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EXPANDING KNOWLEDGE OF HOTHOUSE CONDITIONS THROUGH THE STUDY OF PALEOSOLS IN THE SOUTHERN GOLFO SAN JORGE BASIN

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ABSTRACT

Hothouse periods, such as the mid-Cretaceous and early Eocene, were times of global warming with high levels of greenhouse gases, elevated temperatures, and ice-free poles that provide a case study for understanding past climate dynamics. This study examines the paleo-Ultisols from the Bajo Barreal Formation (BBF; Cenomanian) and the Las Flores Formation (LFF; early Eocene) in central Patagonia (southern region of the Golfo San Jorge Basin). Due to their prolonged soil formation, these well-developed paleosols serve as valuable climate indicators. These paleosols were analyzed using a multi-proxy approach to understand their significance during those two periods in the Southern Hemisphere. The BBF Ultisols (mid-Cretaceous, ~51° paleo-S) display kaolinite-rich Bt horizons, formed under intense chemical weathering conditions and leaching processes, linked to a temperate and humid climate. On the other side, the LFF Ultisols (early Eocene, ~52° paleo-S) with kaolinite-dominated Bt and/or Btv horizons reflect their formation under higher chemical weathering and leaching processes, under a temperate-tropical and humid climate. For the times of formation of both BBF and LFF paleo-Ultisols, both localities were within the Warm Temperate climate zone. In contrast, this zone currently extends to approximately 40° N and S latitude. Present-day Patagonia is in the Arid climate zone, with much drier and cooler climate that contrasts with the warmer, wetter conditions of the Cenomanian and early Eocene localities analyzed. These findings highlight significant latitudinal displacement of climate zones during hothouse periods, emphasizing their importance in understanding past climate dynamics and providing insights into future climate change scenarios.

INTRODUCTION

During episodes of global warming, known as hothouse periods, the high levels of greenhouse gases, mainly CO_2, result in Earth's average temperatures that may exceed 20 °C, with polar regions relatively warm above 5 °C, preventing ice accumulation (*e.g.*, Scotese *et al.*, 2021). During those times, the equatorial and subtropical belts expand slightly poleward, and the Polar and Cool Temperate belt are replaced by an expanded Warm Temperate belt that brings tropical conditions to latitudes above 50° N and S (Boucot *et al.*, 2013; Scotese *et al.*, 2021). If one imagines where the current phase of anthropogenic global warming is heading, one immediately thinks of the hothouse worlds of the Late Cretaceous and Eocene, two critical episodes in Earth's climatic history (Huber *et al.*, 2000). Particularly, during the mid-Cretaceous, global average temperatures (GAT) reached approximately 28 °C, while the early Eocene also experienced elevated global temperatures, peaking at a GAT during the early Eocene Climatic Optimum of approximately 25 °C. In contrast, the modern GAT is significantly lower, averaging 15 °C (Scotese *et al.*, 2021).

These periods are well documented, primarily through high-resolution marine records from the Northern Hemisphere (*e.g.*, Jenkyns *et al.*, 1994; Voigt *et al.*, 2008; Merhabi *et al.*, 2022; Zachos *et al.*, 2010; Westerhold *et al.*, 2020; Filippi and Luciani, 2025). In contrast, continental successions from the Southern Hemisphere remain relatively scarce for both the mid-Cretaceous and early Eocene, leaving critical gaps in our understanding of terrestrial responses to extreme climatic conditions during these key intervals.

Paleosols are invaluable archives of Earth´s climatic history, as their providing insights into temperature, precipitation, and vegetation through their morphological, mineralogical, and geochemical data. The intrinsic connection between soils and climate makes studying paleosols a powerful tool to investigate the mechanisms of past global climate change (Retallack, 2001) and validate both model predictions of paleoclimate and future climate scenarios (Sheldon, 2006).

Within the southern part of the Golfo San Jorge Basin, in central Argentinean Patagonia, the Cenomanian Bajo Barreal Formation (BBF) and the early Eocene Las Flores Formation (LFF) are fluvial units that record well-developed paleosols, providing an excellent opportunity to reconstruct paleoclimatic conditions in this part of the Southern Hemisphere. This study synthesizes existing data on the paleosols of the BBF and LFF (Raigemborn *et al.*, 2022; Lizzoli *et al.*, 2025). Hence, by combining macro-, micro-, and nanomorphological observations with clay mineralogy and geochemical data, we investigate these paleosols to understand their significance in the context of past extreme climate events, such as those of the mid-Cretaceous and the early Eocene. This study also contributes to a more refined understanding of paleoclimate dynamics in the Southern Hemisphere during these periods.

GEOLOGICAL SETTING AND SEDIMENTOLOGICAL–PALEOPEDOLOGICAL CONTEXT

The Golfo San Jorge Basin (Fig. 1a), located in the central region of Patagonia in Argentina (~44–48° S), has a complex geological history genetically linked to the Gondwana break-up (Fitzgerald *et al.*, 1990). The basin contains an early Cretaceous–Cenozoic infilling dominated by clastic, volcaniclastic, and volcanic rocks, interbedded with marine transgressions and continental deposits (Barcat *et al.*, 1989). During the Cretaceous deposition, the Chubut Group was dominated by lacustrine (Pozo D-129 Formation) and fluvial systems (Matasiete, Castillo, and Bajo Barreal formations). See further details in Paredes *et al.* (this volume). In the Paleogene, the stratigraphic record of the basin includes marine and continental units such as the marine Salamanca Formation and the continental Peñas Coloradas, Las Violetas, Las Flores, Koluel-Kaike, and the Sarmiento formations (see a review in Raigemborn *et al.*, 2010; Krause *et al.*, 2017, and Raigemborn and Beilinson, 2020).

