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THE AUSTRAL-MAGALLANES BASIN (SOUTHERN PATAGONIA): A SYNTHESIS OF ITS STRATIGRAPHY AND EVOLUTION

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ABSTRACT

The Austral-Magallanes is an oil-producing basin located in southern Argentina and Chile, containing a siliciclastic stratigraphic record ranging from the Late Jurassic to late Cenozoic. This short paper finalize the two special volumes of the Latin American Journal of Sedimentology and Basin Analysis dedicated to the basin, and aims to provide a comprehensive synthesis based on the current knowledge about the chronology of deposition, stratigraphy, and tectonic events that shaped this basin. During the breakup of Gondwana in the Jurassic, an extensional phase was responsible for the beginning of accumulation of volcaniclastic material within grabens, which subsequently were covered by widespread Lower Cretaceous shallow and deep marine deposits that conforms the main hydrocarbon system. From Late Cretaceous onward, the subduction-related compressive regime associated to Andean uplift and fold and thrust belt migration was responsible for the onset of the foreland stage. During the Late Cretaceous, the foredeep zone accumulated a thick pile of deep marine deposits that graded upward to shallow marine and terrestrial deposits. During the Cenozoic, the foredeep was less marked and shallow marine and terrestrial sediments accumulated in wide areas, punctuated by important unconformities associated to foreland uplift. Future developments should focus on: i) improving the age-controlled stratigraphy; ii) joining the information provided by subsurface and outcrop studies; and iii) developing source to sink models to address the Andean impact in the sedimentation of the basin.

WHY THIS WORK?

The Austral-Magallanes Basin is the southernmost basin of South America, comprising the southern region of Patagonia in Argentina and Chile and part of the Tierra del Fuego Island. It includes geographic regions such as the Southern Patagonian and Fuegian Andes, the Patagonian steppe and the continental shelf. This basin is of major relevance for scientific and industrial research, especially because it has a superb record of paleoenvironmental, paleontological, climatic, paleogeographic, and tectonic events, and constitutes one of the main oil-basins in Argentina both on-shore and off-shore (Biddle *et al*., 1986; Robbiano *et al*., 1996). This basin was deeply studied till 1980's mainly by the YPF (the Argentine national oil company) geological team (*e.g.* Feruglio, 1949; Russo and Flores, 1972; Arbe, 1989 and references therein), but after that, there was a nearly twenty years-gap with few contributions about this region. Despite the importance of this basin, the level of knowledge remains under evolution. During the last 20 years several important advances regarding its stratigraphy and evolution were made, mainly triggered by several PhD thesis and the conformation of research teams specialized on the Austral-Magallanes Basin (mainly from La Plata, Buenos Aires and Stanford universities).

The aim of this contribution is to provide a comprehensive synthesis based on the current knowledge about the chronology of deposition, stratigraphy and tectonic events that characterize the Austral-Magallanes Basin. We focus on the stratigraphic arrangement for the foredeep region between the Lago San Martín in the north (Santa Cruz province, Argentina), to the Última Esperanza Region (Chile) in the south. In addition, we summarize and contextualize into a regional stratigraphic framework the new contributions provided in two special issues of the Latin American Journal of Sedimentology and Basin Analysis (25.2 and 26.2), which have been dedicated to specific aspects of the basin. These new research papers comprise different approaches, including detailed stratigraphic and facies analyses of shallow marine, deltaic and fluvial systems (Moyano Paz *et al*., 2018; Parras and Cuitiño, 2018; Tettamanti *et al*., 2018; Odino Barreto *et al*., 2018), paleopedology (Raigemborn *et al*., 2018), tectonostratigraphy (Aramendía *et al*., 2019), biostratigraphy (González Estebenet *et al*., 2019) and tectonic evolution (Gallardo Jara *et al*., 2019). Finally, we aim to highlight some future challenges for scientific research in this basin.

