

Reconstruction of a deep-time critical zone in southern patagonia (mid-high paleolatitude) during the mid-cretaceous greenhouse

Sabrina Lizzoli^{a,*}, Augusto N. Varela^{b,c}, M. Sol Raigemborn^{a,b}, Sebastian M. Richiano^{d,e},
Patricio Santamarina^f, Valeria S. Perez Loinaze^g

^a CONICET – UNLP. Centro de Investigaciones Geológicas, Diagonal 113 n.o 275 (1900) La Plata, Argentina

^b Cátedra de Micromorfología de Suelos, Facultad de Ciencias Naturales y Museo, UNLP, Calle 122 y 60 s/n (1900) La Plata, Argentina

^c Y-TEC S.A. and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Av. Del Petróleo s/n (1923), Berisso, Argentina

^d Instituto Patagónico de Geología y Paleontología (CONICET-CENPAT), Puerto Madryn, Argentina

^e Universidad Nacional de la Patagonia San Juan Bosco, Puerto Madryn, Argentina

^f División Paleobotánica, Facultad de Ciencias Naturales y Museo, CONICET, Paseo del Bosque s/n, B1900FWA, La Plata, Buenos Aires, Argentina

^g División Paleobotánica, Museo Argentino de Ciencias Naturales “Bernardino Rivadavia” (CONICET), Av. Ángel Gallardo 470, Ciudad Autónoma de Buenos Aires, C1405DJR, Argentina

ARTICLE INFO

Keywords:

Paleosols

Climate-reconstruction

Mid-Cretaceous

Greenhouse

Southern Hemisphere

ABSTRACT

The mid-Cretaceous was a period characterized by a global greenhouse climate. Paleosols can be used to reconstruct Critical Zones of the Earth's past and enhance our comprehension of such greenhouse conditions. Through macro- and micromorphological, clay-mineralogy, and bulk geochemical analyses of the paleosols, we conducted a deep-time Critical Zone reconstruction at mid-high paleolatitudes of the mid-Cretaceous Puesto El Moro Formation in the southern Patagonia (Austral-Magallanes Basin). Paleosols were classified as hydromorphic Histosol-like paleosols (Kachaike pedotype), Alfisols like-paleosols (La Lila pedotype), and Vertisol like-paleosols (La Bernarda pedotype). The analysis of these paleosols facilitated the reconstruction of the deep-time Critical Zone and enables us to infer the four scientific spheres (lithosphere, hydrosphere, biosphere, and atmosphere). Different types of paleosols developed under different parent materials with specific soil-moisture regime and drainage class. Overall, paleosols took place during temperate and humid conditions with a marked seasonality of the precipitations. The paleoclimate reconstruction obtained here provides new data from mid-high paleolatitudes and agrees with the current mid-Cretaceous climate reconstructions in the context of a greenhouse world.

1. Introduction

The Critical Zone (CZ), defined in 2006 by the US National Science Foundation, extends from the top of the vegetation canopy to the groundwater table. The CZ is a way to integrate the research of the four scientific spheres (lithosphere, hydrosphere, biosphere, and atmosphere) at the surface of Earth, and to study the linkages, feedback, and record of processes. Nordt and Driese (2013) extend the CZ concept to deep-time Critical Zones (DTCZ), arbitrarily defined as pre-Quaternary (>2 Ma). The recent advances in the study of paleosols, especially those refined by geochemical paleoclimate proxies, make it now possible to reconstruct paleoenvironmental conditions from paleosols preserved in the sedimentary record in deep time (Nordt and Driese, 2013; Lukens

et al., 2017). Therefore, paleosols can be used to reconstruct Critical Zones of the Earth's past (e.g., Nordt et al., 2012, 2013; Brantley et al., 2017; Lukens et al., 2017; Beverly et al., 2018; Ashley, 2020; Driese et al., 2021).

In southern Patagonia, at mid-high paleolatitude (~54° paleo-S, calculated according to Van Hinsbergen et al., 2015) crops out the Puesto El Moro Formation (mid-Cretaceous, Austral-Magallanes Basin at Lago San Martín area; Fig. 1). The sedimentological aspects were studied by Varela et al. (2019), who divided the unit into three informal sections. The lower section represents a shallowing-upward estuary bay transgressive succession characterized by tidal ravinement omission surfaces (Richiano et al., 2023), the middle section is characterized by braided and high-sinuosity meandering fluvial systems, and the upper

* Corresponding author.

E-mail address: slizzoli@cig.museo.unlp.edu.ar (S. Lizzoli).

<https://doi.org/10.1016/j.catena.2024.108054>

Received 19 December 2023; Received in revised form 16 April 2024; Accepted 18 April 2024

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section corresponds to a distributive fluvial system (Varela et al., 2019). Palynological aspects of the lower and middle sections of this unit were studied by Santamarina et al. (2023). In the lower section, gymnosperm pollen dominates palynological assemblages, while spores constitute a subordinate group. Conversely, the middle section exhibits a higher prevalence of spores (Santamarina et al., 2023). Varela et al. (2019) showed that the Puesto El Moro Formation accumulated synchronously with the estuarine-fluvial Mata Amarilla Formation (located ~ 100 km towards the south-east of the Puesto El Moro deposits; Fig. 1) during Cenomanian times (Varela et al., 2012b). The paleosols of the Mata

Amarilla Formation are widely known (Varela, 2015; Varela et al., 2011, 2012a, 2016, 2018, 2021), and although the development of paleosols in the Puesto El Moro was mentioned (Varela et al., 2019), there are no detailed studies on them so far.