The mid-Cretaceous context

The Cerro Ballena anticline in the South Flank of the Golfo San Jorge Basin provides a well-exposed record of mid-Cretaceous sedimentation, encompassing two distinct stratigraphic intervals (Sections A and B) within the early Cenomanian Bajo Barreal Formation (BBF; see Figure 1a and b). Section A is characterized by isolated, small-scale channel belts of low connectivity embedded in siliciclastic mudstones. Upward, Section B transitions into sheet-like, interconnected channel-belt complexes interbedded with thinner volcaniclastic floodplain deposits (Paredes *et al.*, 2018). The paleosols in Section A are dominated by smectite-rich paleo-Vertisols and subordinate paleo-vertic Alfisols, in which argilluviation, vertization, hydromorphism, and calcification were the main pedogenic processes. These processes occurred under moderate chemical weathering conditions (Lizzoli *et al.*, 2025). In contrast, the paleosols in Section B are kaolinite-rich paleo-Ultisols and paleo-hydromorphic Inceptisols, dominated by lixiviation (ferruginization), argilluviation, and hydromorphism as main pedogenic processes, developed under intense chemical weathering conditions. Paleoclimate reconstructions suggest a shift from temperate and subhumid conditions with seasonal rainfall (Section A) to warmer (temperate) and humid conditions (Section B) (Lizzoli *et al.*, 2025).

The Eocene context

The Las Flores Formation (LFF) of the Río Chico Group, cropping out at Estancia Laguna Manantiales in the southernmost Golfo San Jorge Basin, provides a valuable record of early to middle Eocene environmental conditions (Figure 1a and b). The LLF is deposited over the informally named Laguna Manantiales Strata (Quattrocchio *et al.*, 2024) and unconformably overlain by the Koluel-Kaike Formation, forming a stratigraphic succession approximately 36 m thick. The LFF primarily comprises massive mudstones and sandstones, representing distal floodplain and moderate- to high-sinuosity fluvial systems. Paleosols are strongly-developed paleo-Ultisols and paleo-plinthitic Ultisols dominated by illuviation, hydromorphism, and plinthization as main pedogenic processes, developed under high degree of chemical weathering conditions. Paleoclimate reconstructions suggest a temperate-tropical and humid climate (Raigemborn *et al.*, 2022).