THE AUSTRAL-MAGALLANES BASIN

The stratigraphic evolution of the Austral-Magallanes Basin, developed between the Late Jurassic and the Cenozoic, was strongly related to the tectonic forces that acted along the western boundary of the South American Plate, including an initial extensional stage followed by a compressional stage. The basin is limited by the Andes to the west and south, the Deseado Massif to the northeast, and the Río Chico-Dungeness High and Malvinas Basin to the east (Fig. 1). Three tectono-sedimentary stages of infilling are defined for this basin, each with a particular stratigraphic record, including: i) a Late Jurassic rift stage; ii) an Early Cretaceous thermal subsidence stage; iii) an Aptian – Miocene foreland stage.

Tectono-stratigraphic stages

The development of the Austral-Magallanes Basin is strongly tied to the geodynamic evolution of the curved southernmost Andes, were the N-S oriented Southern Patagonian Andes, turns towards the Fuegian Andes trending W-E (Fig. 1). The basin developed in the concave side of the curvature, while the hinge sector contains the thickest depocenter (Diraison *et al*., 2000).

After late Paleozoic-Triassic cratonic accretion and basement consolidation (Giacosa *et al*., 2012; Hervé *et al*., 2008), a Jurassic extensional event established the basic configuration (or substratum) of the Austral-Magallanes Basin, which deeply affected the ensuing Cretaceous-Cenozoic tectonic and sedimentary stages. During extension related to the last stages of Gondwana break-up, the back-arc oceanic Rocas Verdes Basin opened along the continent margin (Calderón *et al*., 2016), while a regional system of N-S to NE-SW oriented grabens with synrift infill of continental and volcanic sequences affected the whole Austral-Magallanes Basin at the continental scale (Uliana *et al*., 1989). Overall ocean opening along the Rocas Verdes Basin increased from north to south; strong continental crustal stretching affected particularly the Última Esperanza depocenter to the south of Lago Argentino (Fig. 1) (Dalziel, 1981; Arbe and Hechem 1984; Biddle *et al*., 1986; Wilson 1991; Calderón *et al*., 2007).

Due to the increased spreading rates in the South Atlantic Ocean, coupled with elevated convergence and subduction on the western margin of South America at ~100 Ma, a compressional uplift pulse advanced from north to south along the Patagonian Andes (Fildani *et al*., 2003; Fosdick *et al*., 2011; Varela *et al*., 2012a; Ghiglione *et al*., 2015; Malkowski *et al*., 2016, 2017b). During the Late Cretaceous, the