Mid-Cretaceous climate reconstructions indicate that greenhouse conditions prevailed, characterized by high atmospheric CO₂ rates, reduced latitudinal temperature gradients, high precipitation rates through poles, and an enhanced hydrological cycle. (e.g. Barron, 1983; Caldeira and Rampino, 1991; White et al., 2005; Poulsen et al., 2007; Royer, 2010; Hay, 2011; Ludvigson et al., 2015; Jenkyns et al., 2017; Ó

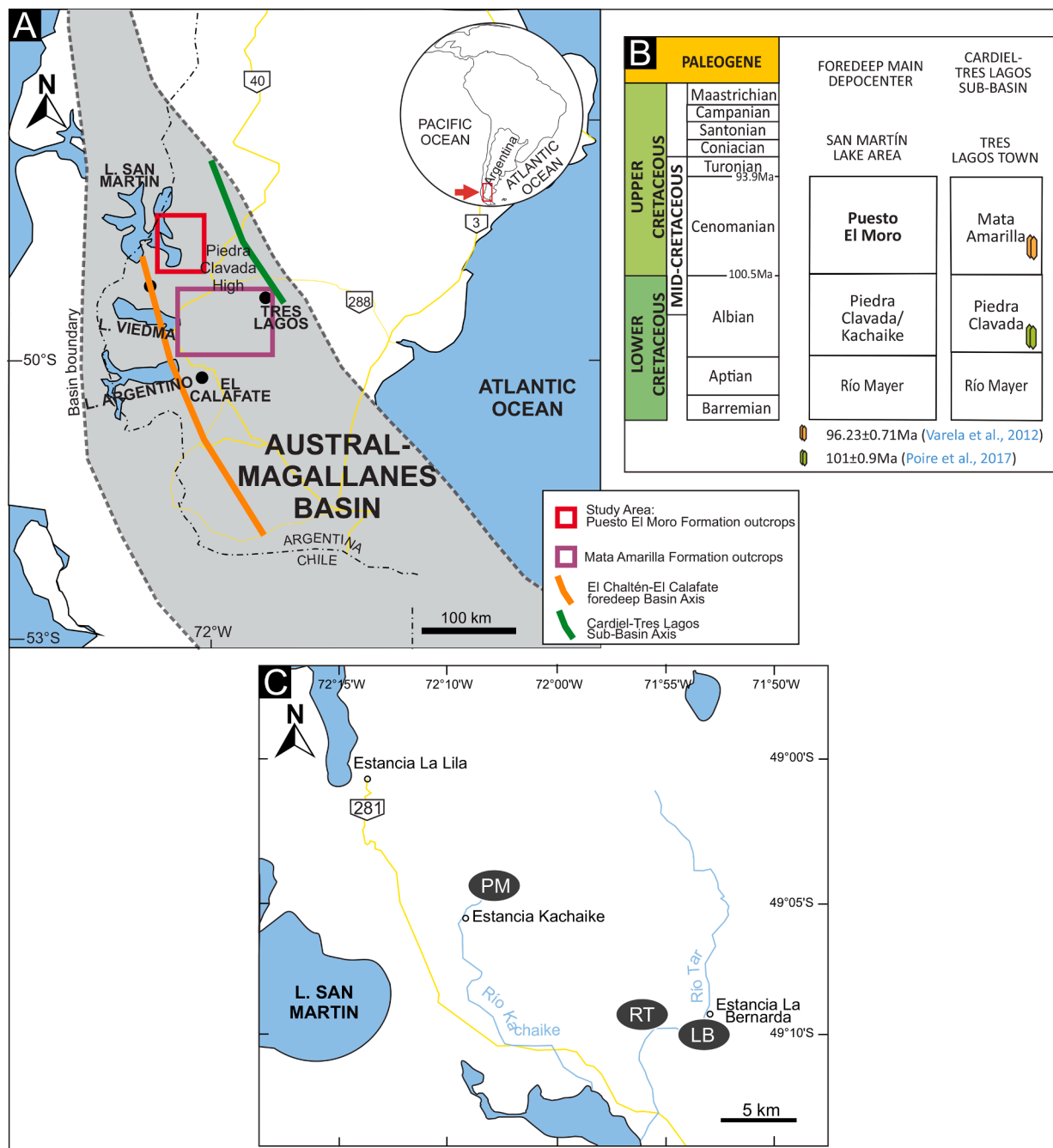


Fig. 1. A: Location map of the Cretaceous Austral-Magallanes Basin configuration showing the Cardiel-Tres Lagos sub-basins axis and the main foredeep depocenter with the El Chaltén-El Calafate axis (modified from Varela et al., 2019). The study area with the Puesto El Moro outcrops, near the Lago San Martín, is shown with a red rectangle. The Mata Amarilla outcrops are also indicated with a violet rectangle. B: Stratigraphic summary of the Cretaceous strata of the Austral-Magallanes Basin (modified from Cuitiño et al., 2019). C: Detail of the study area and location of the study localities near the Lago San Martín. PM: Puesto El Moro locality RT: Río Tar locality LB: Estancia La Bernarda locality. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Connor et al., 2019; Klages et al., 2011; Burgener et al., 2023). Therefore, the study of the record of paleosols within an estuarine-continental sequence at mid-high paleolatitudes in the southern Hemisphere becomes relevant. This research not only facilitates the reconstruction of a deep-time Critical Zone but also places a distinct emphasis on unraveling the paleoclimatic conditions prevalent during the development of these paleosols. By delving into this exploration, we not only gain valuable insights into the deep-time Critical Zone but also enhance our comprehension of past greenhouse conditions, thereby contributing substantially to our broader understanding of Earth's geological and climate evolution.

Here, we made a detailed paleopedological analysis of the Puesto El Moro Formation in the southern of the Austral-Magallanes Basin through macro- and micromorphological, clay-mineralogy, and bulk geochemical analyses of the paleosols, considering the sedimentological context, to perform a DTCZ reconstruction. Specific objectives of this paper are: (1) describe the characteristics of the paleosols in each one of the three sections of the Puesto El Moro Formation, (2) reconstruct the pedosphere, lithosphere, hydrosphere, biosphere, and atmosphere conditions that took place during the mid-Cretaceous in Southern Patagonia, and (3) link the paleoclimate reconstruction obtained here with the paleoclimate reconstructions obtained in other localities based on paleosol data to improve the mid-Cretaceous global climate reconstructions in the context of the Cenomanian greenhouse.

2. Geological setting and sedimentological context

The Austral-Magallanes Basin (Fig. 1a) is the southernmost basin of South America, comprising the southern region of Patagonia in Argentina and Chile. Three tectonic-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; and iii) an Aptian-Miocene foreland stage (Cuitiño et al., 2019).