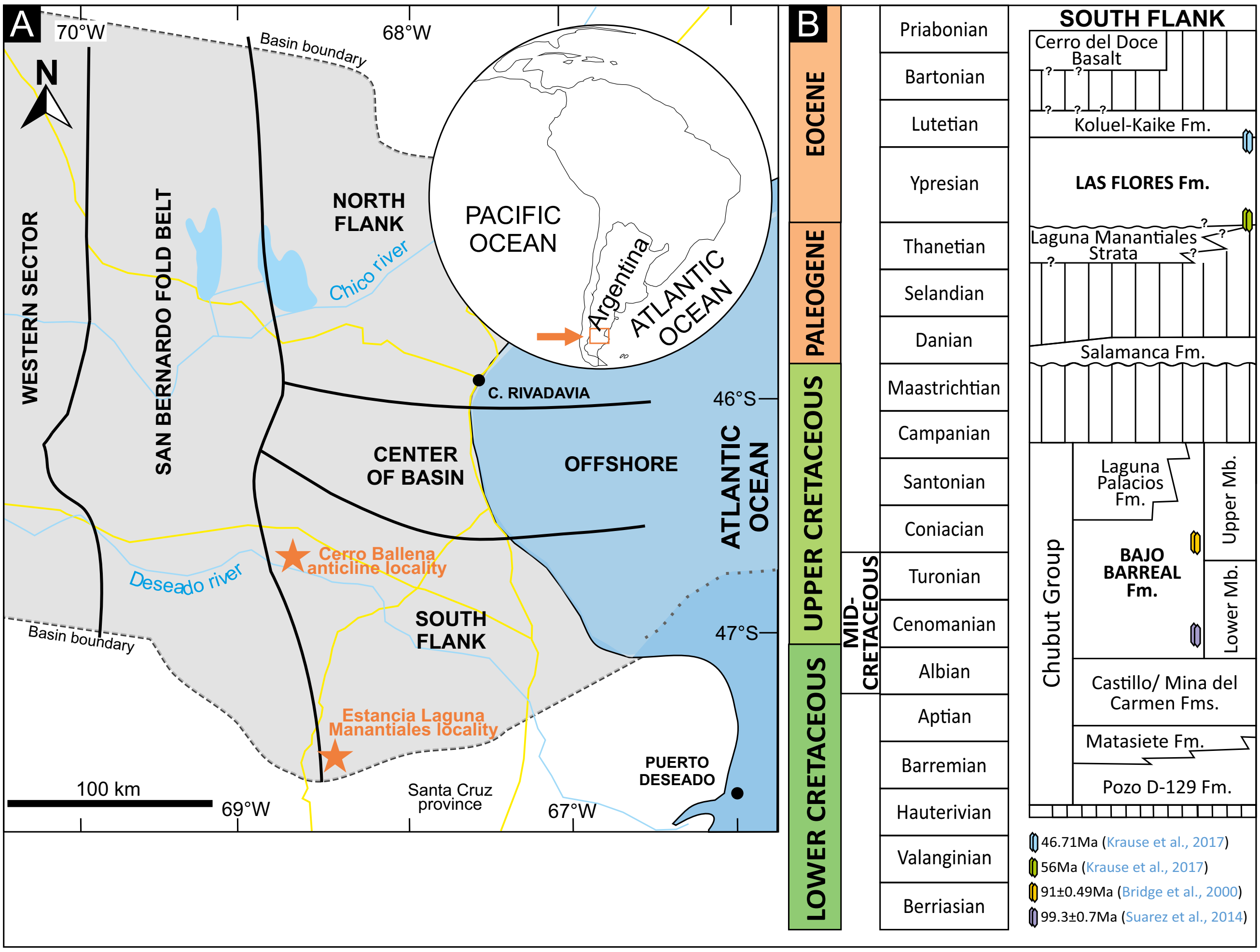

Figure 1. a) Location map of the Golfo San Jorge Basin configuration. The study localities are shown with an orange star. **b)** Stratigraphy summary of the South Flank of the Golfo San Jorge Basin. Note the Bajo Barreal and Las Flores formations in bold type. Modified from Lizzoli *et al.* (2025) and Quattrocchio *et al.* (2024). Ages from Krause *et al.* (2017) were from the east of the San Bernardo Fold Belt.

MATERIAL AND METHODS

In this synthesis, we used previously published paleopedological data (Raigemborn *et al.*, 2022; Lizzoli *et al.*, 2025) of the paleosols from the Cenomanian BBF (Cerro Ballena anticline locality; Log Y: 46°41'2'' S; 69°11'40'' W; Log Z: 46°40'70'' S; 69°12'15'' W) and from the early-Paleogene LLF (Estancia Laguna Manantiales locality; 47°33'20" S, 68°13'50" W) (see Fig. 1a). We use paleo-Ultisols of both units because this type of soils has been the sufficient time of soil formation to equilibrate with climate conditions and thus better reflects the environmental and climate conditions during the time of their formation (Retallack, 2001). These paleosols were analyzed using a multi-proxy approach integrating macro-, micro-, and nanomorphology, clay mineralogy, and bulk paleosol geochemistry (see Raigemborn *et al.*, 2022; Lizzoli *et al.*, 2025).

Although there is a specific classification system for deep-time (pre-Quaternary) paleosols (Mack *et al.*, 1993), we used the modern system (Soil Taxonomy classification) for easier communication and comparison with their modern analogs because it is the most commonly used classification for paleosols studies to date (*e.g.*, Retallack, 1991). In this sense, we add the term "paleo" before the group name, understanding its limitations in the fossil record. This change is introduced because paleosols can be complicated by destroying or lossing key characteristics during compaction and burial (Retallack, 1991). As the sediments of both the BBF and LFF indicate little in the way of burial compaction and the preservation of pedogenic features suggest no significant evidence of post-burial alteration, they can be used for paleoenvironmental and climate reconstructions (Raigemborn *et al.*, 2022; Lizzoli *et al.*, 2025).

We compare the mid-Cretaceous and early Eocene Ultisols from the Golfo San Jorge Basin with their modern analogs to validate the paleosols´ use as reliable proxies for past climates. The position of the studied localities during the mid-Cretaceous and early Eocene was estimated using the paleogeographic and paleoclimate reconstructed maps of Boucot *et al.*, (2013). To see modern Ultisol´s global distribution we used the USDA Global Soil Map (Soil Survey Staff, 2022).

RESULTS

Here, we present a synthetic description of the paleo-Ultisol features of the BBF and LFF. In Table 1, we highlight the key diagnostic features of modern Ultisols (based on Soil Taxonomy, Soil Survey Staff, 2022, and Buol *et al.* 2011), and compare them with those observed in the ancient Ultisols described by Raigemborn *et al.* (2022) and Lizzoli *et al.* (2025).

The mid-Cretaceous BBF Ultisols are exposed in Section B of the Bajo Barreal Formation, located in the Cerro Ballena anticline (Fig. 2a). These lithified paleosols consist of stacked Bt horizons forming a Bt1-Bt2-Bt3 soil profile (Fig.2b). The Bt horizons (where the suffix t indicates clay illuviation or translocated clay accumulation) are composed of mudstones with a matrix ranging in color from gray to dusky red, with angular to subangular blocky peds (Fig.2c). Macro- and micropedofeatures include reddish-yellow mottles, and Fe-oxide nodules, clay coatings, Fe-oxide hypocoatings, and Fe-Mn oxide nodules and coatings (Fig. 2c-e). The clay fraction is dominated by kaolinite (Fig. 2f-g). Geochemical proxies indicate high weathering (low Base Loss, high CIA and CIA-K, and low PWI; see Table 1). Climofunctions indicate a mean annual temperature (MAT) of 13.2 ± 2.1 °C (derived from the PWI proxy of Gallagher and Sheldon, 2013), and a mean annual precipitation (MAP) of 1287 ± 181 mm/yr (derived from the CIA-K proxy of Sheldon *et al.*, 2002). For more details, see Lizzoli *et al.* (2025).

