Lithofacies, architecture, and depositional environments of the Santa Cruz Formation in Chilean Patagonia

Raúl Ugalde[1]*, Enrique Bostelmann[2], Karina E. Buldrini[2,3], and José Luis Oyarzún[4]
1: PEDECIBA Geociencias, Facultad de Ciencias, Universidad de la República, Iguá 4225, Montevideo, Uruguay.
2: Red Paleontológica U-Chile, Laboratorio de Ontogenia y Filogenia, Departamento de Biología, Facultad de Ciencias, Universidad de Chile, Santiago, Chile.
3: Laboratorio de Zoología de Vertebrados, Facultad de Ciencias, Universidad de Chile, Santiago, Chile.
4: Parque Geopaleontológico La Cumbre-Baguales, Ruta 9 km 284, Magallanes, Chile.
** email: raugaldep@gmail.com*

Abstract. Early Miocene fluvio-lacustrine deposits are widespread throughout Patagonia. In Chile, remarkable but isolated outcrops of the Santa Cruz Formation include the highest plains on the Meseta Cosmelli in Aysén, and the Sierra Baguales in Magallanes. At both areas, stratigraphic sections were measure and fossil content recorded. The Pampa Guadal profile at Meseta Cosmelli includes the formation's lower packages, which consists of fine-grained mudstones and sandstones, interbedded with subordinate conglomeratic horizons. Abundant and well-preserved fossil mammals are present in the upper half of the section. The strata characterize a fluvial environment, with thick floodplains and restricted gravel to coarse sand channels, recording a change from an anastomosing to a meandering river system. The Morro Bayo profile at Sierra Baguales begins with sedimentological aggregates of the estuarine Patagonian oyster *Crassostrea orbignyi*, followed by mudstone and fine sandstone levels, interbedded with subordinate coarse-grained sandstone. Clastic sedimentary structures, abundant fossil mammals, and floodplain facies characterize the top of the succession, indicating a transition from a low energy estuarine system to a meandering river, with wedged bars. Both localities represent a variable energy fluvial environment with high sedimentary input, similar to those described for the westernmost exposures of the Santa Cruz Formation in Argentinean Patagonia.

Key word: Santa Cruz, Fluvial, Lithofacies, Early Miocene, Aysén, Magallanes, Chilean Patagonia.

1 Introduction

The Santa Cruz Formation is an extensive early Miocene siliciclastic fluvial unit of the Magallanes-Austral basin, initially described by Florentino Ameghino based on field observations gathered by his brother Carlos during successive expeditions in the homonymous Argentinean province (Ameghino, 1906). Its abundant fossil content, mostly mammals, had made it a well-known study unit since the mid-19th century (Vizcaíno *et al*., 2012). In Chile, the formation has been recognized in two major areas: the highlands of the Meseta Cosmelli immediately south of Lake General Carrera, Aysén, and the northern valleys of Sierra Baguales, in Última Esperanza province, Magallanes (Figure 1). At both localities initial investigations were performed during the middle to late 90's (Flint *et al.*, 1994; Flynn *et al*., 2002), followed by later work in the last decade (De la Cruz and Suárez, 2006; Bostelmann and Buldrini, 2012; Bostelmann *et al*., 2013). In spite of its relevance, most of these studies did not address in further detail the lithostratigraphic and depositional attributes of the units. This study contributes new lithofacies analysis and depositional architecture of two relevant outcrops at each locality: the Pampa Guadal in Meseta Cosmelli, and the Morro Bayo section at Sierra Baguales.

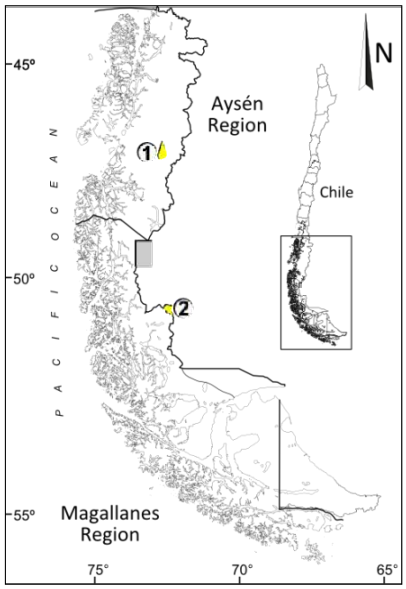

Figure 1. Locations of the study areas in the Chilean Patagonia. 1: Pampa Guadal, Meseta Cosmelli, General Carrera province, Aysén. 2: Morro Bayo, Sierra Baguales, Última Esperanza province, Magallanes.