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

The foredeep main depocenter shows a regressive pattern and it grades from a deep-marine setting in the south to a continental setting in the north (Cuitiño et al., 2019). From south to north, the onset of the foreland stage was recorded by the 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, the shallow marine deposits of the Lago Viedma Formation (Malkowski et al., 2016, 2017a, b), and the estuarine-continental deposits of the Puesto El Moro Formation (Varela 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, b; 2018, 2021; Varela, 2015) and to a lesser extent to the La Anita Formation (Moyano Paz et al., 2018; 2020).

The Puesto El Moro Formation (Fig. 1b) was originally described by Turic (1971), as a succession of continental sediments that overlies the Kachaike/Piedra Clavada Formation (Arbe, 1986; Varela et al., 2012a). Due to the absence of age constraints for the Puesto El Moro Formation, a correlation with the Mata Amarilla Formation was established based on their stacking patterns and internal facies arrangement (Varela et al., 2019). Consequently, we assume a mid-Cretaceous (Cenomanian) age for the unit. The succession crops out in the region of the Lago San Martín, near the homonymous outcrop belonging to the Estancia La Lila. Outcrops in the study area (Fig. 1b, 2) are distributed from the Río Kachaike to the Puesto El Moro (complete section); and continue parallel

to the provincial route 31. The Puesto El Moro Formation is transitional to the Mata Amarilla Formation (Varela, 2015), and consists of siltstones from brown, pink, gray to olive-gray with abundant rootlets, which alternate with yellowish to grayish conglomerates and purple-grayish, grayish, and olive-gray sandstones (Varela et al., 2019). They were previously interpreted as alluvial fan environments deposited in a humid climate context (Arbe, 1986).

The vertical distribution of the different facies associations (Table 1; Fig. 2) endorses the informal differentiation into three sections (Varela et al., 2019).

2.1. The lower section of the Puesto El Moro Formation

The lower section of the Puesto El Moro Formation (Table 1; Fig. 2) consists of tidal/estuary bay deposits and estuarine coastal plain deposits that change transitionally to estuarine and coastal plain deposits interbedded with bioclastic rudstones, and in a lesser proportion with sandy high-sinuosity meandering channels (Varela et al., 2019; Richiano et al., 2023). This lower section was deposited in response to transgression and is composed of several retrogradational intertidal to subtidal units that culminate in coastal plain deposits and mark the beginning of the foreland stage of the basin (Varela et al., 2019). The lower portion of the unit shows the stacked alternated fine-grained heterolithic and sandstone. The base of the sandstone packages represents a Tidal Ravinement Surface (TRS) produced by erosion and exposure of firm sediment (Richiano et al., 2023).

2.2. The middle section of the Puesto El Moro Formation

The contact between the lower and middle sections of the Puesto El Moro (Table 1; Fig. 2) is characterized by braided fluvial systems (Varela et al., 2019). Over these deposits, the middle section (Fig. 2) is characterized by a high-sinuosity meandering fluvial system which comprises deposits of sandy sheet channels interbedded with floodplain deposits with paleosols development, crevasse splay, and crevasse channels (Varela et al., 2019).

2.3. The upper section of the Puesto El Moro Formation

The upper section of the Puesto El Moro Formation (Table 1; Fig. 2) was interpreted as part of a distributive fluvial system and shows a predominance of unconfined flow deposits interbedded with short-lived channels and, in a lesser proportion with the channelized high-sinuosity meandering rivers, both interbedded with floodplain deposits (Varela et al., 2019).

3. Material and methods

The paleosols of the Puesto El Moro Formation were studied in the outcrops of the Puesto El Moro locality (PM: W 72°6.3'W, 49°4.3'S), Estancia La Bernarda locality (LB: 71°55.8'W, 49°9.8'S), and Río Tar locality (RT: 71°56.8'W, 49°9.6'S), where a complete a detailed sedimentary section were previously studied by Varela et al. (2019).

3.1. Macromorphology

Paleosols were identified in outcrop based on macroscopic pedo-features such as structure, mottles, nodules, color, slickensides, cutans, rhizoliths, thickness, mean grain size, and evidence of bioturbation (e.g., Retallack, 2001). Colors were described according to the Munsell Soil Color Chart (Munsell Color, 2010). We produced detailed paleopedological logs following Retallack (2001), Schoeneberger (2012), and Tabor et al. (2017).

Horizon designations were based on observable pedogenic features in the field (Soil Survey Staff, 2015), and supported later by thin-section detailing.

Table 1
Facies Associations (FAs) of the Puesto El Moro Formation. Modified from Varela et al. (2019).

