Latin American Journal of Sedimentology and Basin Analysis

ISSN 1851-4979
Published by the Asociación Argentina de Sedimentología

ACCEPTED MANUSCRIPT

Cenozoic stratigraphy of the Golfo San Jorge Basin (Argentina): an integrated record of tectonic, climatic, and eustatic controls on basin evolution

Nicolás Foix, José M. Paredes, Francisco E. Oporto Romero, José O. Allard

Received date: March 4, 2025
Accepted date: June 4, 2025
Available online: June 15, 2025

Handling Editor: José I. Cuitiño

Please cite this article as

Foix, N., Paredes, J.M., Oporto Romero, F.E., Allard, J.O. Cenozoic stratigraphy of the Golfo San Jorge Basin (Argentina): an integrated record of tectonic, climatic, and eustatic controls on basin evolution (in press). *Latin American Journal of Sedimentology and Basin Analysis*.

Cenozoic stratigraphy of the Golfo San Jorge Basin (Argentina): an integrated record of tectonic, climatic, and eustatic controls on basin evolution

Foix N.[1,2], Paredes J. M.[1], Oporto Romero F. E.[1,3], Allard J. O.[1]

1 – Departamento de Geología, Facultad de Ciencias Naturales y Ciencias de la Salud (FCNyCS), Universidad Nacional de la Patagonia "San Juan Bosco". Ruta Prov. N° 1 S/N, Km 4 (9005), Comodoro Rivadavia, Chubut, Argentina.

2 – Instituto Multidisciplinario para la Investigación y el Desarrollo Productivo y Social de la Cuenca Golfo San Jorge (IIDEPyS-GSJ, CONICET-UNPSJB), Comodoro Rivadavia, Chubut, Argentina.

3 – CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas), Argentina.

* *Corresponding author*: nicofoix@hotmail.com

ABSTRACT

The Golfo San Jorge Basin (GSJB) preserves the thickest Cenozoic stratigraphic record in extra-Andean Patagonia (Argentina), reaching approximately 1500 meters. This record was subdivided into three major second-order transgressive-regressive (TST-RST) sedimentary sequences: (1) The early Paleogene T-R cycle (~ 600 m thick; early Paleocene–late Eocene), comprising the Salamanca Formation (marine), Río Chico Group (fluvial), and part of Sarmiento Formation (pyroclastic loess). This sequence reflects a marine-to-continental transition, with an early marine stage marked by tidally-influenced, shallow-marine and inner-shelf sedimentation, followed by fluvial systems and long-lived accumulation and reworking of fine ash in a low-gradient continental setting. (2) The late Paleogene-early Neogene T-R cycle (~ 200 m thick, late Eocene-early Miocene), composed of the El Huemul Formation (marine) and the upper part of Sarmiento Formation (pyroclastic deposits). (3) The Neogene T-R cycle (~ 700 m thick; early–middle Miocene), includes the Chenque Formation (marine) and the Santa Cruz or Escalante Formation (fluvial-eolian). The three marine second-order TSTs share similar temporal duration (<5 million years) and sedimentation patterns are strongly influenced by continental slope inheritance. However, the continental second-order RSTs differ significantly: (i) the early Paleogene RST lasted ∼ 22 million years, compared with the ∼ 10 million years of the late Paleogene-early Neogene cycle and the ∼ 5 million years of the Neogene; (ii) the Paleogene records extensive global climatic fluctuations, whereas the Neogene is characterized by a single wet to dry cycle; (iii) pyroclastic deposits dominate the early Paleogene and late Paleogene-early Neogene sequences, but they are nearly absent in the Neogene; (iv) the first two second order continental cycles preserves an exceptional assemblage of continental mammal faunas, serving as a biostratigraphic reference for South America. Although the GSJB's macrostratigraphy correlates strongly with regional sea-level fluctuations, additional controlling factors have been proposed, including extensional tectonic reactivations, Andean orogenic uplift, intrusion-related tectonic loading, sustained pyroclastic input, climatic variability, and dynamic topography.

Keywords: second-order T-R sequences, Atlantic, Paleogene, Neogene, extra-Andean, Patagonia.

INTRODUCTION

The eastern paleoslope of Patagonia originated approximately 100 million years ago, shaped by a combination of regional uplifts and extensional subsidence. Much of the Cenozoic extra-Andean stratigraphic record in Patagonia commenced when sedimentary systems established a connection with the Atlantic Ocean, marking the termination of Cretaceous continental sedimentation in extensive endorheic basins such as those preserving the Chubut Group deposits in the Golfo San Jorge Basin (GSJB). This first-order paleogeographic transformation, occurring near the Cretaceous–Paleogene (K–Pg) boundary, introduced sea-level changes as a new allocyclic control, fundamentally influencing the stratigraphic evolution and linking extra-Andean sedimentary sequences throughout the Cenozoic (Legarreta *et al.*, 1990).

The GSJB (Fig. 1a) encompasses a Cenozoic stratigraphic succession comprising thirteen marine and continental sequences (1–10 Ma), each bounded by discontinuities associated with sea-level fluctuations (Legarreta and Uliana, 1994). The basin preserves a calibrated Paleogene record of continental mammal faunas, providing a biostratigraphic reference framework for South America (Woodburne *et al.*, 2014). Spanning ~ 150,000 km² and extending ~ 500 km along a W–E orientation (71°–65° W), the GSJB's large dimensions rendered it susceptible to the combined influences of Andean orogenic activity and Atlantic marine processes.