The early Eocene LFF Ultisols are exposed in the Estancia Laguna Manantiales locality and display well-developed paleosol stacked profiles, typically arranged in Bt-BC (Pedotype 1; P1) and Btv-Bt-BC-C and Bt-Btv-BC (Pedotype 2; P2) soil profiles (Fig. 3a). The Bt horizons of P1 have a blocky microstructure or a massive arrangement (Fig. 3b). Macro- and micropedofeatures of Ultisols of P1 include illuvial clay and Fe-clay features, Fe and Mn-rhizoliths, -nodules and concretions, Fe-mottles, slickensides, reworked pedofeatures and pedorelicts (Fig. 3c). While macro- and microfeatures of the Bt horizons of the P2 are similar to those described for Bt horizons of the P1, Btv horizons (where the suffix v indicates presence of plinthite, an iron-rich material that hardens irreversibly upon exposure to repeated wetting and drying) of the plinthitic Ultisols of the P2 show a blocky microsctructure or a massive arrangement and present illuvial clay, silty-clay and

Table 1. Syntethic description of the main features of the paleo-Ultisols from the Bajo Barreal Formation (BBF) and the Las Flores Formation (LFF), based on Raigemborn et al. (2022) and Lizzoli et al. (2025), respectively. The key features of current Ultisols are referred to US Soil Taxonomy (Soil Survey Staff, 2022) and Buol et al. (2011).

Soils/Paleosols	Diagnostic features (macro- and micro-)	Clay-mineralogy	Chemical properties	Pedogenic Processes
Modern Ultisols	Argillic or kandic horizon (Bt) Subsurficial horizons with clay (kaolinite) coatings Common (not definitive) plinthite and fragipans Redoximorphic features (mottled pattern and/or Fe-Mn oxide nodules)	Kaolinite-dominated	Low base saturation status	Leaching In situ chemical weathering and clay formation Illuviation Bioturbation (Plinthization) (Hydromorphism)
LFF Ultisols (Eocene)	Bt-BC (Pedotype 1), Btv-Bt-BC-C and Bt-Btv-BC (Pedotype 2) soil profiles Clay and clay-Fe coatings Fe-nodules and mottles Reworked pedofeatures Plinthite	Kaolinite-dominated	Low base loss (~0.12) High CIA (~93) and CIA-K (~91) Very low PWI (~5)	Leaching In situ chemical weathering and clay formation Illuviation Hydromorphism Plinthization Vertization Biotubation
BBF Ultisols (mid-Cretaceous)	Bt1-Bt2-Bt3 soil profile Clay and clay-Fe coatings Fe-nodules	Kaolinite-dominated	Low Base Loss (~0.27) High CIA(~80) and CIA-K (~89) Low PWI (~20)	Leaching In situ chemical weathering and clay formation Illuviation Hydromorphism

Table 1. Synthetic description of the main features of the paleo-Ultisols from the Bajo Barreal Formation (BBF) and the Las Flores Formation (LFF), based on Raigemborn *et al.* (2022) and Lizzoli *et al.* (2025), respectively. The key features of current Ultisols are referred to US Soil Taxonomy (Soil Survey Staff, 2022) and Buol *et al.* (2011).

ferric silty-clay features, reddish Fe-mottles amidst the light-colores matrix with different shapes and patterns, Fe/Mn nodules and pedorelicts (Fig. 3d-f). The clay fraction of both P1 and P2 is dominated by abundant kaolinite (Fig. 3g-h). Geochemical proxies indicate high weathering for the Bt and Btv horizons of both pedotypes (low Base Loss, high CIA and CIA-K, and very low PWI; see Table 1). Climofunctions indicate a MAT of 17 ± 2.1 °C (derived from the PWI proxy of Gallagher and Sheldon, 2013) and 22 ± 4.0 °C (derived from the PPM 1.0 proxy of Stinchcomb *et al.* 2016), and a MAP of 1390 ± 181 mm/yr (derived from the CIA-K proxy of Sheldon *et al.*, 2002) and 1670 ± 512 mm/yr (derived from the PPM 1.0 proxy of Stinchcomb *et al.* 2016). For more details, see Raigemborn *et al.* (2022).

DISCUSSION

Soils are formed in direct contact with the atmosphere, lithosphere, hydrosphere, and biosphere, so paleosols should be a good record of former physical, biological, and chemical information about past conditions near Earth's surface (Tabor and Myers, 2015). In this study, we integrate pedogenic features with clay mineralogy and geochemical data that can be correlated with soil forming processes linked to climate during past hothouse periods (*i.e.*, the mid-Cretaceous and the early Eocene). The Ultisols from BBF and LFF display Bt (and/or Btv) horizons with abundant clay coatings. Argillic features form in relatively well-drained soils above the water table and confirm sustained clay translocation processes. The abundance of these features in the studied paleosols suggests a high degree of horizon development reflecting prolonged pedogenesis (*e.g.*, Stoops *et al.*, 2018). Weathering indices are overall high, indicating enhanced weathering and intense pedogenic action (Base Loss ~ 0.27, CIA ~ 80, CIA-K ~ 89 and PWI ~ 20 for BBF, and Base Loss ~ 0.12, CIA ~ 93, CIA-K ~ 91 and PWI ~ 5 for LFF).