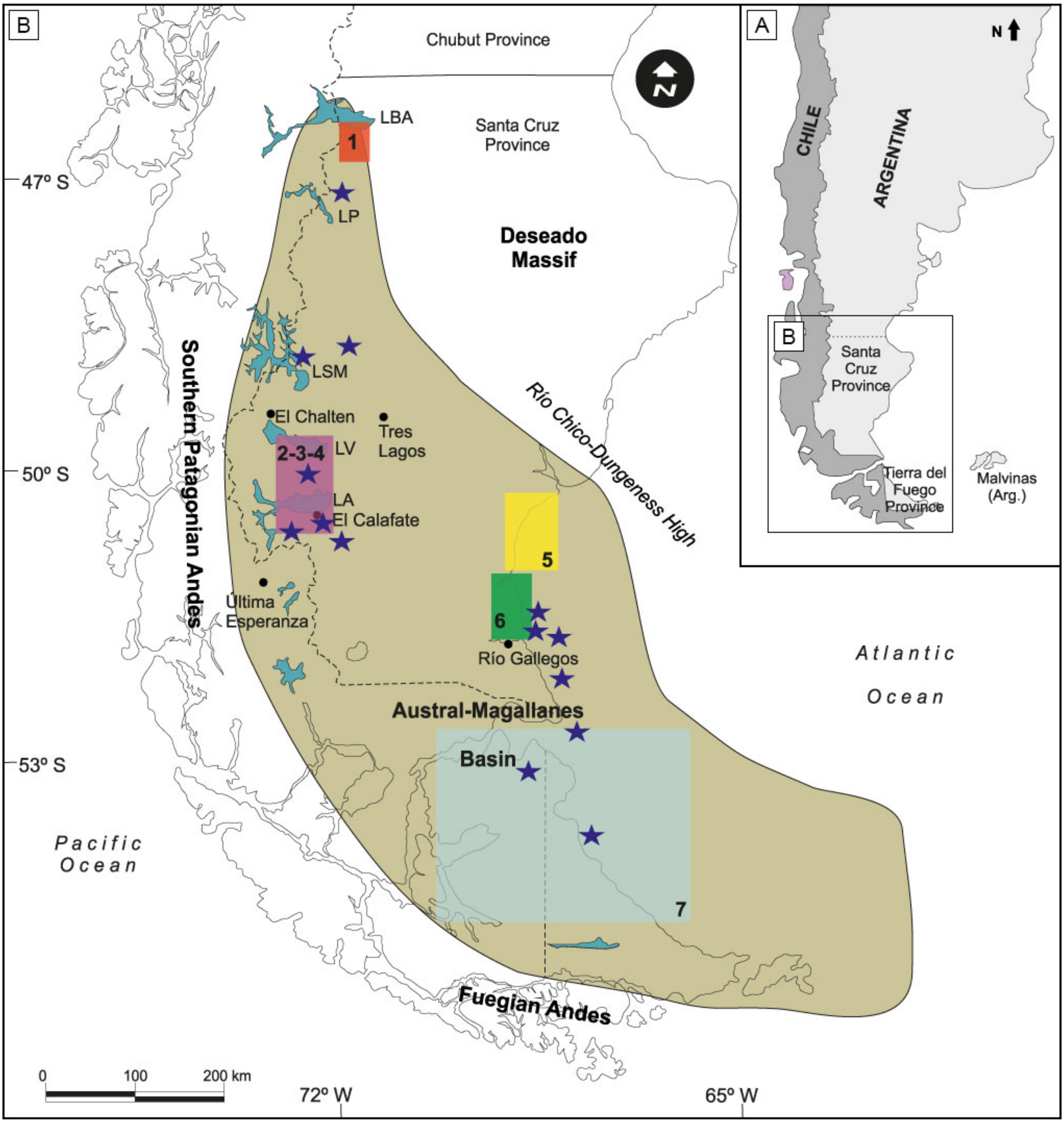

Figure 1. General map of the Austral-Magallanes Basin at Southern Patagonia. **a)** Location of the basin at the southernmost region of Argentina and Chile. **b)** Location of the study areas (color boxes) of the works form the special volumes dedicated to the Austral-Magallanes Basin. 1: Aramendía *et al*. (2019); 2: Moyano Paz *et al*. (2018); 3: Tettamanti *et al*. (2018); 4: Odino Barreto *et al*. (2018); 5: Parras and Cuitiño (2018); 6: Raigemborn *et al*. (2018); 7: Gallardo Jara *et al*. (2019). Blue stars correspond to localities included in the work of González Estebenet *et al*. (2019). LBA: Lago Buenos Aires; LP: Lago Pueyrredon/Posadas; LSM: Lago San Martín; LV: Lago Viedma; LA: Lago Argentino.

progressive N to S closure of the Rocas Verdes Basin produced a diachronic uplift of the cordillera, in parallel to the onset of the foreland basin in the same direction. As a consequence, the northwestern region of the Austral-Magallanes basin underwent an early onset of foreland sedimentation during the Aptian-Albian (Aramendía *et al*., 2018), while first sandy turbidites related to Andean uplift appeared in the

Cenomanian in the Última Esperanza depocenter (Wilson, 1991; Fildani *et al*., 2003; Fosdick *et al*., 2011; Varela *et al*., 2012a), and reached the eastern tip of Tierra del Fuego in the Campanian (Olivero and Malumián, 2008). As a consequence, a particular N-S deep axial depocenter developed in the Late Cretaceous foreland, with an uplifted northern realm sourcing sediments toward the southern deep-marine basin, heritage of the Jurassic stretching.