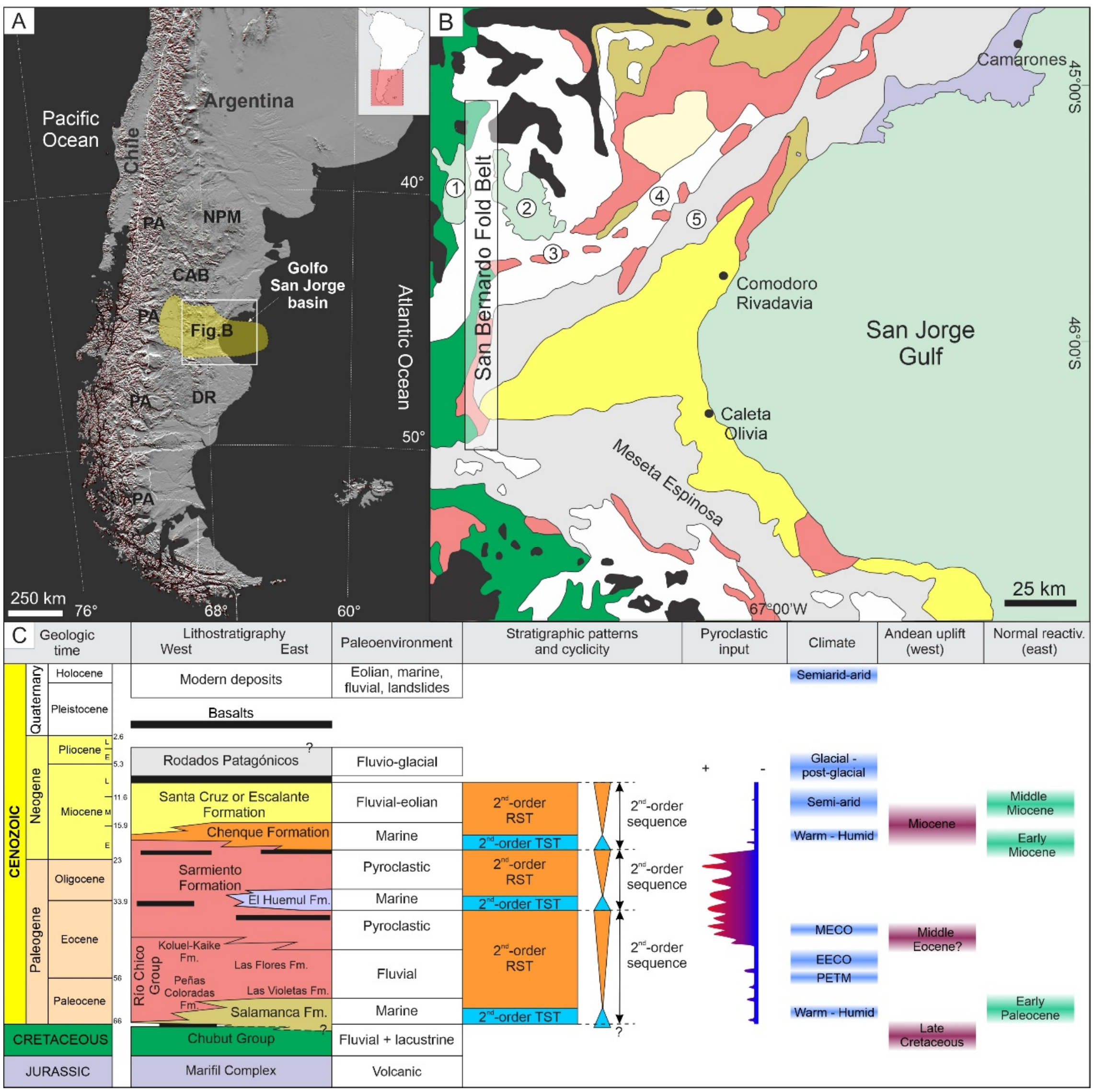

Figure 1. a) Location of the Golfo San Jorge Basin. NPM: Northpatagonian Massif, CAB: Cañadón Asfalto Basin, DR: Deseado Region, PA: Patagonian Andes. **b)** Map highlighting the outcrops of Cenozoic rocks. Keys: 1) Musters Lake, 2) Colhué Huapi Lake, 3) Gran Barranca, 4) Chico River, 5) Pampa del Castillo/Salamanca. **c)** Cenozoic chronostratigraphic scheme, including stratigraphic patterns and sequences, estimated curve of pyroclastic input and main tectonic activity. After Legarreta *et al*. (1990), Bellosi and Jalfin (1996), Paredes *et al*. (2006, 2008, 2015), Raigemborn *et al*. (2010), Bellosi (2010a,b), Foix *et al*. (2012, 2021), Bellosi and Krause (2014), Clyde *et al.* (2014), Cuitiño *et al*. (2015), Krause *et al.* (2017), Plazibat *et al*. (2019), Allard *et al*. (2020), Bilmes *et al.* (2021), Oporto Romero *et al*. (2023, 2024a). Key: EH Fm.: El Huemul Formation, TST: second-order Transgressive System Tracts, RST: second-order Regressive System Tracts, PETM: Paleocene-Eocene Thermal Maximum, EECO: Early Eocene Climatic Optimum, MECO: Middle Eocene Climatic Optimum.

As observed during the Cretaceous, the basin received substantial Andean-sourced Cenozoic volcaniclastic input, significantly modifying its stratigraphy. Throughout the Cenozoic, the generation of accommodation space within the GSJB exhibited spatiotemporal complexities, transitioning from a post-rift phase—linked to the break-up of Gondwana—to periods dominated by the uplift of the Northpatagonian Andes and the extra-Andean broken foreland. These processes were further modulated by sea-level variations, climatic shifts, and dynamic topography (Foix *et al*., 2021).

This study synthesizes the Cenozoic stratigraphic evolution of the GSJB, offering critical insights into the interaction between internal tectonic dynamics and external geodynamic controls, as recorded within the sedimentary succession.

STRATIGRAPHIC MACROARCHITECTURE

The Cenozoic record of the GSJB has multiple lithostratigraphic equivalents across various Patagonian geological regions, including the North Patagonian Massif, Cañadón Asfalto Basin, Patagonian Andes, and Deseado Region. The most significant outcrop exposures occur along the coastal region north of Comodoro Rivadavia and on the slopes of Pampa del Castillo/Salamanca, the Chico River, and the Gran Barranca (Fig. 1b).

The stratigraphic macroarchitecture of the GSJB consists of marine and continental sedimentary successions, several hundred meters thick, > 10 Ma duration, which are interpreted as three second-order sequences (*sensu* Catuneanu *et al*., 2009) with a transgressive-regressive (TST-RST) depositional architecture (*sensu* Embry, 2009) (Fig. 1c): (i) an early Paleogene T-R cycle that represents the first Atlantic marine incursion into the basin, recorded in the Salamanca Formation, followed by epiclastic (Río Chico Group) and pyroclastic (Sarmiento Formation) continental deposits; this second-order cycle reaches up to 600 meters in thickness (TST ~ 250 m; RST ~ 350 m) and spans from the early Paleocene to the late Eocene. (ii) A late Paleogene-early Neogene T-R cycle, that includes the second Atlantic marine transgression, only preserved in the subsurface of the southeastern part of the basin (El Huemul Formation, Paredes *et al*., 2015), and the youngest deposits of the Sarmiento Formation; this second order sequence is up to 200 m thick (TST ~ 110 m; RST ~ 90 m) and extends from the late Eocene to early Miocene. (iii) A Neogene T-R cycle, that begins with the third regional Atlantic transgression, represented by the Chenque Formation, followed by a regressive fluvial-eolian continental succession (Santa Cruz/Escalante Formation); this sequence attains a thickness of up to 700 meters (TST ~ 450 m; RST ~ 250 m) and extends from early to middle Miocene (Fig. 1c).

The Cenozoic record also includes frequent alkaline intrusive/extrusive rocks (Plazibat *et al*., 2019; Navarrete, this issue) and widely distributed Late Miocene-Pliocene? fluvio-glacial deposits (Bilmes *et al*., 2021) (Fig. 1c).

Paleogene T-R Cycle (early Paleocene-late Eocene)

The deposits of the Salamanca Formation represent the initial transgression within the GSJB (second-order TST) (Fig. 1c), which overlies a near-flat to irregular ravinement surface developed on the Cretaceous Chubut Group (Fig. 2a). The informal members originally defined by Feruglio (1949) are readily identifiable in both outcrops and subsurface records (Fig. 2b). These members include, in ascending order, the Glauconítico Member (estuarine to shallow-marine deposits), Fragmentosa Member (inner-shelf deposits), Banco Verde Member (shallow-marine deposits), and

Banco Negro Inferior Member (swamp deposits). The Salamanca Formation reaches a maximum thickness of 300 meters at the center of the basin (Sciutto *et al*., 2000), gradually thinning westward until it completely pinches out on the eastern margin of the San Bernardo Fold Belt (SBFB) (Fig. 2c). The stratigraphic architecture of the Salamanca Formation can be simplified into two primary subcycles (Fig. 2b), each representing distinct paleoenvironments (Figs. 2d–g): (i) transgressive stage, characterized by estuarine-coastal sandy deposits, transitioning upward into inner-shelf deposits, indicating a progressive marine transgression, and (ii) a regressive stage, marked by an upward change from inner-shelf, shallow-marine, fluvial-deltaic, swamp, and minor evaporite deposits, reflecting a retreating sea and the reestablishment of continental conditions. Additionally, the identification of 170 synsedimentary mesoscopic normal faults and seismites within the Salamanca Formation has enabled the characterization of an early Paleocene extensional tectonic event in the northeastern sector of the basin (Foix *et al*., 2012).

Beyond the Cretaceous continental sedimentation zone, the marine deposits of the Salamanca Formation typically start with a basal bioclastic member (Bustamante Member, Andreis *et al*., 1975). While paleontological evidence from outcrops indicates a Danian age (Náñez and Malumián, 2008; Clyde *et al*., 2014), subsurface oilfield data suggest Maastrichtian ages (Barcat *et al*., 1989). The fossil assemblage of the Salamanca Formation is diverse, comprising marine invertebrates, microfossils, macroflora, pollen/spores, crocodilians, and turtles, with a notable record of terrestrial mammals from the Banco Negro Inferior (Woodburne *et al*., 2014).