Quartz was the dominant component of the coarse fraction, and especially in the LLF, the presence of runiquartz suggests in situ or relict intense weathering

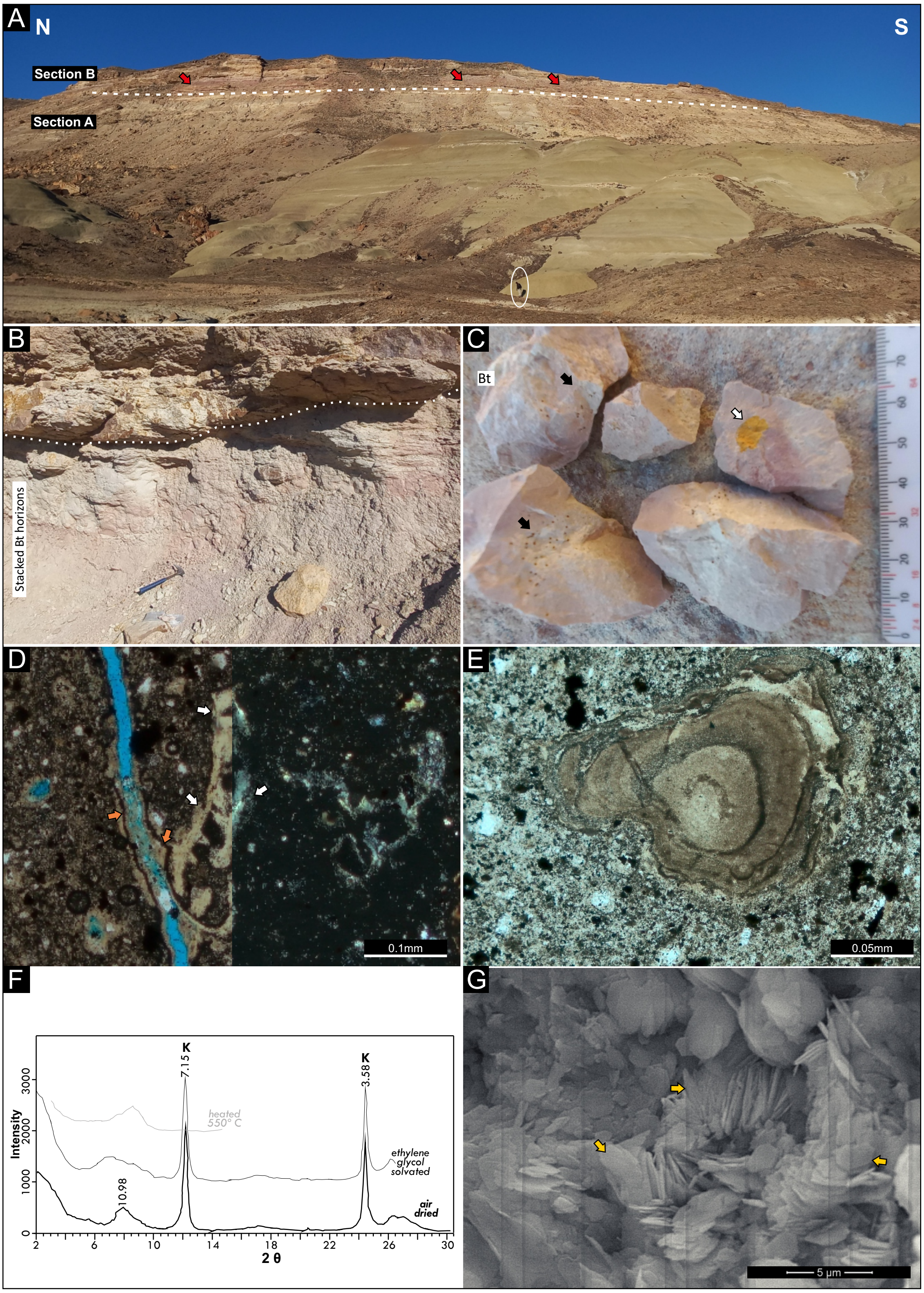

Figure 2. Main macro- and micropedofeatures from the paleo-Ultisols from the Bajo Barreal Formation. **a)** General appearance of the Bajo Barreal Formation (BBF) in the Cerro Ballena anticline. The white circle indicates a person for scale. The paleo-Ultisols are indicated with red arrows. **b)** Stacked Bt horizons showing angular blocky peds. **c)** Detail of a Bt horizon with Fe-oxide nodules (black arrow) and a reddish-yellow mottle (while arrow). **d)** Channels with dense incomplete infillings of limpid clay in a Bt horizon (white arrows) and clay with Fe-oxide coatings (left: PPL, x2.5; right: XPL, x2.5). **e)** Dense complete laminated infilling of clay with Fe-oxide in a Bt horizon (PPL, x10). **f)** Representative X-ray diffraction pattern of the clay fraction (oriented sample) of a Bt horizon, showing a kaolinite (K) peak. **g)** Kaolinite coating showing a typic book-like morphology in a Bt horizon under scanning electron microscopy (SEM). For details, see Lizzoli *et al.* (2025).