1.1 Stratigraphic context

At Pampa Guadal, the Santa Cruz Formation overlies the Guadal Formation, an epiclastic shallow marine unit deposited during the early Miocene "*Patagonian*" transgression (Bostelmann *et al*., this congress). Estimated thickness of the outcrops measured from the San Martín River is >700 m, composing the nucleus of the Las Dunas syncline (De la Cruz and Suárez, 2006). In Sierra Baguales, the Santa Cruz Formation transitionally overlies the Estancia 25 de Mayo Formation (Cuitiño and Scasso, 2010), which also represents the local expression of the "*Patagonian*" Sea in southwestern Santa Cruz province. The upper contact of the Santa Cruz Formation is

characterized by an apparent angular unconformity with the plateau basalts of Meseta Las Vizcachas, assumed as late Miocene(?)-Pliocene(?) in age (Bostelmann *et al*., 2013).

2 Methods

Successive fieldwork campaigns were carried during 2012 and 2014 in Pampa Guadal, and 2012 to 2015 in Morro Bayo. Stratigraphic sections were described and measured at the centimeter-scale, taking fresh rock color data, lithology, sedimentary structures, erosive surfaces and depositional styles. Vertebrate fossils were collected or georeferenced for future excavations. Sandstone and key pyroclastic levels were sampled for radiometric dating. Depositional environments were interpreted trough the lithofacies association analysis, following the methodology of Miall (2006). Figure 2 comprises a description of all the symbols in Figure 3, which shows the rasterized stratigraphic sections.

3 Results

3.1 Lithologies and fossil content

The log made in Pampa Guadal has a thickness of 75.8 m, covering near a quarter of the complete succession. The lithologies are dominated by massive dark brown mudstones, middle to coarse sandstones with dark tones and some structures and subordinate, matrix-supported channelized conglomerate lenses. In the second portion, a tuffaceous marker unit with a diagnostic light pink-reddish color was found. Fossils include 17 species of small, medium and big size mammals, all of them referable to the classic Santacrucian SALMA (South American Land Mammal Age). Poorly preserved centimeter-scale vegetal remains were also evident.

The Morro Bayo section thickness is 172.8 m. The main domain is represented by dark massive, parallel laminated mudstones and brown fine to coarse sandstones. In the second third, local matrix- to clast-supported conglomerates have been found. At the basal portion, a vitreous reworked light yellow tuff of ~0.5 m thick is observed. Similar levels at the Lago Argentino area renders a U-Pb age of 18.8 Ma. (Cuitiño *et al*., 2013). Disarticulated specimens of *Crassostrea orbignyi* were found at the base of the section conforming biogenic associations of sedimentary character. Poorly preserved leaf imprints and low carbonization index vegetal material are also present at this level. Fragmentary fossil mammals of 25 different species occurs since 91 m as reworked isolated or *in situ* disarticulated elements. Taxonomic identities allow chronostratigraphic assignation of them to the "*Notohippidian*" stage (Ameghino, 1906). Bostelmann *et al*. (2013) report a U-Pb age of 18.23 Ma for the top of this succession.

3.2 Lithofacies and depositional environments

The more common lithofacies on Pampa Guadal are massive mudstones and sandstones (Fsm, Sm). The lower third of the section (0-25 m) is composed exclusively of these lithofacies, whereas the middle third (25-50 m) shows some coarse massive levels (Gmg), parallel and trough-bedded sandstones (Sh, St), and parallel laminated mudstones (Fl). The upper third (50-75.8 m) has diverse sandy facies (Ss, Sm, Sh, Sp), with subordinated massive mudstones (Fsm) and localized gravels (Gmm, Gmg). The fluvial interpreted architecture is based on the following; a lower third with fine floodplain sediments within restricted gravitational flows; a middle third with floodplains and sand bodies intercalations; and an upper third with channels, sand bodies, and less common floodplains. The fluvial system represents an up section change from an anastomosing river to a later meandering system in the upper half of the section.