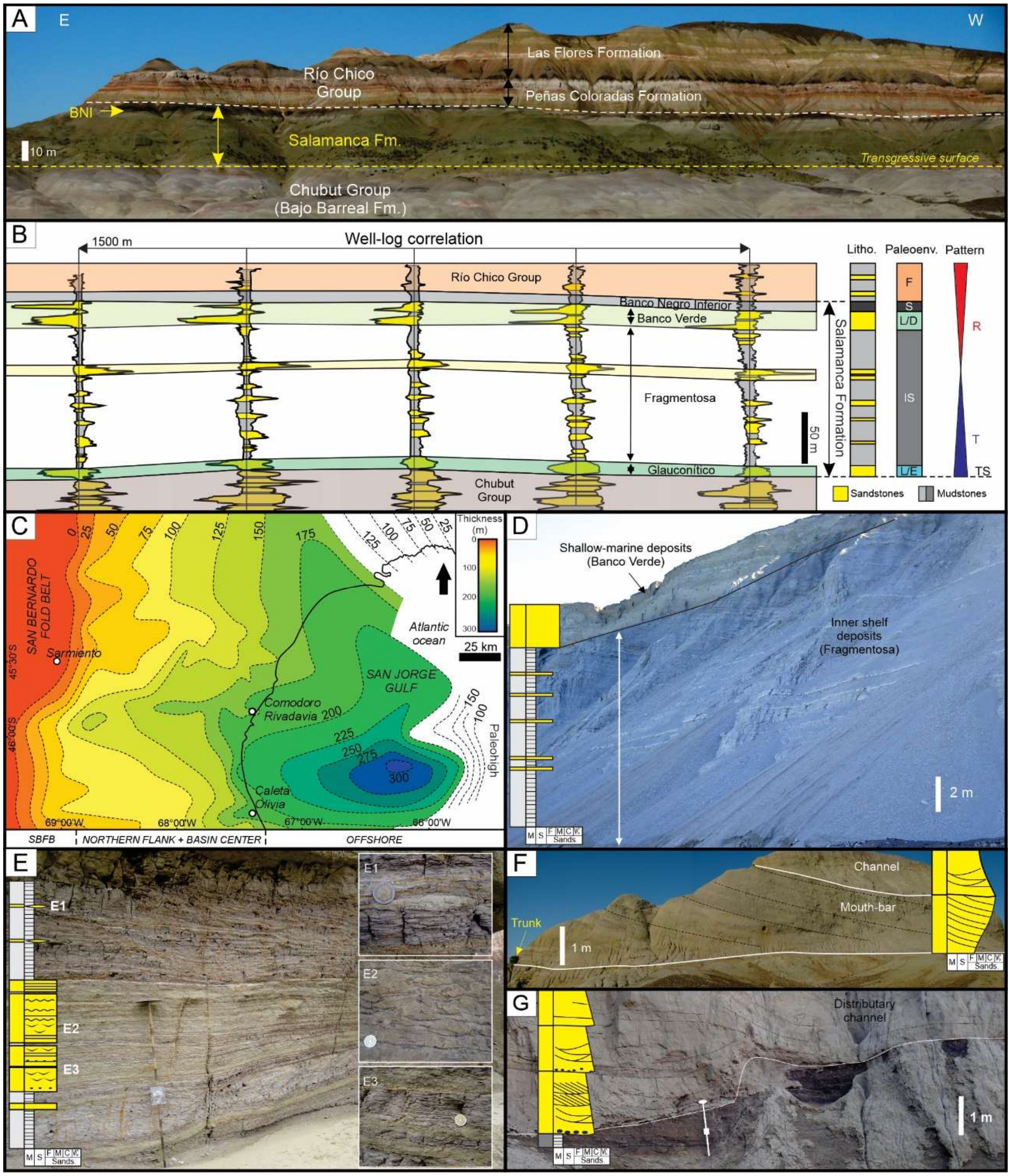

Figure 2. Marine Paleocene record. **a)** Green-colored, Salamanca Formation covering the Chubut Group on a transgressive surface, Sarmiento petrified forest (Abigarrado hill). **b)** Well-log correlation in the Northern Flank of the basin, showing the main stratigraphic intervals (L: littoral, E: estuarine, IS: inner-shelf, L/D: littoral-deltaic, S: Swamp, F: fluvial, TS: transgressive surface, T: transgression, R: regression). Modified from Foix (2009). **c)** Isopach map of the Salamaca Formation from outcrop and subsurface data (modified from Sciutto *et al.*, 2000). **d)** Inner-shelf (Fragmentosa) and shallow-marine (Banco Verde) deposits, north of Puerto Visser (taken from Foix *et al.*, 2021). **e)** Tide-influenced

deposits (lenticular, flaser, and heterolithic stratification). **f)** Channel-bar deposits of tide-influenced/dominated delta-front environment. **g)** Deltaic channels. **e-g**: Sarmiento petrified forest (taken from Foix *et al*., 2021).

Following the regional regressive stage (second-order RST), the basin experienced the deposition of 180–200 m-thick, predominantly reddish epiclastic continental deposits of the Río Chico Group (Fig. 1c) since the latest Danian to late Lutetian (~ 20.3 million of years, Krause *et al*., 2017) (Figs. 3a-g). This group consists of four formations (Raigemborn *et al*., 2010): Las Violetas Formation (Fig. 3a), Peñas Coloradas Formation (Fig. 3b), Las Flores Formation (Fig. 3c), and Koluel-Kaike Formation (Fig. 3d). Sedimentation within the Río Chico Group is predominantly fluvial (Raigemborn *et al*., 2010), with the Koluel-Kaike Formation featuring lateritized tephric paleosols formed under greenhouse climatic conditions (Krause *et al*., 2010). Fluvial deposits include low-sinuosity, meandering and braided channels, sheet-flood and proximal/distal floodplain deposits (Foix *et al*., 2013). Paleocurrent measurements from the northeastern portion of the basin indicate a SE paleodrainage direction. The Río Chico Group displays spatiotemporal variations in thickness, stacking patterns, geometry, and fluvial styles, associated with temporo-spatial changes in the accommodation space (Foix *et al*., 2013) (Fig. 3e). Extending from the Late Danian to the Middle Eocene (Krause *et al*., 2017), the Río Chico Group contains mammalian fossils grouped into three faunistic zones: Carodnia, Kibenikhoria, and Ernestokokenia (Legarreta and Uliana, 1994).