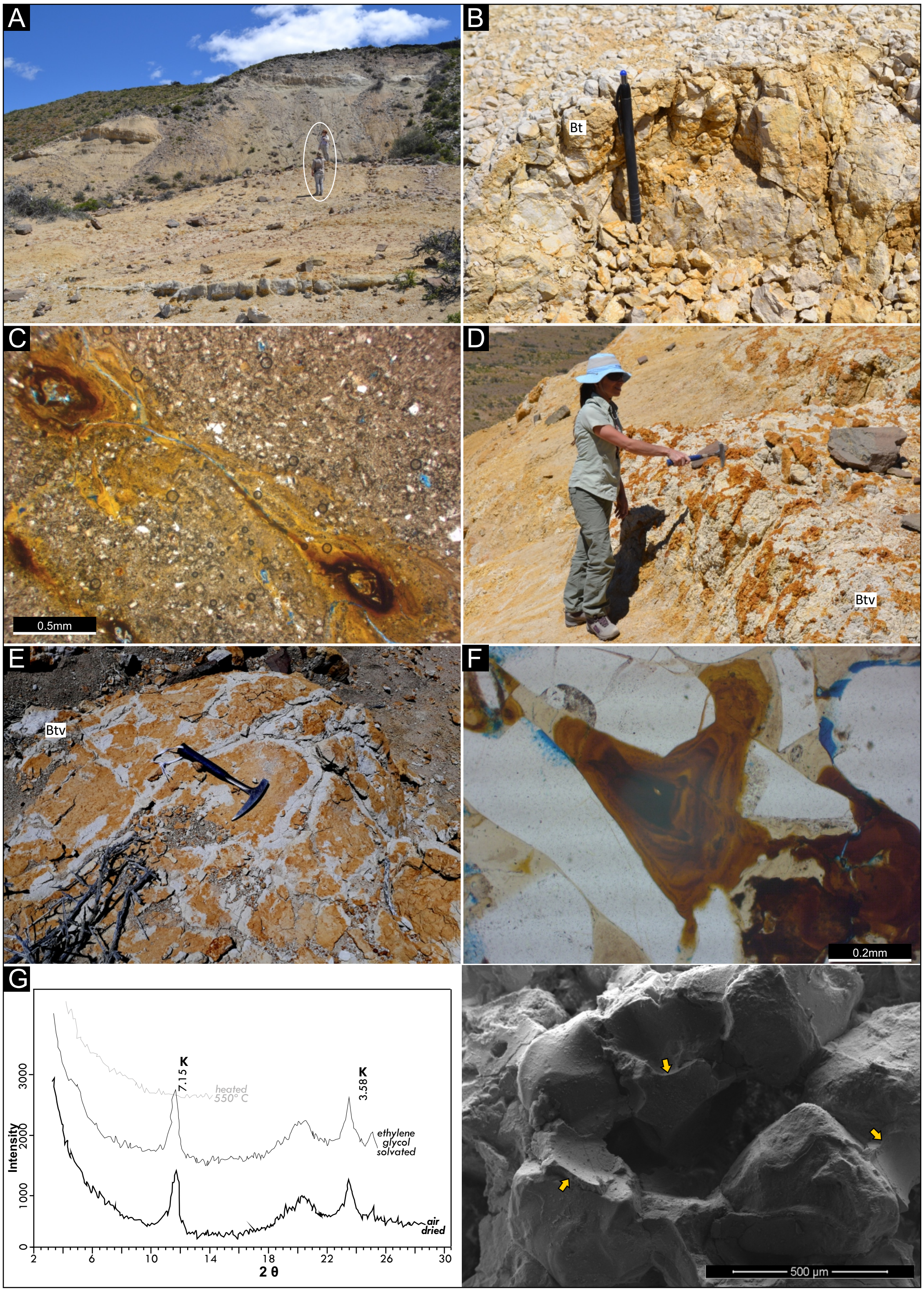

Figure 3. Main macro- and micropedofeatures from the paleo-Ultisols from the Las Flores Formation. **a)** Outcrop of the pedogenized Las Flores Formation (LFF) at the Estancia Laguna Manantiales locality. **b)** Bt horizon of Pedotype 1 with blocky structure. **c)** Illuvial clay and Fe-clay coatings in channel and chambers in a Bt horizon from Pedotype 1. **d)** Btv-Bt-BC soil profile of Pedotype 2. **e)** Plan view of polygonal Fe-mottles. Note the prominent contrast between the gleyed matrix and the oxidized mottles. **f)** Thick microlaminated Fe-coating and Fe-impregnation (yellow arrows) in the mottled area of a sandy Btv horizon (PPL, x4). **g)** A representative X-ray diffraction pattern of the clay fraction (oriented sample) of a Bt horizon shows a kaolinite (K) peak. **g)** Kaolinite Fe-clay coating (yellow arrow) covering quartz grains in a Bt horizon under scanning electron microscopy (SEM). For more details, see Raigemborn *et al.* (2022).

(*e.g.*, Muggler *et al.*, 2007). The clay mineral assembly of the BBF is rich in kaolinite but also contains mixed-layers of illite/smectite. In contast, the LFF is dominated by kaolinite, suggesting slightly higher weathering intensity than BBF. Additionally, the development of Btv horizons in LFF is consistent with more intense weathering conditions. Mid-Cretaceous BBF paleosols provide evidence of a temperate and humid climate ($MAT_{(PWI)}$ of ~ 13.2 ± 2.1 °C and $MAP_{(CIA-K)}$ ~1287 ± 181 mm/yr). Geologically younger early Eocene LFF paleosols suggest temperate-tropical and humid climate ($MAT_{(PWI;\ PPM\ 1.0)}$ of ~ 17 ± 2.1 °C and 22 ± 4.0°C and $MAP_{(CIA-K;\ PPM\ 1.0)}$ ~1390 ± 181 mm/yr and 1670 ± 512 mm/yr). Although weathering conditions were more intense during the early Eocene compared to the mid-Cretaceous, overall MAT and MAP values are compatible with their standard errors of estimates. Therefore, paleosols from mid-Cretaceous and early Eocene in the southern Golfo San Jorge Basin consistently point to temperate (to tropical) and humid conditions.