The Cenozoic was a time of pulsatory sedimentation, during which migration of the foreland basin system occurred from west to east in Patagonia and from south to north in Tierra del Fuego, following the continuous advance of the curved fold and thrust belt. While the Patagonian Andes suffered episodes of oceanic ridge collision and periods of oblique subduction, the Fuegian Andes were influenced by stretching and strike-slip kinematic in the context of the Drake Passage and Scotia Sea opening. The Miocene uplift and cratonward advance of deformation produced a change from initial marine sedimentation (Patagonian transgression) towards the continental Santa Cruz orogenic wedge (Fosdick *et al*., 2011; Cuitiño *et al*., 2012; Parras and Cuitiño 2018; Aramendía *et al*., 2019), representing the last stages of foreland sedimentation. Due to uplifting of the foreland, most of the basin became inactive after ~14-12 Ma, while sediment bypassed towards the offshore basin (Baristeas *et al*., 2013; Ghiglione *et al*., 2016; Sachse *et al*., 2016).

The beginning: rifting during the breakup of Gondwana

The rift stage of sedimentation in the Austral-Magallanes Basin (called Austral Basin) occurred during the uppermost Jurassic and the end of the Early Cretaceous. This extensional phase corresponds to the El Quemado Complex (equivalent to the Tobífera Formation; Fig. 2) syn-rift sequence (Féraud *et al*., 1999; Pankhurst *et al*., 2000, Poiré and Franzese, 2010). This complex, which presents a variable thickness between 100 and more than 1000 m, is mainly composed of volcano-sedimentary sequences, in which felsic ignimbrites dominate (Riccardi, 1971; Ramos *et al*., 1982; Kraemer and Riccardi, 1997). On top of the El Quemado Complex is the Springhill Formation, representing the initial transgressive infill on the previously formed grabens and half-grabens (Biddle *et al*., 1986; Arbe and Fernández Bell Fano, 2002; Schwarz *et al*., 2011; Richiano *et al*., 2016; and references therein). This unit was firstly defined in subsurface studies and represents the most important conventional reservoir in the Austral Basin (Thomas, 1949 a, b; Spalletti *et al*., 2006; Schwarz *et al*., 2011, among others). Studies related to sedimentological and palaeontological aspects of the outcrops of this unit are scarce (Riccardi, 1971; Kielbowicz *et al*., 1983; Arbe, 1986, 2002; Richiano *et al*., 2016). In general terms, the Springhill Formation was traditionally divided into a lower continental interval and an upper marine interval by Cecioni (1955), starting with coal and coaly shales to mainly sandstone bodies, interpreted as having developed in a coastal-plain to lagoonal palaeoenvironments, transgressed by a succession of estuarine and open-marine siliciclastic deposits (Biddle *et al*., 1986; Arbe and Fernández Bell Fano, 2002; Schwarz *et al*., 2011; Richiano *et al*., 2016).

The transgression represented by the Springhill Formation continues causing the deposition of the marine black shales of the Río Mayer Formation (Fig. 2) (Berriasian-Albian) (Arbe, 2002; Richiano *et al*., 2012). This unit, interpreted as the sag (thermal) phase of the rifting process, presents a thickness of up to 1000 m in the Lago Argentino region and can be subdivided into three informal sections (Richiano *et al*., 2012). The lower section is dominated by laminated black shales interbedded with marl levels accumulated in an outer shelf setting (Richiano *et al*., 2012), showing the highest Total Organic Carbon (TOC) content (up to 2.81%, Richiano, 2014; Richiano *et al*., 2015). The middle section is composed of intensely bioturbated dark marls and shales, with a well-preserved and highly evolved *Zoophycos* ichnofacies (Richiano *et al*., 2013; Richiano, 2015). The upper section is composed of massive black shales intercalated with very fine- to fine-grained sandstones, interpreted as an outer shelf with distal low-density turbidity current deposits (Richiano *et al*., 2012). The frequent intercalation of sandstones in the uppermost part of the section is related to the distal influence of deltaic deposition whose lithologic expression at the basin margins to the north is the Piedra Clavada Formation (Richiano *et al*., 2012; 2015). Recently, the geochemistry of the Río Mayer Formation was compared to the Rocas Verdes Basin units, showing no relation with the contemporaneous Zapata