Facies Association (FA)	Location	Lithology	Sedimentary structures	Geometry	Dimensions	Boundaries	Pedogenic features	Interpretation
AF-1: Massive bioturbated sandstones	Lower section	Upper medium-to coarse-grained sandstones	Massive. Diffuse cross-bedding. High degree of bioturbation. Plant debris.	Tabular bodies	1.3 to 0.3 m thick; more than 50 m of lateral continuity	Horizontal sharp to transitional bases and tops	—	Subtidal and intertidal bars in estuarine environment
AF-2: Heterolithic deposits	Lower section	Heterolithic intervals with coarsening upward trends.	Parallel and cross-lamination. Wavy, lenticular and flaser lamination. Organic debris and high degree of bioturbation	Tabular bodies	0.2–2 m thick; 250 m to 1 km lateral continuity	Horizontal sharp to transitional bases and tops	—	Tidal flat and tidal bars in estuarine environment
AF-3: bioclastic rudstones	Lower section	Rudstones	Massive bioclastic rudstones with mud rip-up clasts. Bioclasts dominated by oysters.	Tabular to lenticular bodies	13–41 cm thick; more than 250 m of lateral continuity	Sharp slightly erosive to horizontal bases; sharp horizontal to slightly convex-up tops	—	Storm events that remobilized bioclasts into the estuary very proximal to the source reef
AF-4: Mudstones with shell pavements	Lower section	Mudstones with shell pavements.	Horizontal lamination. Shell pavements of mollusc, fish scales and vertebrae.	Tabular bodies	Centimetres to metre thick	Sharp and horizontal bases and tops	—	Storm deposits
AF-5: Gravelly sheet bodies	Contact between the lower and middle section	Fine-grained conglomerates with a sandstone matrix	Large-scale tangential cross-bedding, low-angle planar cross-bedding, and less frequently, trough cross-bedding. Mud intraclasts at the base	Tabular bodies	2 m thick; more than 1 km of lateral continuity. W/T ratio > 30.	Erosional lower boundaries.	—	Fluvial channel-belt deposits. Braided fluvial system.
AF-6: Complex sandy sheet bodies	Middle and upper section	Coarse-to upper medium-grained sandstones.	Fining-upward succession. Cross trough cross-bedding and planar cross-bedding. Mud rip-up clasts at the base.	Lenticular bodies	1.3–7 m in thick; 200 m up to 800 m wide. W/T ratio is > 30	Erosional, concave-up bases; sharp horizontal tops	—	Fluvial channel-belt deposits of high sinuosity. Meandering fluvial system.
AF-7: Simple sandy sheet bodies	Middle and upper section	Coarse-to upper medium-grained sandstones	Fining-upward succession. Small-scale trough cross-bedding. Mud intraclasts at the base	Lenticular to tabular bodies	0.7 and 1.5 m thick; more than 500 m wide. W/T ratio > 30	Concave-up and erosional bases; sharp and horizontal tops	—	Fluvial channel-belt deposits of high sinuosity. Meandering fluvial system.
AF-8: Large-scale simple wide ribbon with wings bodies	Upper section	Coarse-grained sandstones	Trough and planar cross-bedding. Abundant mud intraclasts at the base	Lenticular bodies	0.6 to 1.2 m thick; 30 to 40 m wide. W/T ratio is < 30 (ribbon-shaped)	Concave-up and erosional bases; sharp and horizontal tops	—	Short-lived small channels. Transition from channelized to unchannelized flow in a distributive fluvial system.
AF-9: Gravelly small-scale simple ribbon bodies	Middle and upper section	Fine-grained conglomerates to very coarse-grained sandstones with sandy matrix	Small-scale trough cross-bedding, low-angle planar cross-bedding. Mud rip-up clasts	Lenticular bodies	20 and 80 cm thick; lateral extent up to 10 m wide. W/T < 15	Irregular concave-up lower surface	—	Deposition in crevasse channels generated during episodes of high river discharge
AF-10: Sandy small-scale simple ribbon bodies	Middle and upper section	Medium to very fine-grained sandstones	Small-scale trough cross-bedding, ripples and cross-lamination toward the tops of the bodies.	Lenticular bodies	30 and 40 cm thick; lateral extent up to 6 m wide. W/T < 15	Irregular concave-up lower surface	—	Overflow channels. Deposition in crevasse channels generated during episodes of high river discharge
AF-11: Tabular fine-grained sandstones	Middle and upper section	Very fine-grained sandstones and fine to very fine-grained tuffaceous sandstones	Massive. Sometimes also current ripples and cross-lamination	Tabular bodies	50 cm to 2 m thick and more than 500 m lateral exposure	Bases and tops are sharp to transitional	Rhizoliths, mottles, Fe-Mn nodules, cutans and slickensides	Levee and crevasse splay deposits with paleosol development in floodplains
AF-12: Tabular fining-upward succession	Upper section	Fine to very fine-grained sandstones, mudstones, fine to very fine-grained tuffaceous sandstones and tuffaceous mudstones.	Massive, often showing diffuse parting lineations and parting planes towards the base.	Tabular bodies	40 cm up to 1 m thick	Bases and tops are sharp to transitional	Rhizoliths and mottles	Unchannelized flow deposition in floodplains
AF-13: Fine-grained deposits	FA-13a: lower section FA-13b: middle section FA-13c: upper section	Mudstones, tuffaceous mudstones and tuffs	Generally massive. Lamination is rarely preserved.	Tabular bodies	centimetres to tens of metres thick	Bases and tops are sharp to transitional	Pedogenic structures such as rhizoliths, mottles, nodules, cutans and slickensides.	Coastal plain (FA-13a) and distal floodplain (FA-13b and c) with paleosol development