Global climate reconstructions of the mid-Cretaceous and early Eocene, as presented by Boucot *et al.* (2013), suggest that the south region of the Golfo San Jorge Basin (~51° paleo-S latitude and ~52° paleo-S latitude, respectively, according to van Hinsbergen *et al.*, 2015) was situated in the Warm Temperate climate zone (Fig. 4). For the Mid-Cretaceous, this zone expanded up to 90° S and ~80° N, while, during the early Eocene, this zone expended up to ~65° S and 90° N (Boucot *et al.*, 2013).

To strengthen the modern-ancient soil-paleosol analog approach, we compare the paleo-Ultisols with the general charactherisctics of their modern counterparts. Modern Ultisols are generally found in warm, humid climates with perennial rainfall, responding to regional climate conditions (Buol, 2011; Soil Survey Staff, 2022). These soils are characterized by intense leaching, kaolinite-dominated clay assemblages, and well-developed Bt horizons (see Table 1). These base-poor soils commonly form in older, stable landscapes such as rolling hills, high terraces, and plateau tops under coniferous or hardwood forests. They typically have molecular weathering ratios of alumina to bases greater than two, reflecting their low base status due to prolonged soil formation over tens to hundreds of thousands of years. These characteristics make modern Ultisols valuable analogs for interpreting mid-Cretaceous and early Eocene paleoclimate conditions.

In the modern world, the Warm Temperate climate zone extends to approximately 40° N and S latitude (Peel *et al.,* 2007). Modern-day analogs for the paleo-Ultisols of the BBF and LFF paleosols can be found between the equator and up to mid-latitudes, between ~40° N and ~45° S (Fig. 4). For instance, in the Southern Hemisphere, in South America are found in the south of Brazil and northeast of Argentina (~33° S and ~27° S, respectively). These modern Ultisols occur under the warm temperate, fully humid, and hot summer (Cfa) climate of the Köppen-Geiger Climate Classification (Rubel and Kottek, 2010). In particular, in the northeastern of Argentina (~28–25° S), modern Ultisols are influenced by high precipitation and sustained weathering processes, which take place under subtropical humid climate (MAT between 19 and 20 °C and MAP between 1700 and 2000 mm/yr), and hyperthermic and udic regimes (Panigatti, 2010; INTA DIGITAL GEO). These MAT and MAP values are similar or slightly lower than the obtained for the mid-Cretaceous and early Eocene paleoclimate reconstructions. In contrast, modern central Patagonia, where the BBF and LFF studied localities are situated (~46–47° S), has arid, desert and cold arid (BWk) and arid, steppe, and cold arid (BSk) climates, respectively, following the Köppen-Geiger climate classification (Rubel and Kottek, 2010). The region's present-day soils include Aridisols (*i.e.*, Haplosalid, Haplocalcid sódic, and Natragid), characterized by saline crusts, natric and/or calcic horizon, and minimal pedogenic development (Panigatti, 2010). These Aridisols form under arid conditions (MAT between 6 and 9°C and MAP between 100 and 200 mm/yr) and mesic and aridic regimes (INTA DIGITAL GEO). This stark contrast highlights two key differences: first, present-day Ultisols develop in lower-latitude regions such as northeastern Argentina, unlike the higher paleolatitude (~51°S) of the Golfo San Jorge Basin during the Cretaceous and early Eocene; and second, Ultisols indicate humid and warm conditions, which contrast with the Aridisols that currently dominate central Patagonia. The well-developed paleo-Ultisols found in the BBF and LFF thus provide strong evidence that during the mid-Cretaceous and early Eocene, the southern Golfo San Jorge Basin was significantly warmer and more humid than today.

Therefore, the record of the studied paleosols provides compelling evidence for past climatic conditions markedly different from those of the present at similar laititudes. In general, during