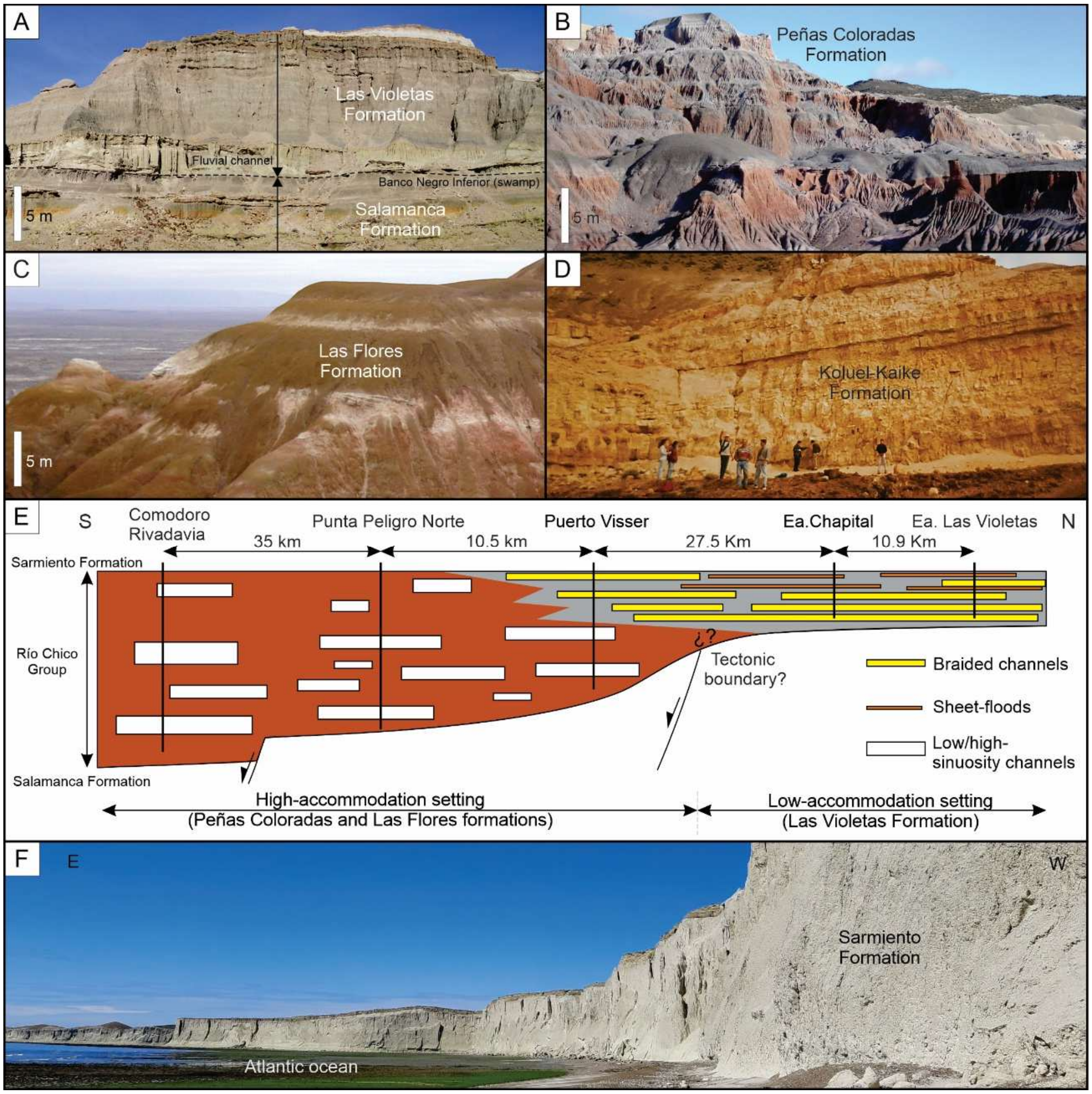

Figure 3. Continental Paleogene record. **a)** Las Violetas Formation at its type locality. **b)** Peñas Coloradas Formation, petrified forest near Punta Peligro Norte. **c)** Las Flores Formation, Sarmiento petrified forest. **d)** Koluel-Kaike Formation, national route N° 26 (km 170). **e)** Spatio-temporal variations in the macro-architecture of the Río Chico Group (modified from Foix *et al*., 2013). **f)** Whitish tuffaceous deposits of the Sarmiento Formation, Solano Bay.

The overlying Sarmiento Formation reflects the delivery of large volumes of pyroclastic materials derived from explosive volcanic activity in the Andes for up to 20 million years (Fig. 1c), which profoundly altered the continental sedimentation style (Fig. 3f). The Sarmiento Formation is primarily composed of grayish-white tuffs and reworked tuffs in a low gradient, continental setting, with a thickness reaching up to 170 meters in Gran Barranca (Bellosi, 2010a). This unit lies transitionally or in angular unconformity over the Río Chico Group.

Intraplate volcanism coeval with the deposition of the Sarmiento Formation is evidenced by shallow intrusives, basaltic lava flows, and volcaniclastic deposits associated with Strombolian events (Fig. 1c) (Paredes *et al*., 2008; Plazibat *et al*., 2019). Based on the hierarchy of internal bounding surfaces, it has been divided in ascending order, into six members (Bellosi, 2010a,b): Gran Barranca, Rosado, Lower Puesto Almendra, Vera, Upper Puesto Almendra, and Colhué-Huapi.

The development of tephric loess sedimentation and paleosols within the Sarmiento Formation offers critical insights into paleoenvironmental and climatic changes across Middle Cenozoic Patagonia, particularly regarding global cooling since the Middle Eocene (Bellosi and Krause, 2014). The formation's rich continental mammal fauna (e.g., Notostylops, Astraponotus, Phyrotherium, Colpodon) has been instrumental in defining several South American Land Mammal Ages (SALMAs), including the Casamayoran and Mustersan in this RST. From the Middle Eocene to the Early Miocene, the Sarmiento Formation represents the longest-lived Cenozoic formation within the GSJB.

The Río Chico Group and the overlying Gran Barranca Member of the Sarmiento Formation have been further subdivided into four stratigraphic sequences, each composed of high- and low-accommodation system tracts (Raigemborn and Beilinson, 2020).

Late Paleogene – early Neogene T-R Cycle (late Eocene-early Miocene)

Partially synchronous with the Sarmiento Formation, a late Eocene to early Oligocene, 80–110 m-thick, transgressive-regressive (T-R) marine cycle—referred to as the El Huemul Formation (Fig. 1c)—has been only identified in the subsurface of the Southern Flank of the GSJB over an area up to 3500 km^2 (Paredes *et al*., 2015). The El Huemul Formation comprises of a thin lag of glauconitic sandstones, followed by a mudstone-dominated succession that coarsening-upward to sandstones, evidencing a complete T-R cycle (Paredes *et al*., 2015). The second order sequence is completed with the late Eocene-early Miocene continental deposits of the Sarmiento Formation (e.g., Deseadan and Colhehuapian), probably correlatable with the Pinturas Formation, Santa Cruz Province (Kramarz and Bond, 2005).

Neogene T-R Cycle (Miocene)

The third regional Atlantic transgression (second-order TST) in the GSJB is represented by the Chenque Formation (Fig. 1c), which reaches thicknesses of up to 450 meters (Bellosi, 1990). This formation primarily comprises inner-shelf and shallow marine deposits evidencing tide- (Carmona et al., 2009) and storm-dominated delta environments with distinctive bioclastic levels (Cuitiño *et al*., 2015). The marine record of the Chenque Formation can be subdivided into four to five third-order sequences (Bellosi, 1990; Paredes, 2002), each composed of transgressive and highstand systems tracts, corresponding to the previously described "Patagonian" and "Superpatagonian" units (Fig. 4a–e).

The vertical facies succession is marked by decameter-thick, regressive prodelta to delta-front cycles, which display shallowing-upward patterns and are frequently interrupted by storm-related deposits (Paredes *et al*., 2024). The Chenque Formation hosts a diverse fossil assemblage, including invertebrates, palynomorphs, vertebrates, and exceptionally preserved ichnofaunas (Carmona *et al*., 2008). Besides, previous research in angiosperm pollen and dinocysts assemblages of the Chenque Formation and regional climatic reconstructions indicate the occurrence of a Mid-Miocene Climatic Optimum from 16-14.5 Ma (Foix *et al*., 2021), a timelapse associated with "Superpatagonian" deposits (Fig. 4b).

In the subsurface of the San Bernardo Fold Belt, Paredes *et al*. (2006) recognized episodes of Miocene tectonic uplift during the sedimentation of the Chenque Formation (350 m thick), including a tectonically-induced forced regression. Additionally, the identification of 276 synsedimentary mesoscopic normal faults within this unit has provided key evidence for extensional tectonic conditions during the Early and Middle Miocene in the eastern sector of the GSJB (Oporto Romero *et al.*, 2023).