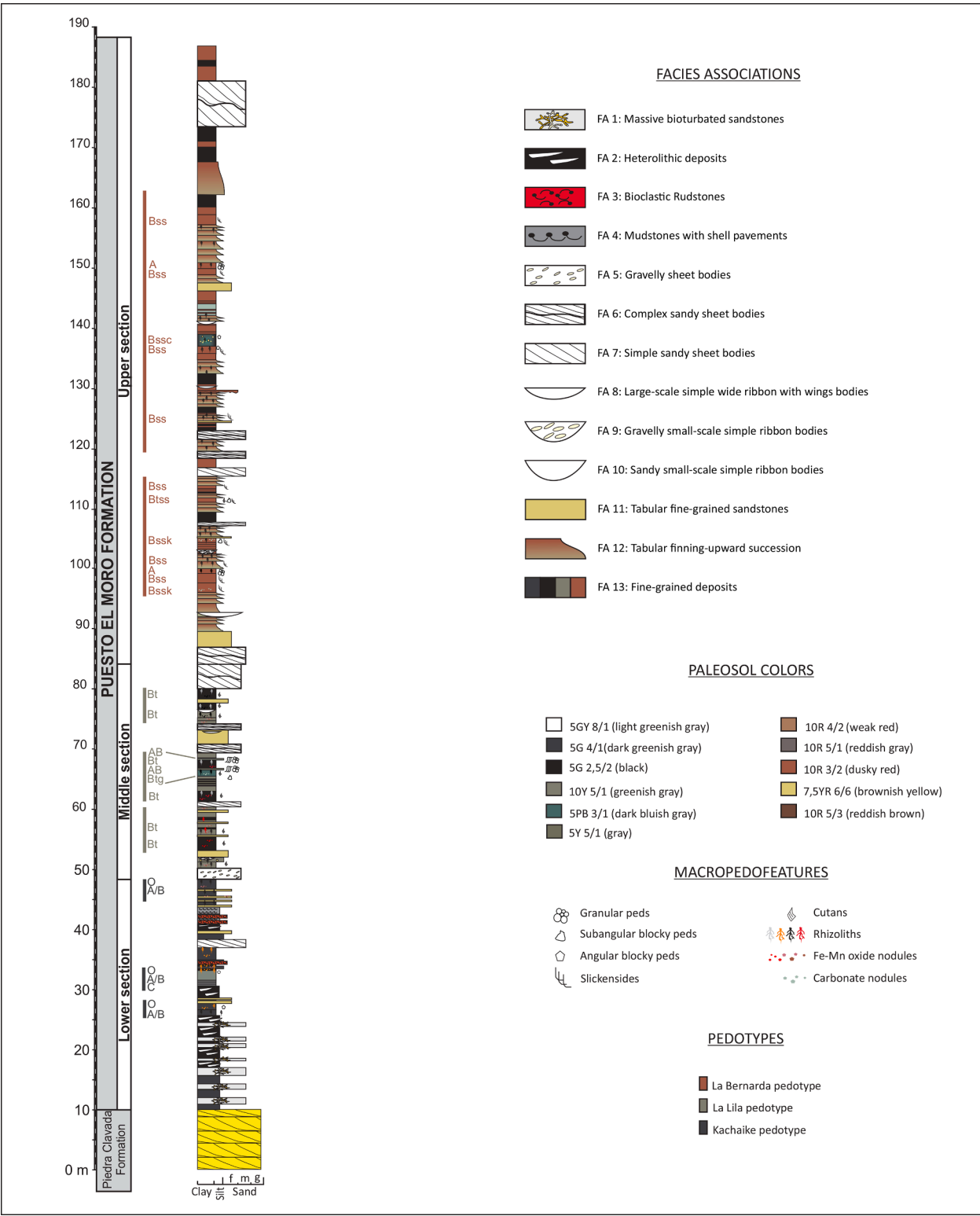


Fig. 2. Detailed measured sections of the Puesto El Moro Formation showing the vertical distribution of sedimentary facies (modified from Varela et al., 2019) and paleosols bearing levels.

3.2. Micromorphology

The paleosols were trenched to a depth of 30 cm to avoid weathering from modern materials during subsequent sampling. Thus, 28 samples consisting of paleosols were obtained for micromorphological studies. Thin sections of these materials were studied to establish mean grain

size, mineralogical composition, porosity, microstructure, microfabrics, groundmass, coarse/fine (c/f)-related distribution, coarse/fine (c/f)-ratio, vughs, and pedofeatures following the criteria of Bullock et al. (1985), Stoops (2003), and Stoops et al., (2010,2018). The modal percentages were calculated based on a comparison with modal percentages based on Stoops (2003). The degree of mineral alteration was based

on the scale of five classes of Stoops (1979) where: class 0 (fresh or nearly fresh), class 1 (slightly altered), class 2 (moderately altered), class 3 (strongly altered), and class 4 (completely altered). These data allowed us to characterize the kind and intensity of pedogenic processes, and refine macroscopic observations and horizon taxonomy.

Based on prevalent pedogenic features three pedotypes were defined following the criteria of Retallack (1994), in which the name is referring to geographic localities in the vicinity of the study area (Fig. 2).

Classification of the paleosols was made based on macro- and micromorphological features recognized in the constituent horizons. We use the Soil Taxonomy (Soil Survey Staff, 2022) and add the term “similar to modern” before the group name understanding its limitations in the fossil record. Additionally, we also used the Mack’s classification made specifically for paleosols (Mack, 1993).

3.3. X-ray diffraction

The bulk-rock and clay-mineral compositions of 44 paleosol samples were determined by X-ray diffraction (XRD) using a PANalytical X’Pert PRO diffractometer (Centro de Investigaciones Geológicas, La Plata, Argentina), using Cu radiation ($K\alpha = 1.5 \text{ \AA}$) and a Ni filter, and generation settings of 40 kV and 40 mA. Sample preparation followed Moore and Reynolds Jr. (1989) both for randomly oriented mounts and for the clay fraction ($< 2 \text{ mm}$). Routine air-dried mounts were run between 2 and $32^\circ 2\theta$ at a scan speed of $2^\circ 2\theta/\text{min}$. Samples were ethylene glycol-solvated without saturation pre-treatment and heated to 550°C , and they were run from 2 to $27^\circ 2\theta$ and 3 – $15^\circ 2\theta$, respectively, at a scan speed of $2^\circ 2\theta/\text{min}$. The methodology used for sample preparation follows Brown and Brindley (1980). Semi-quantitative estimations of the relative percentages of clay minerals were based on the peak area method (Biscaye, 1965) on glycolated samples (001 for illite, smectite, kaolinite, and illite/smectite; 002 for chlorite) by applying empirical factors (Moore and Reynolds Jr., 1989). The estimation of the mineralogical components is classified according to the following abundances: T: traces ($< 1\%$); VS: very scarce (1 – 5%); S: scarce (5 – 15%); M: moderate (15 – 25%); A: abundant (25 – 50%), and VA: very abundant ($> 50\%$).

3.4. Scanning electron microscopy-energy dispersive X-ray spectroscopy

To characterize textural, morphological, and mineralogical specific pedofeatures (such as clay infillings and coatings, organic matter, and Fe-Mn oxide nodules) we conducted scanning electron microscopy (SEM) with Energy Dispersive X-ray Spectroscopy (EDS) on 3 samples.

Samples were air-dried to constant weight and coated with Au and then analysed with a FEI Quanta 200 SEM. Their composition was analyzed using X-ray energy dispersive spectroscopy (EDS) and semi-quantitatively estimated using a Thermo Scientific Ultra Dry Silicon Drift Detector (Facultad de Ingeniería, Universidad Nacional de La Plata, Argentina).

This methodology enables to perform a comprehensive analysis of the textural, morphological, and mineralogical characteristics of the paleosols and pedofeatures, providing valuable insights into their composition and origin.

3.5. Bulk geochemistry

Geochemical analyses of the paleosols were undertaken on powdered materials from individual paleosol horizons of 10 samples that were powdered and analyzed by ICP-AES at ALS Global (Mendoza, Argentina). Sampling was performed following the criteria of Hyland and Sheldon (2016), where there is no evidence that diagenesis has modified the geochemistry of the sediment and paleosols. Analyses reported on a major-oxide basis were converted from weight percent to molar percent to calculate paleosol indices and paleoclimate proxies.