At Sierra Baguales the section has well differentiated intervals, conditioned by the exposure and preservation degree. The base (0-29 m) has a transitional configuration, from oyster-rich horizons to massive sandy facies (Sm), with trough (St) and planar (Sl) cross bedding, interbedded with massive or laminated fines (Fsm, Fl). The second interval (38-60 m) is dominated by stratified sandstones (Sl, Sp) and interbedded massive facies (Fsm, Fm) to the top. Continue massive sandstones (Sm) with possible poor developed paleosols (P) (60-74 m), conglomeratic levels (Gt, Gcm) and coarse sediments with trough stratification (St, Sh) (79-89 m), and a half-covered portion with fine massive intercalations (Sm, Fsm) (120-148 m). The top (148-172.8 m) interval shows more well stratified and massive sandy packages (Sl, St, Sm), with distinctive facies which characterize the Morro Bayo package. The architectural elements support the interpretation of a transition from a wave-dominated estuary head in the basal section to a meandering river with oscillating energy in the upper portions of the outcrop. At this same locality Bostelmann *et al*. (2013) mention a similar fluvial system with a sinuosity index of 1.28, according to paleocurrent data (n=60), coherent with the high-energy associations described in the central and upper segments.

4 Discussion and conclusions

The fluvial systems studied can be characterized by significant oscillations in energy, broad floodplains and subordination of coarse sediment channels. Tabular sand bodies are abundant in spite of the lateral accretion geometries. Pampa Guadal and Morro Bayo shows similar sediment caliber and facies, but their dissimilar thickness suggests a very different sedimentation rate, a time spaced deposition or both. The absence of estuarine biogenic aggregates at the base of the Pampa Guadal section precludes attempts to clearly define the contact with the underlying unit, and regional correlation. Nevertheless, the occurrence of volcanic tuffs may prove to be a good indicator for the correlation between both places. The

Pampa Guadal faunal assemblage is characteristic of the Santacrucian age. Recently, a 17.8-16 Ma age has been suggested for the classic Santacrucian localities in the Atlantic coast of Patagonia (Perkins *et al*., 2012). In Morro Bayo the section covers almost the totality of the unit, but significant lateral changes in other areas of Sierra Baguales could not be discarded. The fossil fauna matches the assemblages described from localities like Karaiken near Lago Argentino, representing a slightly earlier interval, the "*Notohippidian"* stage. U-Pb ages of these levels bracketed between 18.8 and 18.23 Ma (Bostelmann *et al*., 2013; Cuitiño *et al*. 2013). Further work on characterizing the sedimentary provenance through the Chilean-side outcrops will allow a better understanding of the effects of the Andean Neogene tectonic reactivation in the Magallanes Basin and its paleogeographic implications on the extra-Andean zone.

Acknowledgements

We express our gratitude to Pascual Díaz and his family, for logistic support in Aysén. The Maclean family, Hielos Patagónicos, Hotel Remota, Restaurante Afrigonia, Mountain Travel, Alex Von Bischhoffshausen, Paola D'Smet d'Olbecke and the Parque Geológico y Paleontológico La Cumbre Baguales provide funds for field campaigns during 2015. The Project Anillo de Ciencia Antártica ACT-105 gave general funding. Jacobus Le Roux kindly gave us support for the geochronology through its project Fondecyt 1130006. R. Ugalde also thanks ANII for the Uruguayan master scholarship and PEDECIBA Geociencias for providing access to resources. J. Fosdick helped with comments and edits of the draft, which considerably improved the final text.

References

Ameghino, F. 1906. Les formations sédimentaires du Crétacé Supérieur et du Tertiaire de Patagonie avec un parallelé entre leurs faunes mammalogiques et celles de l´ancien continent. Anales del Museo Nacional de Buenos Aires (tercera serie) 8: 1-568.

Bostelmann, E.; Buldrini, K.E. 2012. Late-Early Miocene fossil mammals of the Pampa Guadal Area, Meseta Cosmelli, Aysén Region, Chilean Patagonia. Abriendo ventanas al pasado. In Simposio de Paleontología en Chile, No. 3, Resúmenes III: 38-41.