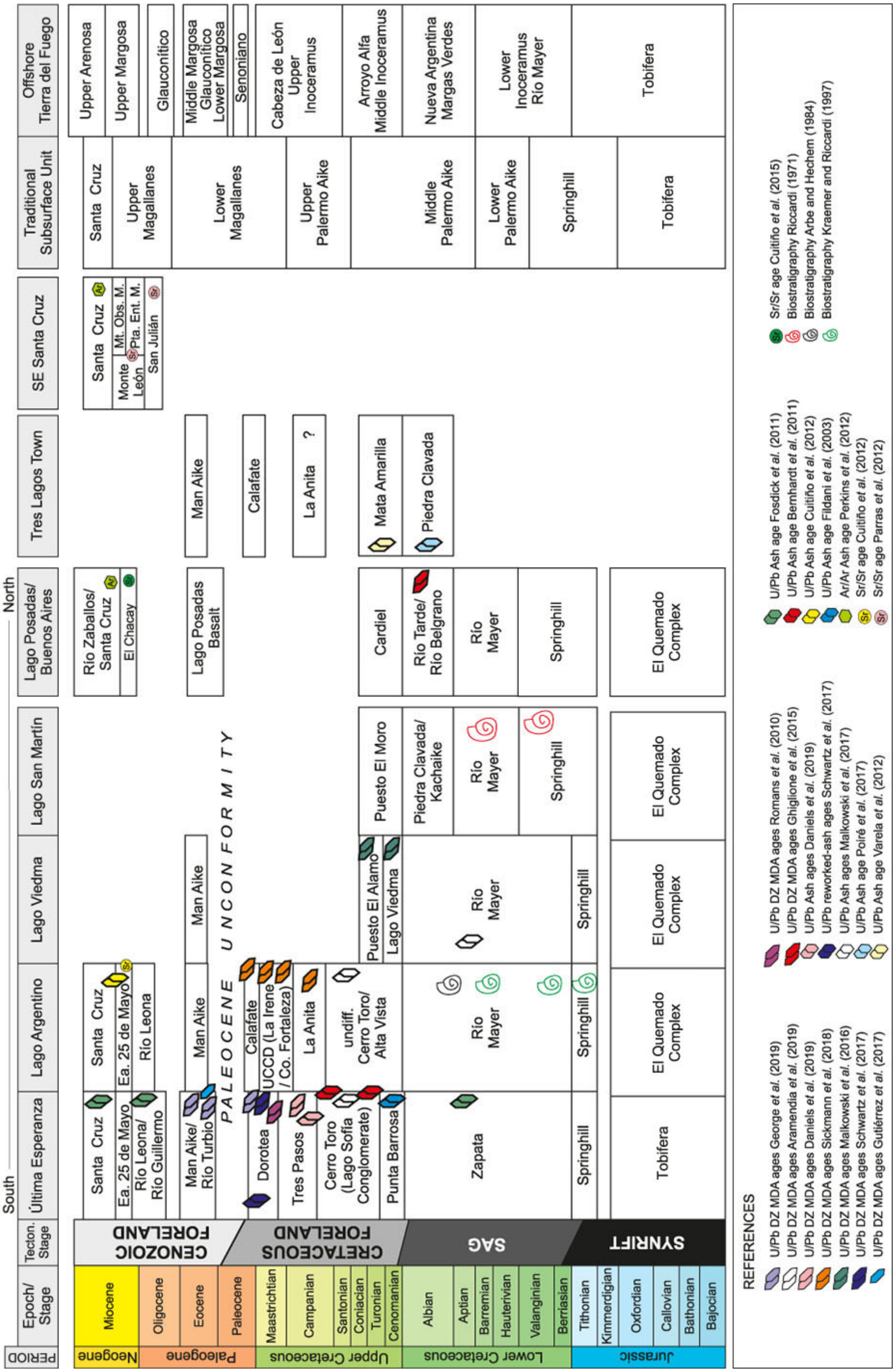

Figure 2. Chronostratigraphic chart of the north-central Austral-Magallanes Basin, showing the units from south to north and northwest to southeast in each evolutionary stages of the basin: Synrift; Sag; Cretaceous and Cenozoic foreland.

Formation, suggesting a compartmentalization between these two depocenters at least during the entire Lower Cretaceous (Richiano *et al*., 2019).