The pedogenic process indices used were: (1) for weathering

processes, Chemical Index of Alteration without Potassium (CIA-K), where $\text{CIA-K} = 100 \times [\text{Al}/(\text{Al} + \text{Ca} + \text{Na})]$ (Maynard, 1992), and the Paleosol Weathering Index (PWI), where $\text{PWI} = 100 \times [(4.20 \times \text{Na}) + (1.66 \times \text{Mg}) + (5.54 \times \text{K}) + (2.05 \times \text{Ca})]$ (Gallagher and Sheldon, 2013), (2) for hydrolysis of alkaline earth elements, loss of exchangeable bases $[(\text{Al}/\Sigma(\text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO} + \text{MgO}))]$, (3) for clayeyness ($\text{C} = \text{Al}/\text{Si}$ ratio, Sheldon and Tabor, 2009), (4) for leaching (Ba/Sr ratio, Sheldon, 2006), and finally, provenance (5) was also estimated using the calculated Ti/Al ratio (Maynard, 1992).

Climofunctions for mean annual temperature (MAT), calculated for B horizons, were estimated using the (1) the Salinization Index ($\text{SAL} = [\text{Na} + \text{K}]/\text{Al}$) of Sheldon et al. (2002) where $\text{MAT} (^\circ \text{C}) = -18.516 (\text{SAL}) + 17.298$, with a standard error associated of $\pm 4.4^\circ \text{C}$. This equation can be used in a temperature range between 2 and 20°C since at higher temperatures Na^+ and K^+ are completely washed out. Although it can be applied to most paleosols orders, it is not usefully applied to soils with near-surface carbonate or evaporate minerals, or soils with highly weathered minerals. It should also be avoided to swamps, bogs, eolian dunes, disturbed soils by human activities, or with high slope paleosols (Sheldon et al., 2002); and (2) the Paleosol Weathering Index (PWI) of Gallagher and Sheldon (2013) where $\text{MAT} (^\circ \text{C}) = 2.74 \ln (\text{PWI}) + 21.39$, with a standard error associated of $\pm 2.1^\circ \text{C}$. This climofunction can be applied only to three soil orders: Inceptisols, Alfisols, and Ultisols. It is recommended to use with values of PWI less than 60 since higher values are considered indistinguishable from the material parental. Being specifically designed for clay-rich paleosols, this equation cannot be used in other soil orders (Gallagher and Sheldon, 2013).

Climofunctions for mean annual precipitation (MAP), calculated for B horizons, were estimated using the (1) the $\Sigma\text{Bases}/\text{Al}$ ratio of Sheldon et al. (2002), where $\text{MAP} (\text{mm}) = -259.3 \ln (\Sigma\text{Bases}/\text{Al}) + 759$, with a standard error associated of $\pm 235 \text{ mm/yr}$; (2) the CIA-K index of Maynard (1992), where $\text{MAP} (\text{mm}) = 221.12 + 0.0197 (\text{CIA-K})$, with a standard error associated of $\pm 181 \text{ mm/yr}$ (Sheldon et al., 2002). This equation can be used in a precipitation range between 200 and 1600 mm/yr, and cannot be used in soils with carbonate or evaporate, or in soils highly weathered (Sheldon et al., 2002). Recently, Lukens et al. (2019), made a calibration and established a standard error of $\pm 564 \text{ mm/yr}$; and (3) the CALMAG index $[(\text{Al}/\text{Al} + \text{Ca} + \text{Mg}) \times 100]$ of Nordt and Driese (2010a), where $\text{MAP} (\text{mm}) = 22.69 (\text{CALMAG}) - 435.8$, with a standard error associated of $\pm 108 \text{ mm/yr}$ (Nordt and Driese, 2010a). This climofunction was specifically developed for Vertisols and soils with vertic features. The CALMAG index also allows inferences about the soil moisture regime defined by the Soil Taxonomy (Nordt and Driese, 2010a).

Climate results are discussed in terms of climate zones. For MAT (based on the terminology proposed by Zhang et al. (2016) and modified by Zhang et al. (2019) and for MAP (based on the terms proposed by Bull (1991)).

4. Results

Pedotypes are described in order of appearance in the stratigraphic section (Fig. 2).

4.1. The paleosols of the lower Puesto El Moro Formation – Kachaïke pedotype

This pedotype (Fig. 3A-H) is lithified and it is developed within the fine-grained deposits in the upper part of the lower section of the unit (Fig. 3A). The representative profile is characterized by O–A/B–C horizons (Fig. 3B).

The O is a black (10Y 6/1) horizon that is 0.20 m-thick. It is characterized by carbonized organic matter (content between 15 and 20 %) and remains of roots and fibers, with different degrees of carbonization. The presence of delicate rhizoliths and mottles disseminated in the matrix, orange in color, are very common (Fig. 3C). The coarse fraction