Bostelmann, J.E.; Le Roux, J.P.; Vásquez, A., Gutiérrez, N.M.; Oyarzún, J.L.; Carreño, C.; Torres, T.; Otero, R.; Llanos, A.; Fanning, C.M.; Hervé, F. 2013. Burdigalian deposits of the Santa Cruz Formation in the Sierra Baguales, Austral (Magallanes) Basin: Age, depositional environment and vertebrate fossils. Andean Geology 40 (3): 458-489.

Cuitiño, J.I.; Scasso, R.A. 2010. Sedimentología y paleoambientes del Patagoniano y su transición a la formación Santa Cruz al sur del Lago Argentino, Patagonia Austral. Revista de la Asociación Geológica Argentina 66: 406-417.

Cuitiño, J.I., Scasso, R.A., 2013. Reworked pyroclastic beds in the early Miocene of Patagonia: Reaction in response to high sediment supply during explosive volcanic events. Sedimentary Geology 289: 194-209

De la Cruz, R.; Suárez, M. 2006. Geología del área Puerto Guadal-Puerto Sánchez: Región Aisén del General Carlos Ibáñez del Campo. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 95: 58 p. 1 mapa escala 1:100.000.

Flint, S.S.; Prior, D. J.; Agar, S. M.; Turner, P. 1994. Stratigraphic and structural evolution of the Tertiary Cosmelli Basin and its relationship to the Chile triple junction. Journal of the Geological Society 151: 251-268.

Flynn, J.J.; Novacek, M.J.; Dodson, H.E.; Frassinetti, D.; McKenna, M.C.; Norell, M.A.; Sears, K.E.; Swisher, III, C.C.; Wyss, A.R. 2002. A new fossil mammal assemblage from the southern Chilean Andes: implications for geology, geochronology, and tectonics. Journal of South American Earth Sciences 15 (3): 285-302.

Miall, A. D. 2006. The geology of fluvial deposits. Sedimentary facies, basin analysis, and petroleum geology. Springer-Verlag: 582 p., Berlin.

Perkins, M.E.; Fleagle, J.G.; Heizler, M.T.; Nash, B.; Bown, T.M.; Tauber, A.A.; Dozo, M.T. 2012. Tephrochronology of the Miocene Santa Cruz and Pinturas Formations, Argentina. In Early Miocene Paleobiology in Patagonia: High-Latitude Paleocommunities of the Santa Cruz Formation (Vizcaíno, S.F.; Kay, R.F.; Bargo, M.S.; editors). Cambridge University Press: 23-40. Cambridge.

Vizcaíno, S.F.; Kay, R.F.; Bargo, M.S. 2012. Early Miocene Paleobiology in Patagonia: High-Latitude Paleocommunities of the Santa Cruz Formation. Cambridge University Press: 392 p. Cambridge.

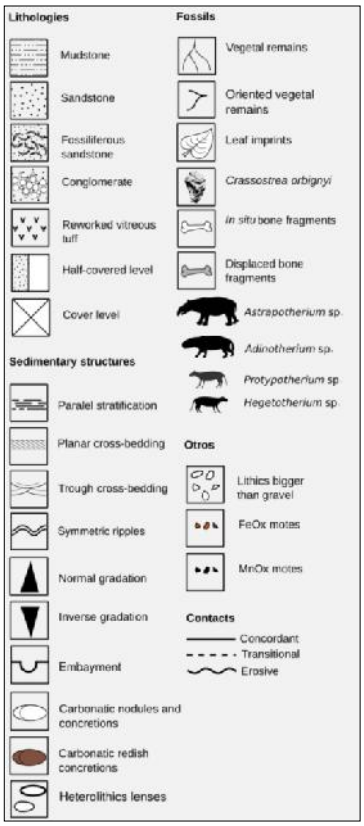

Figure 2. Symbology of the stratigraphic sections in Figure 3.