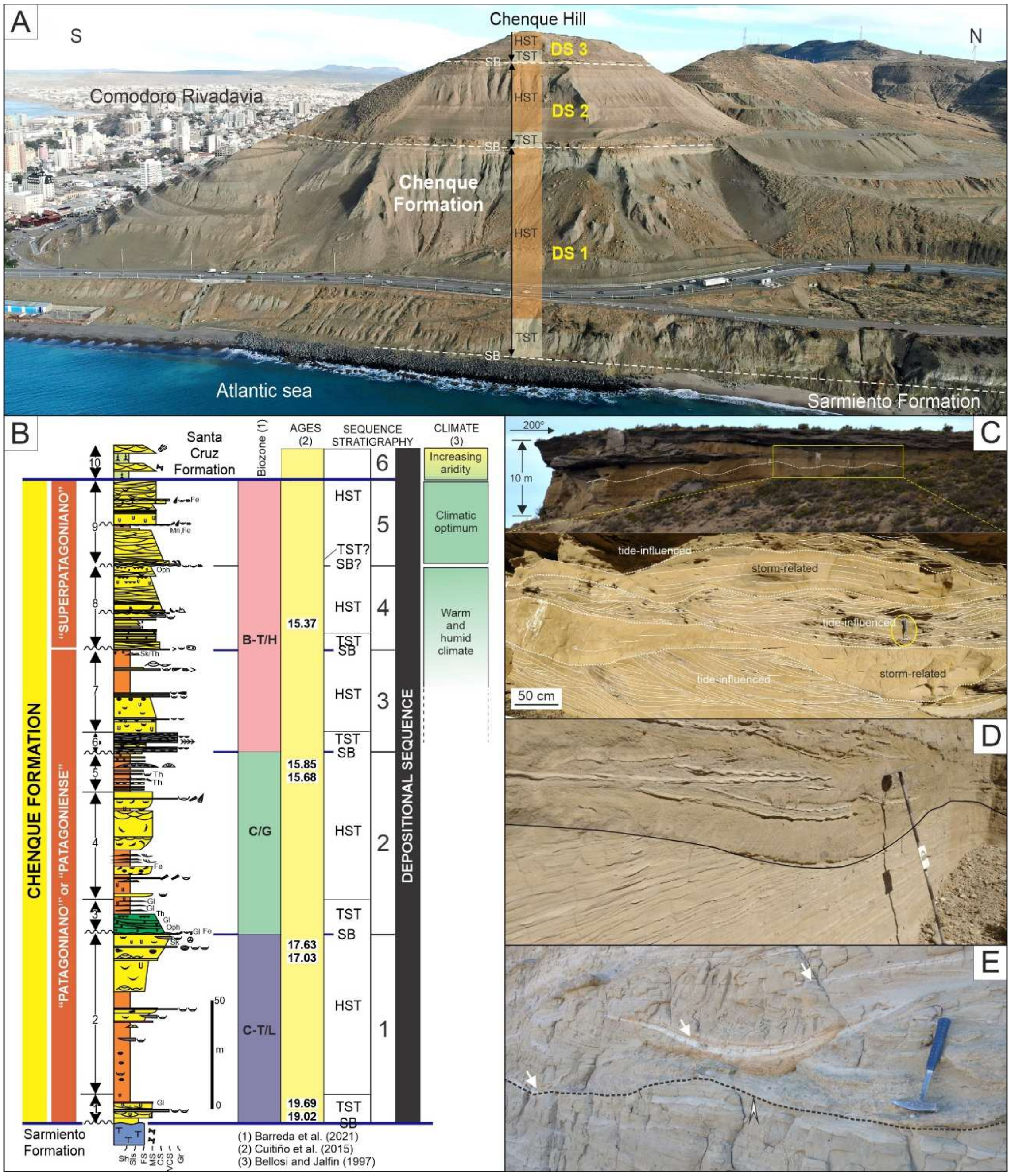

Figure 4. Chenque Formation. **a)** Panoramic view of the Chenque Hill, showing the position of outcropped sequence boundaries, system tracts and sedimentary sequences. **b)** Stratigraphic log of the Chenque Formation, displaying a sequence stratigraphic analysis, biozones (Barreda *et al.*, 2021), ages (Cuitiño *et al.*, 2015) and climate (Bellosi and Jalfin, 1996). **c)** Alternation of storm-related and tidally-

influenced sedimentary bodies. **d)** Sandstones with flaser bedding at the base, overlain by a tidal channel deposit with mud drapes and the presence of symmetrical ripples on bounding surfaces. **e)** Bioclastic sandstone deposit with an erosive base (dotted line) and a fining-upward trend. Note the silt-clay drapes (white arrows) filling local depressions or the topography of depositional structures during low-energy stages. The Jacob staff measures 150 cm, and the hammer used for scale measures 32 cm.

The middle Miocene continental regressive stage (second-order RST) is represented by transitional deposits (tide-dominated deltas) and fluvial-eolian sedimentation (Figs. 5a–c) of the Santa Cruz Formation (Fig. 1c), recently renamed the Escalante Formation in the GSJB (Sosa *et al.*, 2022), with a maximum thickness ranging about 200 (Bellosi, 1995) and 310 meters (Sosa *et al.*, 2022). This unit includes marine-influenced fluvial channels, tidal flat, eolian dunes (2D and 3D), interdunes (dry, damp, wet interdune lagoon, and progranding lobes), ephemeral fluvial channels, intermittent fluvial channels, perennial fluvial channels (frontal accretion, frontal-lateral accretion, and lateral accretion), proximal and distal floodplain deposits (Oporto Romero and Paredes, 2022; Oporto Romero *et al.*, 2024b).

The Escalante Formation can be subdivided into three depositional systems (Fig. 5d), where each starts with a predominance of perennial river systems (except for the basal section, where deltaic plains and marine-influenced fluvial channels were recognized) developed under more humid conditions that grade to humid aeolian systems under semiarid conditions (Oporto Romero *et al.*, 2024b). The fossil record within this formation is limited and poorly studied, primarily comprising mammalian remains from the Pampa del Castillo area. Additionally, the identification of 102 synsedimentary mesoscopic normal faults and soft-sediment deformation structures (seismites) within this unit has provided evidence for extensional tectonic conditions during the middle Miocene in the northeastern sector of the GSJB (Oporto Romero *et al.*, 2024a).

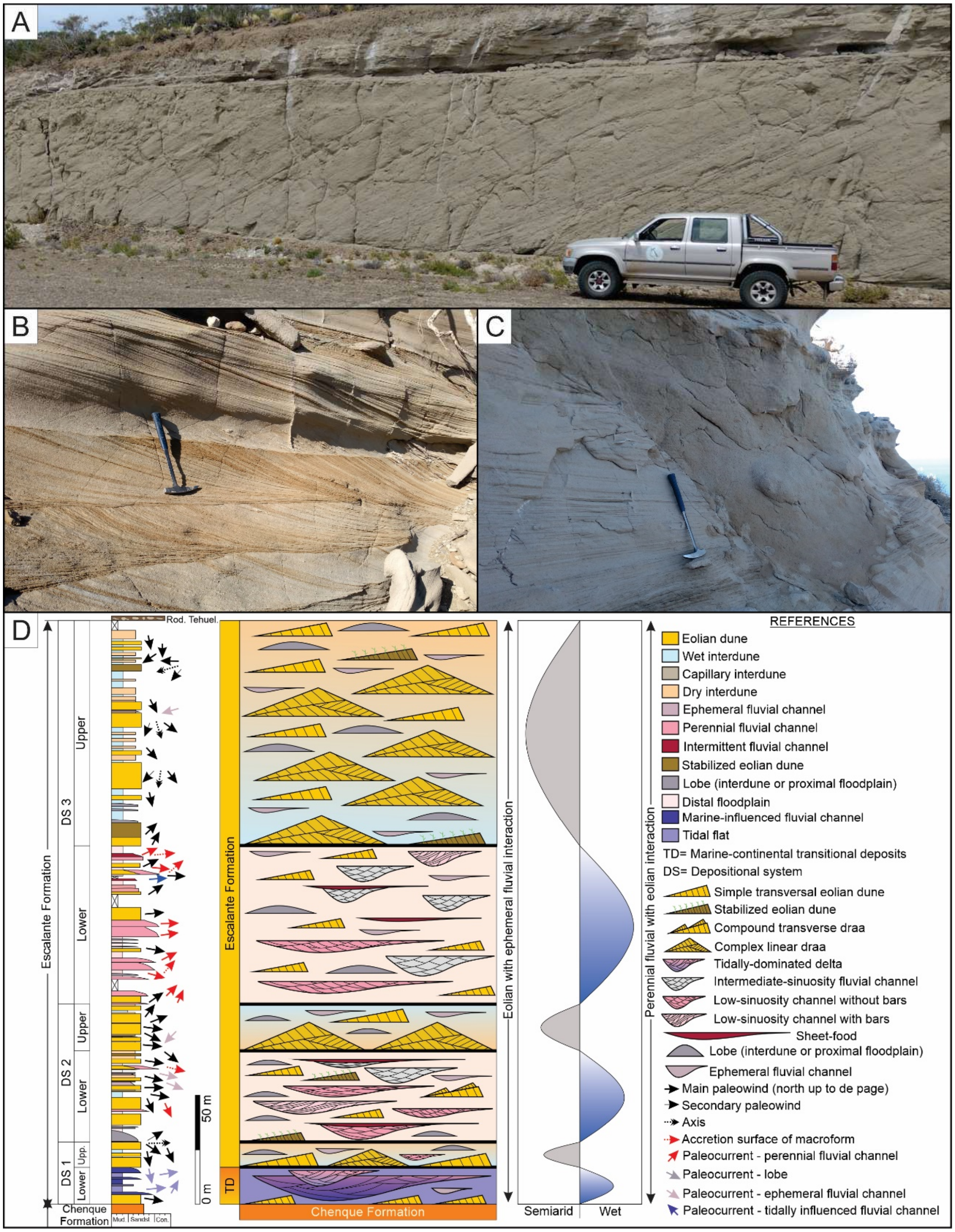

Figure 5. Escalante Formation, formerly referred to as Santa Cruz Formation. **a)** Well-sorted, metric scale, cross-stratified, eolian dune deposits. **b)** The bedset comprises sub-metric (0.3-0.4 m), cross-stratified perennial fluvial sandstones. **c)** Fluvial channel eroding dry interdune deposits. **d)**