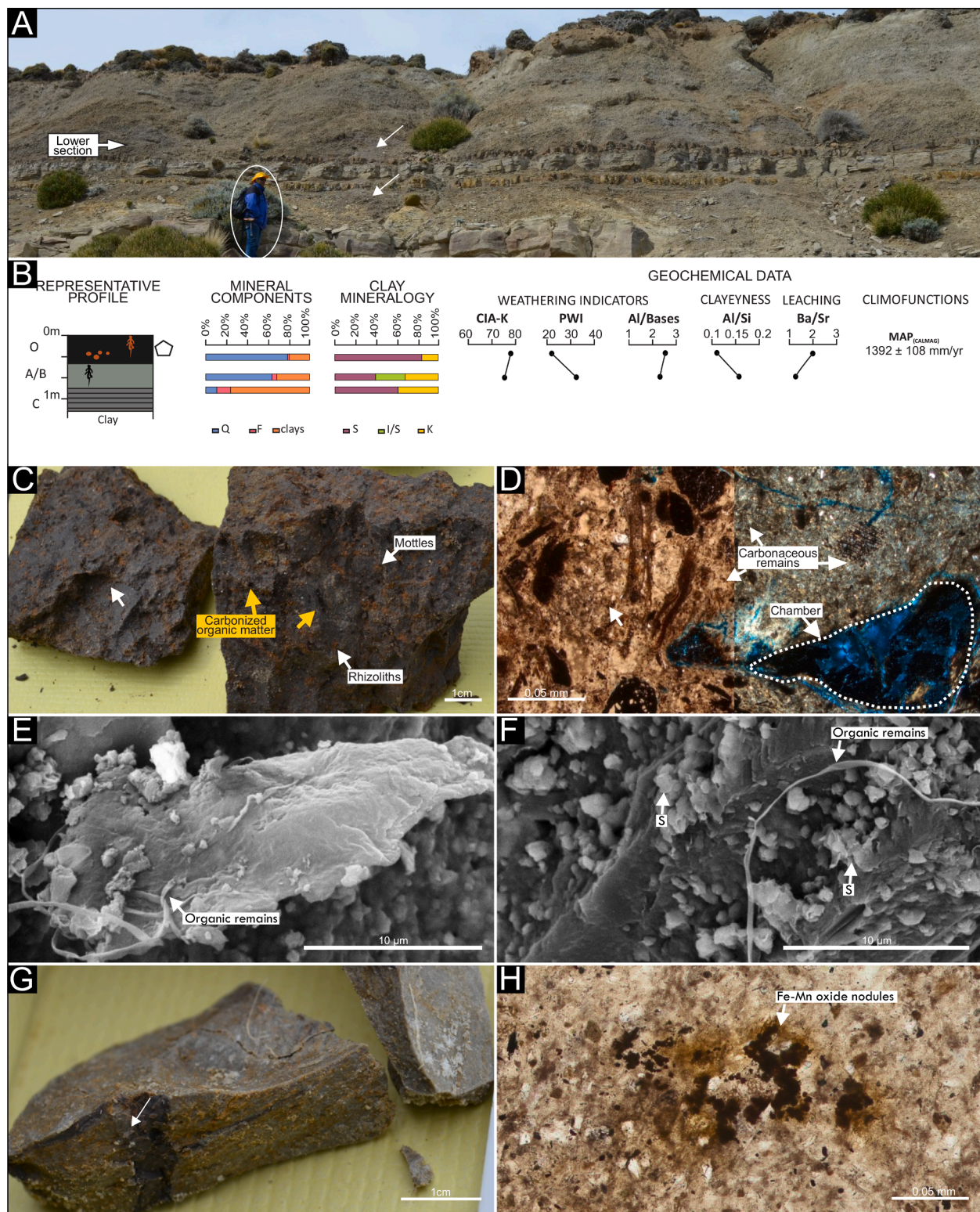


Fig. 3. A: General appearance of the lower section of Puesto El Moro Formation. White arrows indicate the pedogenized profiles of the Kachaikite pedotype. The white circle indicates a person for scale. B: Representative profile, mineral components (Q: quartz; F: feldspars; clays) and clay mineralogy (S: smectite; K: kaolinite; I/S: illite/smectite mixed-layers) determined by XRD, and geochemical data of the Kachaikite pedotype. Climofunctions based on average values of Bg horizons. See key to Fig. 2 for macrofeatures. C-F: O horizon. C: Carbonized organic matter preserved in the matrix (yellow arrows). As pedofeatures rizoliths and mottles, orange in color, are disseminated in the matrix (white arrows). D: Micromass composed of carbonaceous remains (white arrows). A chamber with loose discontinuous infilling of organic matter is indicated by a dotted line (left: PPL, x10; right: XPL, x10). E: Detail of organic remains with filamentous morphology under SEM-EDS. F: Detail of smectites with curled flake morphology associated with filaments under SEM-EDS. G-H: A/Bg horizon. G: Detail of a rhizolith. H: Fe-Mn oxide nodules, with aggregated morphology (PPL, x10). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(>31 μm ; coarse-loamy to sandy texture), is made up mainly of quartz and volcanic lithics (class 0 to 1), and in a lesser extend of feldspars (class 1), amphiboles (class 1), pyroxenes (class 1), and glauconite grains (class 0). The presence of carbonaceous remains, such as tissue and cell fragments, is highlighted. The micromass (<31 μm), with orange and red colors, is mainly formed of clays impregnated with Fe-Mn oxides. The coarse/fine (c/f) ratio ranges from 30 to 35 % of the coarse fraction with a double spaced porphyric coarse/fine (c/f) related distribution pattern. Small vughs, chambers, and channels were preserved in the groundmass. The micromass has a stipple-speckled b-fabric. Micropedofeatures of O horizons include: (1) loose discontinuous infillings, in channels and chambers, of groundmass and organic matter (fecal pellets); (2) loose discontinuous infillings of Fe-Mn oxides; (3) Fe-Mn oxide nodules, moderate to very well impregnated with typical morphology, and Fe-Mn oxide hypocotings are also present. The mineral components identified by XRD are very abundant quartz (~80 %), moderate clays (~15 %), and very scarce feldspars (<5%; Fig. 3B). The clay mineral association was dominated by very abundant (~80 %) smectite and moderate (~20 %) kaolinite (Fig. 3B). Under SEM-EDS, abundant remains of organic matter with filamentous morphology (possible fungal hyphae), with thickness less than a micron and lengths greater than 10 μm (Fig. 3E). Associated with the filaments, clays were identified as smectites, with curled flake morphology and sizes between 2 to 4 μm (Fig. 3F). EDS showed a high Si peak, followed by Al, and minor Fe, Na, Mg, and Ca peaks, which confirm a smectite composition. The weathering indicators show that the CIA-K value is ~ 77 % on average, the PWI is ~ 24 % on average, and the Al/ Σ Bases is ~ 2.1 % on average. The clayeyiness (Al/Si ratio) is ~ 0.10 % on average and the leaching (Ba/Sr ratio) is ~ 2.03 % on average. Finally, the Ti/Al ratio is ~ 0.034 % on average (Fig. 3B).