The Piedra Clavada Formation constitutes the final stage of postrift where deltaic systems prograded south-southwestward during a Highstand Systems Tract. It is 306 m thick and it is composed of bioturbated and fossiliferous yellowish sandstones, interbedded with dark mudstone and heterolithic facies, occasionally with some conglomerate and coquina levels (Poiré and Franzese, 2010). Sedimentologic and paleontological studies suggest an open deltaic depositional environment that changes upward, after a marked omission surface, to restricted coastal marine deposits (Poiré, *et al*., 2002, 2017; Passalia *et al*., 2019). Palynologic studies for the upper part of the Piedra Clavada Formation point to an Albian age (Archangelsky *et al*., 2008), while an U-Pb age of this unit, taken from zircons of two tuffs levels from the upper part, ranges around 100-101 Ma (latest Albian) (Poiré *et al*., 2017).

Late Cretaceous Foreland Basin: the first stage of Andean growth

During the beginning of the foreland stage at about the Albian-Cenomanian boundary (~100 Ma; Fig. 2), the northern Austral-Magallanes Basin was compartmentalized into two main depocenters: 1) the main foredeep depocenter with a central axis oriented N-S from El Chaltén (Argentina) to Última Esperanza Region (Chile); and 2) the southwest-northeast oriented Cardiel-Tres Lagos depocenter (Varela *et al*., 2019), both separated by the Piedra Clavada High (Varela *et al*., 2019).

The foredeep main depocenter shows a regressive pattern and a clear subsidence asymmetry along the north-south axis. It grades from a deep-marine setting (underfilled) in the south, to a continental setting (overfilled) in the north, due to the differences in the flexural rigidity of the crust product of the predecessor basin history (Biddle *et al*., 1986; Romans *et al*., 2010; Sickmann *et al*., 2018). From south to north, the onset of the foreland stage was recorded in the foredeep main depocenter by i) deep-marine deposits of the Punta Barrosa Formation (Fildani *et al*., 2003, 2009; Malkowski *et al*., 2017a,b; Daniels *et al*., 2019), accumulated in largely unconfined submarine fan systems until the Turonian (~90 My); ii) shallow marine deposits of the Lago Viedma Formation (Malkowski *et al*., 2016, 2017a, b) and, iii) estuarine-continental deposits of the Puesto El Moro Formation (Fig. 2) (Varela *et al*., 2019). The Punta Barrosa Formation is correlated with the subsurface Arroyo Alfa and Middle Inoceramus formations in Tierra del Fuego (González Estebenet *et al*., 2019).

Towards the east of the foredeep, the onset of the foreland stage in the Cardiel-Tres Lagos depocenter corresponds to the estuarine-continental deposits of the Mata Amarilla Formation (Varela *et al*., 2011; 2012a; 2012b; 2013; 2015; 2016; 2018; 2019) and to a lesser extent to the La Anita Formation (Fig. 2).

