of about 4 Ma (~22 to ~18 Ma; late Aquitanian to early Burdigalian) is estimated for the “Patagoniense” event in the Austral Basin. This time interval is much shorter than the time lapse of about 12 my traditionally assigned to this event (late Oligocene-early Miocene; *e.g*., Maluminán *et al*., 1999). Differences in the timing of the onset of the transgression may be related to different stages of eustatic sea level rise, different rates of subsidence or different rates of sediment supply in each area. At about 20 Ma ago, the maximum eustatic peak occurred, as recorded by fine-grained, highly fossiliferous fully marine beds throughout the Austral Basin (Fig. 8). At around 18-17.5 Ma ago the continentalization of the whole basin occurred (Fig. 8). This continentalization started somewhat earlier in the western (proximal) area of the Austral Basin (18-19 Ma) and quickly advanced to the east where it is dated at about 17.7 Ma (Perkins *et al*., 2012).

In the Comodoro Rivadavia area of the San Jorge Gulf Basin the continentalization is dated at about 15 Ma (Cuitiño *et al*., in press), which is remarkable younger than that of the Austral Basin.

6.3. Controls on the sedimentation

The El Chacay Formation was deposited above the Posadas Basalt. Basaltic rocks are resistant against weathering and erosion, and can form long-lived topographic highs. The irregular shape of the basaltic substrate controlled the style of sedimentation of the basal strata of the El Chacay Formation. In topographic lows (*i.e*., North Section, El Chacay Section; Fig. 2), the overlying marine deposits are thicker and show evidence of higher sedimentation rates such as large-scale cross-bedding, reduced bioturbation and lack of shell concentrations. On the contrary, above topographic highs (Puesto El Chacay Section; Fig. 2) the marine deposits are thinner and present bases characterized by highly bioturbated sandstones and shell beds suggesting sediment condensation. This interpretation is reinforced by the presence of discontinuity surfaces displaying abundant *Thalassinoides* isp. thus characterizing the *Glossifungites* inchnofacies together with encrusting organisms such as bryozoan colonies and serpulids.

The paleogeographic reconstruction of the "Patagoniense" sea in the northwest region of the Austral Basin gives an engulfment configuration, elongated in a NNW-SSE direction, open to the S (Ramos, 1982). Paleocurrent measurements in this engulfment (Fig. 6) indicate a N-S oriented coastline for the engulfment and an eastward progradation of fluvial systems, meaning that the studied beds form part of the western margin of the engulfment. The initial transgression and the flooding of the large gulf, recorded in the lower beds of the unit, favoured the development of a strong tidal regime within the gulf because of the increment of the tidal prism and possible tidal resonance due to the funnel shape of the basin. Additionally, the irregular topography of the basaltic substrata, favoured the development of strong tidal currents capable of forming large-scale subtidal bars (Fig. 4A). Tidal bars are preserved in regions where accommodation space was higher such as those places where the Posadas Basalt shows paleo-lowlands. After the maximum flooding phase, when the coastline was farther to the west and north, the regressive phase took place. During this period, shallow water did not produce increasing tidal influence and wave-influenced coastal plains were developed. The facies succession is broadly similar to that in the Aisén region of Chile, where Flint *et al*. (1994) recorded three portions: a lower estuarine complex, an intermediate marine shelf, and an upper estuarine complex for the equivalent Guadal Formation.

Eustatic sea-level fluctuations and rate of basin subsidence are both major controls on sedimentation. As pointed out by Ramos (1989) and Cuitiño *et al*. (2012) the relatively thick "Patagoniense" beds close to the eastern margin of the Andes are the result of subsidence in a foreland basin related to the Miocene uplift of the Patagonian Andes. The north-western portion of the Austral Basin is closed to the north and forms a funnel-shaped engulfment that reaches the Aisén region of Chile in its narrow, northwest end. The presence of this engulfment is the result of a Burdigalian eustatic sea level rise which is responsible of the flooding of a large part of the South American continent. This event affected especially Patagonia (Bellosi, 1995; Malumián, 1999; Marengo, 2006; Cuitiño *et al*., 2012; Rossetti *et al*., 2013) and was coupled with a period of high tectonic activity in the Andes (Fosdick *et al*., 2013) that produced high rates of foredeep subsidence. The progradation of the terrestrial deposits of the Santa Cruz Formation, which filled the subsiding foreland trough, can be related to the abundant sediment supply produced by the synchronous uplift and erosion of the Andean chain.

7. Conclusions

The Patagoniense deposits of Lago Posadas-Meseta Belgrano (El Chacay Formation) are composed of sandstone, mudstone and heterolithic beds deposited in a marine engulfment during early Miocene times. Facies analysis revealed different paleoenvironmental scenarios, from tide-dominated shallow marine at the base, grading upward to offshore mudstones, which in turn grade to a complex, wave and fluvial influenced, estuarine system. The estuarine deposits pass upward transitionally to the floodplain-dominated, fluvial Santa Cruz Formation. The age of the marine El Chacay Formation was constrained by means of $^{87}Sr/^{86}Sr$ data derived from oysters distributed along the entire column. The results indicate that deposition initiated at 20.3 Ma and the ended at about 18.1 Ma, which allows a reliable correlation with other Patagoniense deposits of the Austral and San Jorge Gulf basins.

Based on facies analysis, isotopic ages, paleocurrent and paleogeographic considerations, the major controls over the sedimentation were estimated. Eustasy, foreland basin subsidence, paleotopography and Andean tectonics controlled the facies arrangement. Tidal dominance occurred during the initial transgression, whereas wave and fluvial processes dominated during the regressive phase. The funnel shape of the basin augmented the strength of the tidal currents during the initial transgressive phase.

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