Sedimentological log of the Escalante Formation in the El Trébol and El Tordillo oilfields, with main genetic stratigraphic intervals and paleoclimatic inferences (taken from Oporto Romero *et al*., 2024b).

Lying on an erosional unconformity over the Santa Cruz Formation, late Miocene-Pliocene?, fluvio-glacial, up to 20 m thick, gravel sheets were deposited ("Rodados Patagónicos", Fig. 1c), currently crowning tableland reliefs. These widely distributed outwash deposits constituted large sediment transfer systems from the Andes to the Atlantic Ocean through the GSJB (Bilmes *et al*., 2021). The Pleistocene-Holocene record includes a variety of eolian, shallow-marine, fluvial and landslide deposits.

DISCUSSION

The subdivision of the geological record into evolutionary stages allows us to avoid rigid and more subjective lithostratigraphic schemes by incorporating notions such as stratigraphic patterns and cyclicity. We consider that dividing the Cenozoic record into second-order stratigraphic sequences will be useful for contextualizing future studies from an evolutionary perspective. This approach to the stratigraphic macroarchitecture does not seek to reduce the analysis to eustatic control. Instead, it aims to identify regressive-transgressive patterns (which exceed third-order sequences) regardless of their underlying causes.

The presence of Late Maastrichtian continental levels in the GSJB (Lago Colhué Huapi Formation, Chubut Group) allows us to assume the absence of a significant gap between the Chubut Group and the Salamanca Formation; this could mean that the connection to the Atlantic Ocean would be somewhat earlier than the beginning of Cenozoic sedimentation.

Stratigraphically significant surfaces and/or second-order system tracts may or may not coincide with lithostratigraphic boundaries. For example, (a) if the younger fluvial systems of the Chubut Group effectively drained towards the Atlantic Ocean, the initial second-order sequence should also include these late Maastrichtian continental levels, b) the onset of the early Paleogene regression (second-order RST) begins in the upper part of the Salamanca Formation, preceding the arrival of the continental deposits of the Río Chico Group, c) the inclusion of the Miocene marine-continental transitional deposits within the Chenque or Escalante Formation will determine whether the Neogene RST begins in one lithostratigraphic unit or the other.

Periodic marine flooding of the GSJB, extending several hundreds of kilometers west of the shelf-break, forced marine sedimentary systems to develop in a low-gradient setting inherited from continental slopes. This characteristic has amplified tidal effects on marine successions and restricted the deposition of deep-marine systems.

The rate of accommodation creation significantly influences the stratigraphic and paleoenvironmental evolution of sedimentary successions. The analysis of thicknesses and temporal durations indicates non-constant sedimentation rates during the Cenozoic: (i) early Paleocene and Miocene marine stages: 300–450 m thick; ~ 4 Ma duration (0.075–0.112 m/ky), and (ii) early Paleogene continental stage: 350 m thick; ~ 22 Ma duration (0.016 m/ky). Short pulses in accommodation during second-order marine transgressions are attributed to regional sea level rise and/or basin subsidence. Initial interpretations considered the GSJB a passive margin setting, with sedimentation influenced by sea level variations and thermal subsidence (Legarreta *et al.*, 1990; Legarreta and Uliana, 1994). However, Andean and extra-Andean-uplift, initially regarded as exclusively Neogene, are now debated regarding its earlier onset in the late Cretaceous (Allard *et al.*, 2020); this Cretaceous broken foreland structuration conformed an onlapped topographic barrier during the westward displacement of the Paleocene transgression (San Bernardo Fold Belt). During the Miocene, coinciding with the main Northpatagonian Andean uplift, the GSJB host W-E sediment transfer systems from the Andes to the Atlantic shelf (Bilmes *et al.*, 2021). However, synsedimentary normal faulting during early Paleocene (Foix *et al.*, 2012) and Miocene (Oporto Romero *et al.*, 2023) second-order TST further supports tectonic influence on the eastern portion of the basin (Fig. 1c). Sublithospheric processes also would have contributed to marine transgressions through flat subduction zones inducing dynamic subsidence during the late Cretaceous–early Paleocene (Gianni *et* *al.*, 2018), and subduction-induced mantle flow cells caused dynamic subsidence in the late Eocene–middle Miocene (Navarrete *et al.*, 2020). It is necessary to rule out eustatic variations to evaluate the importance of sublithospheric processes in the second-order transgressions, because during the Paleocene major seaways deeply penetrated all continents. The existence of a late Eocene to early Oligocene marine transgression only recorded in the southeastern portion of the basin (El Huemul Formation) implies, for the first time, sufficient latitudinal variations in Cenozoic accommodation to allow the advance of the Atlantic Ocean; in this sense, intrusion-related tectonic loading would explain this more localized behavior (Paredes *et al.*, 2015).

Global climate transitions strongly modulated the internal characteristics and sedimentary environments across the basin (Fig. 1c). In the early Paleogene Cycle, the Peñas Coloradas and Las Flores formations of the Río Chico Group (Paleocene-Eocene transition) show climate changes from temperate, warm, humid and highly seasonal precipitation conditions to subtropical-tropical, more continuous year-round rainfall conditions (Raigemborn *et al.*, 2009), with the early Eocene Climatic Optimum represented in middle-upper sections of the Las Flores Formation (Krause *et al.*, 2017). Besides, the Koluel-Kaike Formation records pedofeatures evidencing seasonal humid to sub-humid or semiarid conditions upward (Krause *et al.*, 2010). In the Neogene Cycle, the final uplift of the Andes favored the development of an orographic barrier to humid winds from the Pacific, leading to efficient orographic rain shadows eastward of the Andes, increasing the aridity during the deposition of the Escalante Formation.

In this overall context, key challenges in understanding the GSJB Cenozoic succession include (i) interdisciplinary collaboration to overcome the focus on isolated topics, (ii) subsurface data integration due to burial under Plio-Quaternary deposits, and (iii) comprehensive basin subsidence studies to clarify the mechanisms driving accommodation space over time.

CONCLUSIONS

The Cenozoic record of the GSJB comprises a succession of marine and continental sequences with an accumulative thickness of up to ~ 1500 m. These deposits are organized into three main second-order transgressive-regressive (T-R) cycles, each spanning several hundred meters thick. The marine stages (second-order TST), represented by the Salamanca, El Huemul and Chenque formations, correspond to brief accommodation pulses. These stages were strongly influenced by inherited slopes, which amplified tidal effects and restricted deep-sea sedimentation.

The early Paleogene continental stage (second-order HST), comprising the Río Chico Group and part of the Sarmiento Formation, reflects a period of extensive fluvial sedimentation under greenhouse climatic conditions. This stage also records significant Andean pyroclastic input over more than 20 million years, modifying sedimentation patterns in a low gradient setting influenced by intraplate volcanic activity. Moreover, the rich mammalian fossil assemblages preserved in these continental formations provide critical insights into the evolution of South American terrestrial ecosystems. Similar continental conditions persist during the late Paleogene-early Neogene continental stage (Deseadan and Colhuehuapian).