The progress of Andean convergence and the development of the Patagonian fold and thrust belt resulted in eastward migration of the foredeep, as well as narrowing and deepening of the basin depocenter (Fosdick *et al*., 2011; Romans *et al*., 2011). The depositional response to this change is reflected by the thick turbiditic deposits of the Cerro Toro Formation in Chile and Argentina, accumulated during the Coniacian up to Campanian (Fig. 2) (Cecioni, 1957; Arbe and Hechem, 1984; Hubbard *et al*., 2008; Romans *et al*., 2011; Ghiglione *et al*., 2014; Malkowski *et al*., 2018). During the middle to late Campanian, deposition in the southern part of the foredeep depocenter is recorded in the subsurface as the Cabeza de León and Upper Inoceramus formations (González Estebenet *et al*., 2019). Towards the north, synchronous deposition is documented by the sandstone and siltstone deposits associated with north-to-south prograding deep-water slope clinoform systems preserved in the Tres Pasos and Alta Vista formations in Chile and Argentina, respectively (Macellari *et al*., 1989; Shultz and Hubbard, 2005; Hubbard *et al*., 2010; Ghiglione *et al*., 2014; Sickmann *et al*., 2018). These deep-water units are genetically related with Campanian to Maastrichtian shelf, marginal marine, and deltaic deposits of the Dorotea Formation in Chile (Covault *et al*., 2009; Schwartz and Graham, 2015; Gutiérrez *et al*., 2017), as well as with the lower unit of the La Anita Formation in Argentina (Manassero, 1988; Macellari *et al*., 1989; Moyano Paz *et al*., 2018). The uppermost Campanian to Maastrichtian interval is recorded in the Lago Argentino region by the upper unit of the La Anita Formation and by the fluvial deposits grouped in the Upper Cretaceous Continental Deposits (UCCD) which includes the Cerro Fortaleza, La Irene and Chorrillo formations in Argentina (Moyano Paz *et al*., 2018; Tettamanti *et al.*, 2018; Sickmann *et al.*, 2018, 2019). Finally, Maastricthian deposits of the Calafate Formation representing a new transgressive event are well exposed at the south margin of Lago Argentino (Odino Barreto *et al.*, 2018). These Campanian-Maastrichtian units are interpreted to record the final phase of Cretaceous infilling which onlap the entire Austral-Magallanes Basin integrating all depocenters (Hubbard *et al.*, 2010; Romans *et al.*, 2011; Moyano Paz *et al.*, 2018). The Late Cretaceous sedimentation is interrupted by a regional unconformity over which the Cenozoic sedimentation stage begins (Fosdick *et al.*, 2015; George *et al.*, 2019; among others).

Cenozoic Foreland Basin: the influence of the modern Andes

The Cenozoic sedimentary record of the central-northern Austral-Magallanes Basin is marked by unconformities as well as thick successions of shallow marine to terrestrial clastic deposits, which are intimately associated to the tectonic evolution of the adjacent Southern Patagonian Andes (*e.g.* Fosdick *et al.*, 2011). Most of the stratigraphic and sedimentologic knowledge for this period is based on observations on the western outcrops of the fold and thrust belt along the foothills of the Andes, from Lago Buenos Aires in the north, to the Río Turbio-Última Esperanza Region in the south (Fig. 1). Although not the focus of this paper, the Tierra del Fuego Cenozoic record shows a remarkable different stratigraphic arrangement, being dominated by deep marine deposits (*e.g.* Ponce *et al.*, 2008).

The Cenozoic history of the Austral-Magallanes Basin begins with an important hiatus known as the “Paleocene unconformity” (Fig. 2), a non-depositional/erosional event recognized at the top of the Maastrichtian-early Paleocene shallow marine/deltaic deposits of the Calafate (Marenssi *et al.*, 2004; Odino Barreto *et al.*, 2018) and Dorotea (Schwartz and Graham, 2015) formations. This unconformity comprises a time lapse of at least 20 my (Fosdick *et al.*, 2015; Gutiérrez *et al.*, 2017; George *et al.*, 2019). Towards the northern part of the basin, this Paleogene gap is more evident since nearly no Paleogene clastic deposits are recognized. In this northern region, the Eocene Posadas Basalt is widespread, intercalated between the Aptian Río Tarde Formation (Ghiglione *et al.*, 2015) and the Miocene El Chacay Formation (Cuitiño *et al.*, 2015) (Fig. 2). In restricted areas of the northern part, thin Eocene fluvial coal-bearing deposits of the Ligorio Márquez (Encinas *et al.*, 2018) and Río Lista (Escosteguy *et al.*, 2017) formations are present.

The Paleocene unconformity is covered by shallow marine to estuarine deposits of the mid-Eocene Man Aike Formation (Casadío *et al.*, 2009; Gutiérrez *et al.*, 2017), interpreted to represent the infill of incised valleys (Marenssi *et al.*, 2002). Towards the Última Esperanza region (*i.e.* closer to the basin depocenter), the Paleogene sedimentary record is represented by either the Eocene Man Aike Formation (Gutierrez *et al.*, 2017), and the equivalent shallow marine to fluvial coal bearing Río Turbio Formation (Fig. 2) (Malumián *et al.*, 2000; Pearson *et al.*, 2012). The Río Turbio Formation is up to 600 m thick (Malumián *et al.*, 2000) and its upper part yielded a zircon MDA of 28 My (Fosdick *et al.*, 2015).