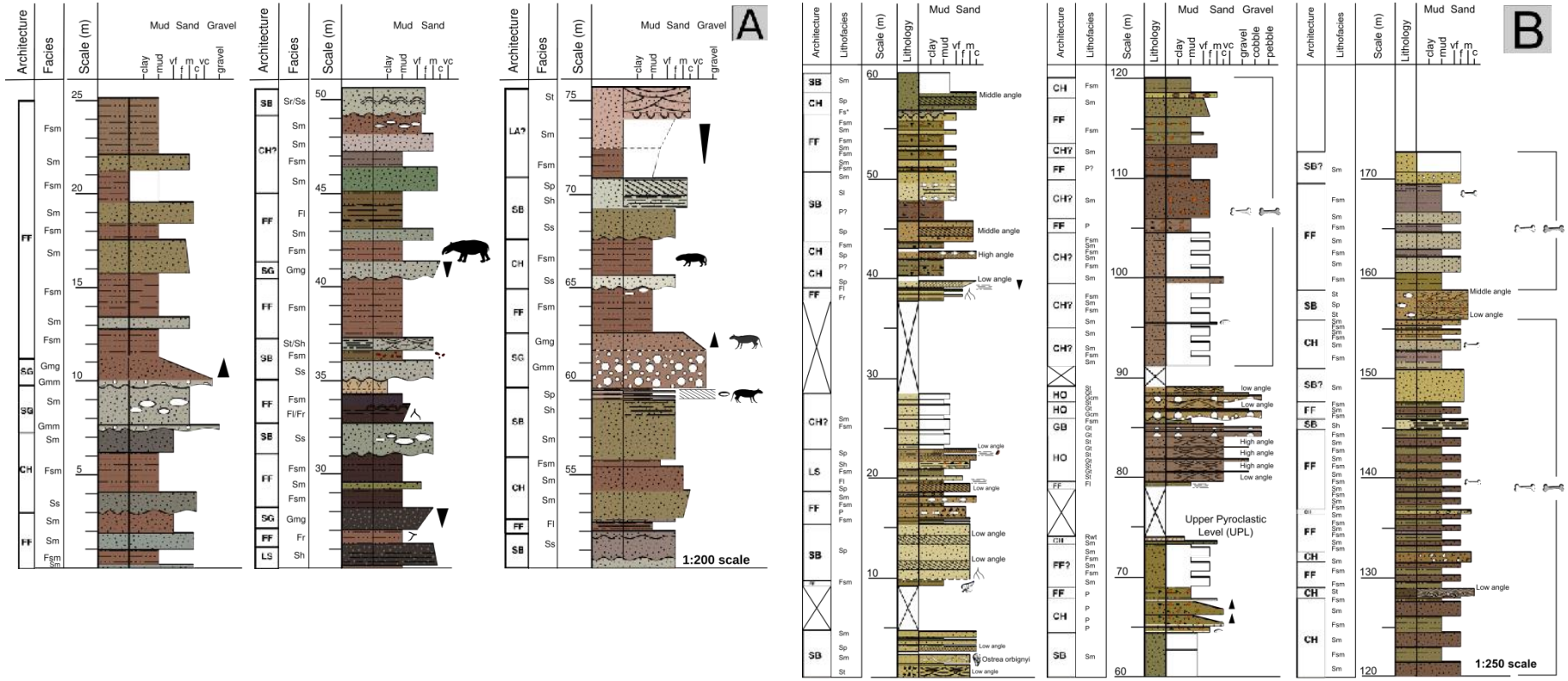

Figure 3. Stratigraphic sections of the Santa Cruz Formation at: **A**. East flank of Pampa Guadal, General Carrera province, Aysén; **B**. Morro Bayo, Última Esperanza province, Magallanes. **Facies**. *P*: Poorly developed paleosol. *Fsm*: Massive fines. *Fr*: Rizolith-bearing fines. *Fl*: Parallel laminated fines. *Sm*: Massive sandstones. *Sh*: Parallel stratified sandstones. *Ss*: Sandstones sheets. *St*: Trough cross-bedded sandstones. *Sr*: Ripple-bearing Sandstones. *Sp*: Planar cross-bedded sandstones. *Gmm*: Matrix-supported massive gravels. *Gcm*: Clast-supported massive gravels. *Gmg*: Inverse graded gravels. Rwt: Reworked vitreous tuff. **Architectural elements.** *FF*: Floodplain fines. *CH*: Channels. *SG*: Gravitational Flows. *LS*: Laminated sands. *SB*: Sand bodies. *LA*: Lateral accretion. *GB*: Gravel bars. *HO*: Hollow holes.