In contrast, the continental Neogene stage (second-order RST), represented by the Santa Cruz (or Escalante) Formation, marks a transition to semiarid conditions. This period is characterized by fluvial-eolian sedimentation, reflecting drier climatic regimes and changing depositional environments, linked to orographic rain shadow eastward of the Patagonian Andes.

Acknowledgements. We thank the Departamento de Geología (FCNyCS-UNPSJB) and the IIDEPyS for logistic support. The UNPSJB provided funds through the PI CIUNPAT 1966, directed by JMP. Many thanks to Dr. Juan José Ponce (reviewer) and Dr. José Cuitiño (editor) for the corrections that improved the original version of the manuscript. This paper is dedicated to the memory of our colleague Dr. Miguel Haller (1947-2025).

REFERENCES

Allard, J.O., Foix, N., Bueti, S., Sánchez, F.M., Ferreira, M.L., and Atencio, M. (2020). Comparative structural analysis of outcropped and buried inverted structures in the San Bernardo Fold Belt: evolutionary implications on the Chubut Group tecto-sedimentary context. *Journal of South American Earth Sciences* 97, 102405. https://doi.org/10.1016/j.jsames.2019.102405

Andreis, R.R., Mazzoni, M., and Spalletti, L.A. (1975). Estudio estratigráfico y paleoambiental de las sedimentitas terciarias entre Pico Salamanca y Bahía Bustamante, Provincia del Chubut, República Argentina. *Revista de la Asociación Geológica Argentina* 30, 85–103.

Barcat, C., Cortiñas, J.S., Nevistic, V.A., and Zucchi, H.E. (1989). Cuenca del Golfo San Jorge. In: Chebli, G.A. and Spalletti, L.A. (Eds.), *Cuencas Sedimentarias Argentinas* (pp. 319–345). Serie de Correlación Geológica.

Barreda, V.D., Palamarczuk, S., and Palazzesi, L. (2021). Bioestratigráfía palinológica de la Formación Chenque, Mioceno de la Cuenca del Golfo San Jorge. In: Giacosa, R.E. (Ed.), *Geología y Recursos Naturales de la Provincia de Chubut, Relatorio 21° Congreso Geológico Argentino* (pp. 1128–1136).

Bellosi, E.S. (1990). Formación Chenque: registro de la transgresión patagoniana (Terciario medio) de la cuenca de San Jorge, Argentina. *Actas IX Congreso Geológico Argentino* (pp. 57–60).

Bellosi, E.S. (1995). Paleogeografía y cambios ambientales de la Patagonia central durante el Terciario medio. *Boletín de Informaciones Petroleras* 44, 50–83.

Bellosi, E.S. (2010a). Loessic and fluvial sedimentation in Sarmiento Formation pyroclastics, middle Cenozoic of Central Patagonia. In: Madden, R., Carlini A., Vucetich, M., and Kay, R. (Eds.), *The Paleontology of Gran Barranca: Evolution and Environmental Change through the Middle Cenozoic of Patagonia*. Cambridge University Press, Cambridge, 278–292.

Bellosi, E.S. (2010b). Physical stratigraphy of the Sarmiento Formation (middle Eocene-lower Miocene) at Gran Barranca, central Patagonia. In: Madden, R. Carlini, A., Vucetich, M., and Kay, R. (Eds.), *The Paleontology of Gran Barranca: Evolution and Environmental Change through the Middle Cenozoic of Patagonia.* Cambridge University Press, Cambridge, 19–31.

Bellosi, E.S., and Jalfin, G.A. (1996). Sedimentación en la planicie costera santacrucense-superpatagoniana (Mioceno inferior-medio, cuenca San Jorge). *Actas VI Reunión Argentina de Sedimentología* (pp. 181–186).

Bellosi, E.S., and Krause, J.M. (2014). Onset of the middle Eocene global cooling and expansion of open vegetation habitats in central Patagonia. *Andean Geology* 41(1), 29–48. https://doi.org/10.5027/andgeoV41n1-a02

Bilmes, A., Cuitiño, J.I., and D'Elía, L. (2021). Los depósitos miocenos de Chubut: análisis tectono-estratigráfico desde los Andes Hasta el océano Atlántico. In: Giacosa, R.E. (Ed.), *Geología y Recursos Naturales de la Provincia de Chubut*, *Relatorio 21° Congreso Geológico Argentino* (pp. 1315–1334).

Carmona, N.B., Buatois, L.A., Mángano, M.G., and Bromley, R.G. (2008). Ichnology of the Lower Miocene Chenque Formation, Patagonia, Argentina: Animal-substrate interactions and the Modern Evolutionary Fauna. *Ameghiniana* 45, 93–122.

Carmona, N.B., Buatois, L.A., Ponce, J.J., and Mángano, M.G. (2009). Ichnology and sedimentology of a tide-influenced delta, Lower Miocene Chenque Formation, Patagonia, Argentina: Trace-fossil distribution and response to environmental stresses. *Palaeogeography, Palaeoclimatology, Palaeoecology* 273, 75–86. https://doi.org/10.1016/j.palaeo.2008.12.003

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., and Winker, C. (2009). Towards the standardization of sequence stratigraphy. *Earth-Science Reviews* 92, 1–33. https://doi.org/10.1016/j.earscirev.2008.10.003

Clyde, W.C., Wilf, P., Iglesias, A., Slingerland, R.L., Barnum, T., Bijl, P.K., Bralower, T.J., Brinkhuis, H., Comer, E.E., Huber, B.T., Ibañez-Mejia, M., Jicha, B.R., Krause, M., Schueth, J.D., Singer, B.S., Raigemborn, M.S., Schmitz, M.D., Sluijs, A., and Zamaloa, M.C. (2014). New age constraints for the Salamanca Formation and lower Río Chico Group in the western San Jorge Basin, Patagonia, Argentina: implications for K/Pg extinction recovery and land mammal age correlations. *Geological Society of America Bulletin* 126, 289–306. https://doi.org/10.1130/B30915.1

Cuitiño, J.I., Scasso, R.A., Ventura Santos, R., and Mancini, L.H. (2015). Sr ages for the Chenque Formation in the Comodoro Rivadavia region (Golfo San Jorge Basin, Argentina): stratigraphic implications. *Latin American Journal of Sedimentology and Basin Analysis* 22, 3–12.

Embry, A.F. (2009). Practical Sequence Stratigraphy. Canadian Society of Petroleum Geologists, 76 pp.

Feruglio, E. (1949). Descripción Geológica de la Patagonia. Yacimientos Petrolíferos Fiscales, Vol. 1, 334 pp.

Foix, N. (2009). *Tectónica y sedimentación del registro paleógeno (Formaciones Salamanca y Río Chico) de la Cuenca del Golfo San Jorge, Argentina*. Unpublished Ph.D. Thesis, Universidad Nacional de la Patagonia San Juan Bosco), 313 pp.

Foix, N., Paredes, J.M., and Giacosa, R.E. (2012). Upper Cretaceous-Paleocene normal reactivation phase in the Golfo San Jorge Basin (Argentine): growth-fault models, paleoseismicity and paleostress analysis. *Journal of South American Earth Sciences* 33, 110–118. https://doi.org/10.1016/j.jsames.2011.07.005

Foix, N., Paredes, J.M., and Giacosa, R.E. (2013). Fluvial architecture variations linked to changes in accommodation space: Río Chico Formation (Late Paleocene), Golfo San Jorge basin, Argentina. *Sedimentary Geology* 394, 342–355. https://doi.org//10.1016/j.sedgeo.2013.07.001

Foix, N., Krause, J.M., Bellosi, E.S., and Raigenborn, M.S. (2021). Sedimentitas paleógenas y neógenas del margen atlántico. In R. E. Giacosa (Ed.), *Geología y Recursos Naturales de la Provincia del Chubut*, *Relatorio 21° Congreso Geológico Argentino* (pp. 489–521).