Above the Río Turbio/Man Aike deposits is a 400 m-thick succession of fluvial conglomerates, sandstones and mudstones rich in plant remains, represented by the Río Guillermo and Río Leona formations (Malumián *et al.*, 2000; Marenssi *et al.*, 2005; Panti, 2011). These fluvial deposits wedge-out towards the northern part of the basin. Their age was estimated as Eocene or Oligocene (Malumián *et al.*, 2000), however a maximum zircon depositional age of 32.8 My (Gutierrez *et al.*, 2017) was obtained for the base of the Río Leona Formation, whereas a tuff at the base of the Río Guillermo Formation is dated at 21.7 My (Fosdick *et al.*, 2011). In Addition, based on fossil leaves analysis, Panti (2011) suggested ages younger than previously thought. These new age assignments imply that most of the post-Río Turbio sedimentary record was accumulated during the Neogene, and that there exists other stratigraphic gaps in the Paleogene. Additional work on geochronology and physical stratigraphy of the Río Turbio region is needed in order to solve this issue.

In contrast to the Paleogene, the Neogene stratigraphic record of the Austral-Magallanes Basin is widespread, laterally and vertically continuous, and shows an elevated amount of fine-grained pyroclastic sediments. Additionally, the chronology of its accumulation is relatively well constrained. Two main depositional units are defined: the early Miocene shallow marine deposits assigned to the Patagoniense transgression; and the early-mid Miocene terrestrial deposits of the Santa Cruz Formation and equivalent units (Fig. 2). The former represents one of the largest transgressions occurred in Patagonia, and in the Austral-Magallanes Basin is represented by several lithostratigraphic units deposited in shallow marine, estuarine and deltaic sedimentation (Cuitiño and Scasso, 2010; Cuitiño *et al.*, 2015; Parras and Cuitiño, 2018). These shallow marine deposits grade upward to fluvial deposits that represent a huge fluvial system comprising nearly the entire basin, which drained from the Andes to the Atlantic Ocean. It is mostly composed of fine-grained, flood-plain dominated deposits with poorly developed paleosols (Raigemborn *et al.*, 2018; Cuitiño *et al.*, 2019). Particularly in the Andean foothills, these deposits form a 1000 m thick coarsening upward succession which is thought to be the consequence of the progressive Miocene Andean uplift and eastward migration of the deformation front (Aramendía *et al.*, 2019).

The Miocene succession is truncated by a regional erosional surface that separate from the late Miocene-Quaternary terrace conglomerates, informally known as the Rodados Patagónicos. This unconformity marks the beginning of bypass and erosional processes in the foreland of the Austral-Magallanes Basin, and it is thought to represent uplifting processes in the foreland region of the Andes (Ghiglione *et al.*, 2016).

FUTURE DEVELOPMENTS AND CHALLENGES

After the initial sequence stratigraphic proposals for the whole basin (*e.g.* Biddle *et al.*, 1986; Arbe, 1986), a large amount of new data has been produced both by academy and industry. This represents an opportunity to refine the sequence stratigraphic models and to integrate data sets with different approaches and from different regions of the basin. Of particular interest are the integration of outcrop and subsurface data sets, the petrographic and zircon provenance analyses, the geochronologic calibration of stratigraphic successions and the new detailed facies analyses. Following this idea of integration, source to sink analyses may be of great conceptual relevance in order to link the geodynamic context with the stratigraphic arrangement at several scales. Some questions arise from this analysis, such us how connected were the different depocenters during the basin history? How much of the sediment production is derived from the Andes? What is the relevance of the Deseado Massif-Río Chico High in this context? Can the offshore Malvinas Basin be regarded as the same basin?

The Austral-Magallanes Basin shows excellent and abundant outcrops of sedimentary rocks of very different nature, some of them partly studied and others virtually unknown. This basin is framed by magnificent landscapes in a high latitude part of the world, close to Antarctica. Its complex geologic history was strongly influenced by the tectonic activity associated to several plate boundaries and many relevant geodynamic issues are still to solve. All these features make this basin a great opportunity to develop new exciting geologic, stratigraphic and sedimentologic research.

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