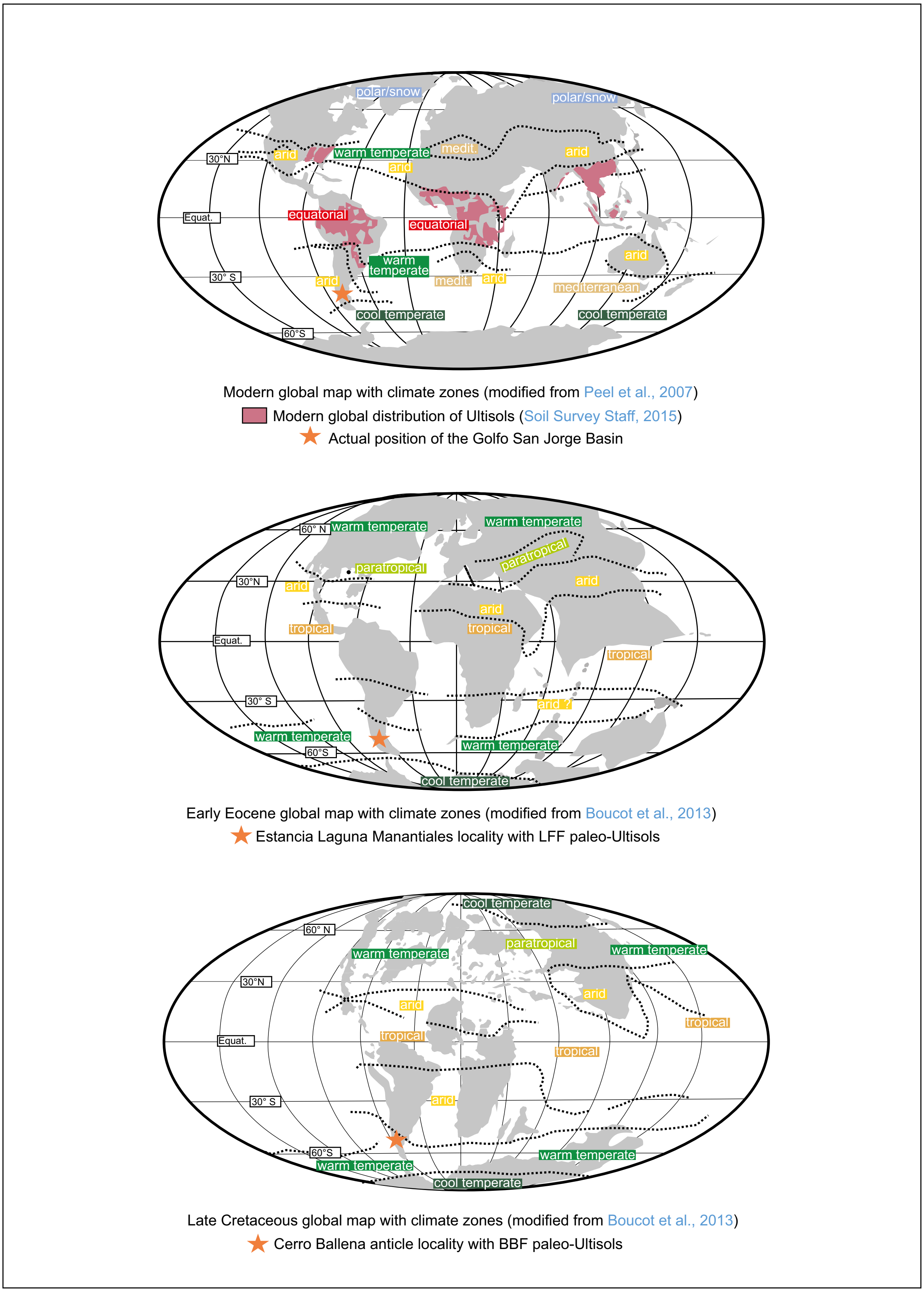

Figure 4. Global climate reconstructions for the mid-Cretaceous and early Eocene with paleoclimate zones (modified from Boucot *et al.*, 2013). Modern global climate map with climate zones (modified from Peel *et al.*, 2007), and modern global distribution of Ultisols (based on Soil Survey Staff, 2022).

times of hothouse conditions, the tropical and arid zones expanded poleward, replacing cold and cool temperate zones with an expanded warm temperate zone that brings tropical conditions to latitudes above 50° N and S (Boucot *et al.*, 2013; Scotese *et al.*, 2021). The presence of paleo-Ultisols at ~51° paleo-S latitude during mid-Cretaceous and ~52° paleo-S latitude during early Eocene suggests that central Patagonia experienced significant latitudinal displacement of climate zones. In fact, during the mid-Cretaceous, in the Southern Hemisphere, the tropical and arid zones expanded poleward and the cold and cool temperate zone were totally replaced by the warm temperate zone (Fig. 4). Meanwhile, during the early Eocene, subtropical regions in South America were displaced toward the poles by at least 19° of latitude compared to their modern counterparts (Fig. 4). This shift implies that subtropical climates extended much closer to the poles than today (Fig. 4).

Overall, the climate record of the BBF and LFF is consistent with long-term global records of the mid-Cretaceous and early Eocene and provides crucial new spatial coverage within existing reconstructions of global latitudinal temperature gradients (*e.g.*, Scotese *et al.*, 2021). Furthermore, the growing literature combining quantitative temperature and precipitation reconstructions allow to develop holistic classifications and maps of deep-time climate. This research is particularly relevant for understanding latitudinal climatic gradients during warm periods like the mid-Cretaceous and the early Eocene, a key knowledge gap for future predictions, and is crucial given the poor resolution of mid-latitude Southern Hemisphere reconstructions at these times. Besides, these historical scenarios emphasize the sensitivity of climate systems, and they can be an analog for future anthropogenic climate change scenarios.

CONCLUSIONS

In synthesis, the similarities observed between the mid-Cretaceous and early Eocene Ultisols of the Southern Golfo San Jorge Basin indicate that, despite differences in weathering intensity, both periods consistently point to temperate (to tropical) and humid climates under intense weathering conditions and leaching processes. These results support the hypothesis that hothouse conditions induce similar pedogenic responses in terrestrial environments, wheather in the mid-Cretaceous or during the early Eocene. The Warm Temperate zone expands, bringing tropical conditions to higher latitudes. The presence of paleo-Ultisols at ~51° paleo-S latitude during mid-Cretaceous and ~52° paleo-S latitude during early Eocene suggests that central Patagonia experienced significant latitudinal displacement of climate zones. Moreover, the data highlight the sensitivity of paleosols as proxies for climatic conditions, providing independent constraints that can be used to calibrate and validate global paleoclimate models.

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