Gianni, G.M., Dávila, F.M., Echaurren, A., Fennell, L., Tobal, J., Navarrete, C., and Giménez M. (2018). A geodynamic model linking Cretaceous orogeny arc migration, foreland dynamic subsidence and marine ingression in southern South America. *Earth-Science Reviews* 185, 26–462. https://doi.org/10.1016/j.earscirev.2018.06.016

Kramarz, A.G., and Bond, M. (2005). Los Litopterna (Mammalia) de la Formación Pinturas, Mioceno Temprano-Medio de Patagonia. *Ameghiniana* 42(3), 611–625.

Krause, J.M., Bellosi, E.S., and Raigemborn, M.S. (2010). Lateritized tephric palaeosols from Central Patagonia, Argentina: a southern high-latitude archive of Palaeogene global greenhouse conditions. *Sedimentology*, 57, 1721–1749. https://doi.org/10.1111/j.1365-3091.2010.01161.x

Krause, J.M., Clyde, W.C., Ibañez-Mejía, M., Schmitz, M.D., Barnum, T., Bellosi, E.S., and Wilf, P. (2017). New age constraints for early Paleogene strata of central Patagonia, Argentina: implications for the timing of South American land mammal ages. *Geological Society of America Bulletin* 129(7-8), 886–903. https://doi.org/10.1130/B31561.1

Legarreta, L., and Uliana, M.A. (1994). Asociaciones de fósiles y hiatos en el Supracretácico-Neógeno de la Patagonia: Una perspectiva estratigráfico-secuencial. *Ameghiniana* 31(3), 257–281.

Legarreta, L., Uliana, M., and Torres, M. (1990). Secuencias deposicionales cenozoicas de Patagonia Central: sus relaciones con las asociaciones de mamíferos terrestres y episodios marinos epicontinentales. *Actas 3° Simposio del Terciario de Chile*, 135–176.

Náñez, C., and Malumián, N. (2008). Paleobiogeografía y paleogeografía del Maastrichtiano marino de Patagonia, Tierra del Fuego y de la Plataforma Continental Argentina basada en foraminíferos bentónicos. *Revista Española de Paleontología* 23, 273–300.

Navarrete, C., Gianni, G., Massaferro, G., and Butler, K. (2020). The fate of the Farallon slab beneath Patagonia and its links to Cenozoic intraplate magmatism, marine transgressions and topographic uplift. *Earth-Science Reviews* 210, 103379. https://doi.org/10.1016/j.earscirev.2020.103379

Navarrete, C.R. (2025). An overview of the Late Triassic-Pleistocene magmatism in the Golfo San Jorge Basin. *Latin American Journal of Sedimentology and Basin Analysis* (this issue).

Oporto Romero, F.E., and Paredes, J.M. (2022). Arquitectura estratigráfica de sistemas eólicos-fluviales: un ejemplo de la Formación Santa Cruz (Mioceno medio) en la cuenca del Golfo San Jorge, Argentina. *Revista de la Asociación Geológica Argentina* 79(1), 1–29.

Oporto Romero, F.E., Paredes, J.M., Allard, J.O., Foix, N., Valle, M.N., Cortés, M., Rodríguez, A.R., and Bueti, S.A. (2023). Arquitectura y análisis cinemático de fallas normales mesoscópicas: Formación Chenque (Mioceno Inferior-Medio) en el Sector Oriental de la cuenca del Golfo San Jorge, Patagonia central. *Revista de la Asociación Geológica Argentina* 80(3), 511–530.

Oporto Romero, F.E., Paredes, J.M., Allard, J.O. Perez Frasette, M.J., and Almada Báez, N., (2024a). Tectónica extensional en la sucesión continental miocena del Flanco Norte (cuenca del Golfo San Jorge): estructuras de deformación frágil, dúctil y de escape de fluidos. In: T. A. De Sosa., R. Díaz, and L. Farías Fuenzalida (Eds.), *Resúmenes XI Jornadas de las Ciencias de la Tierra "Dr. Eduardo Musacchio"* (pp. 63–64).

Oporto Romero, F.E., Paredes, J.M., Allard, J.O., and Turra, J.M. (2024b). Ciclicidad estratigráfica de sistemas fluviales-eólicos de la Formación Escalante (Mioceno Medio), región oriental de la cuenca del Golfo San Jorge. *Actas XXII Congreso Geológico Argentino*, 129–130.

Paredes, J.M. (2002). Asociaciones de facies y correlación de los sedimentos de la Formación Chenque (Oligoceno-Mioceno) de los alrededores de Comodoro Rivadavia, Cuenca del Golfo San Jorge, Argentina. *Revista de la Asociación Argentina de Sedimentología* 9(1), 53–64.

Paredes, J.M., Azpiroz, G., and Foix, N. (2006). Tertiary tectonics and sedimentation in the Cerro Piedra Oil Field (Golfo San Jorge basin), Argentina. *Actas IV Latinamerican Congress of Sedimentology y XI Reunión Argentina de Sedimentología.* Abstracts, pp. 163.

Paredes, J.M., Colombo F., Foix, N., Allard, J.O., Nillni, A., and Allo, M. (2008). Basaltic explosive volcanism in a tuff-dominated intraplate setting, Sarmiento Formation (middle Eocene- lower Miocene), Patagonia Argentina. *Latin American Journal of Sedimentology and Basin Analysis* 15(2), 77–92.

Paredes, J.P., Foix, N., Guerstein, G.R., Guler, M.V., Irigoyen, M., Moscoso, P., and Giordano, S. (2015). A late Eocene-Early Oligocene transgressive event in the Golfo San Jorge basin: Palynological results and stratigraphic implications. *Journal of South American Earth Sciences* 63, 293–309. http://dx.doi.org/10.1016/j.jsames.2015.08.009

Paredes, J.M., Oporto Romero, F.E., and Valle, M.N. (2024). Storm-related deposits in the Chenque Formation (Lower-Middle Miocene, Golfo San Jorge basin): indirect evidence of the Mid Miocene Climatic Optimum in shallow-marine settings?. *Actas XI Jornadas de las Ciencias de la Tierra "Dr. Eduardo Musacchio"*, 65–67.

Plazibat, S., Rasgido, A.O., and Paredes, J.M. (2019). Subsurface characterization of Cenozoic igneous activity at Cerro Dragón area (Golfo San Jorge Basin, central Patagonia): implications for basin evolution and hydrocarbon prospectivity. *Journal of South American Earth Sciences* 96, 102389. https://doi.org/10.1016/j.jsames.2019.102389

Raigemborn, M.S., and Beilinson, E. (2020). Stratigraphic architecture and paleosols as basin correlation tools of the early Paleogene infill in central-south Patagonia, Golfo San Jorge Basin, Argentinean Patagonia. *Journal of South American Earth Science*s 99, 102519. https://doi.org/10.1016/j.jsames.2020.102519

Raigemborn, M.S., Brea, M., Zucol, A., and Matheos, S. (2009). Early Paleogene climatic conditions at mid latitude Southern Hemisphere: mineralogical and paleobotanical proxies from continental sequences in Golfo San Jorge basin (Patagonia, Argentina). *Geologica Acta* 7(1–2), 125–145. https://doi.org/10.1344/105.000000269

Raigemborn, M.S., Krause, J.M., Bellosi, E.S., and Matheos, S.D. (2010). Redefinición estratigráfica del Grupo Río Chico (Paleógeno Superior), en el norte de la cuenca del Golfo San Jorge, Chubut. *Revista de la Asociación Geológica Argentina* 67, 239–256.

Sciutto, J.C., Césari, O., Escribano, V., and Pezucchi, H. (2000). Hoja Geológica 4566-III, Comodoro Rivadavia, provincia del Chubut. Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino, Boletín 351, 60 pp.

Sosa, D.S, Krause, J.M., and Bellosi, E.S. (2022). Estratigrafía del Mioceno continental de Patagonia Central. In R. E. Giacosa (Ed.), *Geología y Recursos Naturales de la Provincia del Chubut, Relatorio 21° Congreso Geológico Argentino* (pp. 84–85).

Woodburne, M.O., Goin, F.J., Raigemborn, M.S., Heizler, M., Gelfo, J.N., and Oliveira, E.V. (2014). Revised timing of the South American early Paleogene land mammal ages. *Journal of South American Earth Sciences* 54, 109–119. http://dx.doi.org/10.1016/j.jsames.2014.05.003