The A/B is a greenish gray (10Y 5/1) horizon that is 0.40–0.80 m-thick. Macroscopic features are rhizoliths, Fe-Mn oxide mottles and nodules, and slickensides (Fig. 3G). The coarse fraction (>31 μm) shows similar components to the O horizons, except for the organic components while the micromass (<31 μm) is mainly composed of clays. The c/f ratio ranges from 30 to 40 % of the coarse fraction with a chitonic to single space porphyric c/f related distribution pattern. Scarce vughs and channels are preserved in the groundmass. The micromass is massive with an undifferentiated to incipient striated b-fabric. Micropedofeatures of A/B horizons are nodules and coatings and include (1) Fe-Mn oxide nodules very well impregnated with aggregated or amiboidal morphologies; (2) Fe-Mn oxide coatings with typical morphology conforming ferrans and mangnans; (3) loose discontinuous infillings of groundmass inside channels (Fig. 3H). The mineral components identified by XRD are scarce to very abundant quartz (~10–70 %), moderate to very abundant clays (~30–70 %), and scarce feldspars (2–10 %). The clay mineral association was dominated by moderate to very abundant (~40–60 %) smectite and moderate (~20 %) illite/smectite mixed layers. The weathering indicators show that the CIA-K value is ~ 78.6 % on average, the PWI is ~ 32.6 % on average and the Al/ Σ Bases is ~ 2.3 % on average. The clayeyiness (Al/Si ratio) is ~ 0.17 % on average and the leaching (Ba/Sr ratio) is ~ 1.35 % on average. Finally, the Ti/Al ratio is ~ 0.039 % on average.

The C horizon is dark greenish gray (10Y 4/1) and composed of mudstone with horizontal lamination. The coarse fraction (fine to medium sand texture) is made up of quartz and volcanic lithics (class 1), feldspars (class 1), carbonate shell remains (class 1 to 2), glauconite grains (class 1), and biotite (class 1).

4.2. The paleosols of the middle Puesto El Moro Formation – La Lila pedotype

This pedotype (Fig. 4A–H) is lithified and it is developed within the fine-grained tabular sandstones and in the fine-grained deposits of the middle section of the unit (Fig. 4A). La Lila pedotype has two representative profiles: AB–Bt and AB–Btg–C (Fig. 4B).

The AB is a grey to olive grey (5Y 5/1 to 5Y 5/2) horizon that is 0.30–0.50 m-thick. These horizons were characterized by high bioturbation, granular peds, rhizoliths, burrows, and minor Fe-Mn oxide nodules (Fig. 4C). The coarse fraction (>31 μm) is dominated by silt sized grains of quartz, feldspars (class 0 to 1), and sedimentary, volcanic, and metamorphic lithics (class 0 to 1), while the micromass (<31 μm) is mainly composed of clays. The c/f ratio ranges from 20 to 25 % of the coarse fraction with an open to double-spaced porphyric c/f related distribution pattern. Subangular blocky and granular peds were defined by compound packing voids. Vughs, chambers, and channels were also observed. The most conspicuous micropedofeatures on the horizon are coatings. In some cases, they obliterated the porosity, defining loose continuous infillings. They are composed of organic matter and groundmass (Fig. 5D). Hypocoatings of organic matter and Fe-Mn oxide nodules are also present in the groundmass. The mineral components identified by XRD are very abundant quartz (~65–75 %), moderate clays (~20 %), and very scarce feldspars (5–15 %; Fig. 4B). The clay mineral association was dominated by very abundant (~65–80 %) smectite and moderate to abundant (20–35 %) kaolinite (Fig. 5B). The weathering indicators show that the CIA-K value is ~ 72.7 % on average, the PWI is ~ 26.6 % on average and the Al/ Σ Bases is ~ 1.63 % on average. The clayeyiness (Al/Si ratio) is ~ 0.18 % on average and the leaching (Ba/Sr ratio) is ~ 2.71 % on average. Finally, the Ti/Al ratio is ~ 0.053 % on average (Fig. 5B).

The Bt is a dark grey and reddish gray (5Y 4/1 to 10R 5/1) horizon that is 0.40–0.60 m-thick. Abundant red (10R 4/6) rhizoliths, Fe-Mn oxide mottles and nodules, cutans, and slickensides are present (Fig. 4E). The coarse fraction (>31 μm) is similar to the one described for the AB horizon while the micromass (<31 μm) is not always present, when it does it is mainly composed of clays with brownish color mottling with zones more or less impregnated with Fe-Mn oxides. The c/f ratio ranges from 20 to 30 % of the coarse fraction with an open to double-spaced porphyric c/f related distribution pattern. Vughs, chambers, and channels are very common, although in the cases where no groundmass is visible, simple packing voids were observed. Clay and clay with Fe-Mn oxides coatings are the most abundant micropedofeatures. They present typical to crescent morphologies and in some cases, they conform dense complete infillings (Fig. 4F). The mineral components identified by XRD in Bt horizons are very abundant quartz (~50–60 %), abundant to very abundant clays (~40–60 %), and scarce feldspars (>10 %; Fig. 4B). The clay mineral association is dominated by very abundant (~70–90 %) smectite and scarce to moderate (10–30 %) kaolinite (Fig. 4B). Under SEM-EDS, clay coatings were identified, composed of smectite with curved leaves morphology, in some cases, the leaves conform a rosette pattern (Fig. 4G). EDS showed a high Si peak, followed by a moderate Al peak, and minor K and Na peaks, which confirm a smectite composition (Fig. 4G). The weathering indicators show that the CIA-K value is ~ 78.4 % on average, the PWI is ~ 39.4 % on average and the Al/ Σ Bases is ~ 1.98 % on average. The clayeyiness (Al/Si) is ~ 0.19 % on average and the leaching (Ba/Sr ratio) is ~ 1.70 % on average. Finally, the Ti/Al ratio is ~ 0.063 % on average (Fig. 4B).

The Btg is an infrequent greenish grey (5 PB 3/1) mottling with grey greenish (5G 3/1) horizon, that is 0.30–0.50 m-thick. It is characterized by scarce cutans and black rhizoliths. The coarse fraction (>31 μm) is similar to the one described for the AB horizon, while the micromass (<31 μm) is mottled, with brown to red colors, frequently obscured by Fe-Mn oxides. The c/f ratio ranges from 20 to 30 % of the coarse fraction with an open to double-spaced porphyric c/f related distribution pattern. The voids are composed of vughs, channels, and a few chambers. Micropedofeatures as clay and clay with Fe-Mn oxides coatings are the most abundant. They are typical, laminated, and crescent, and in some cases conform dense complete infillings. Extended hypocotings and typical and amiboidal nodules are also observed. In all cases they were composed of Fe-Mn oxides (Fig. 4H). The mineral components identified by XRD in Btg horizons are similar to the one described for the Bt horizons, while the weathering indicators show that the CIA-K value

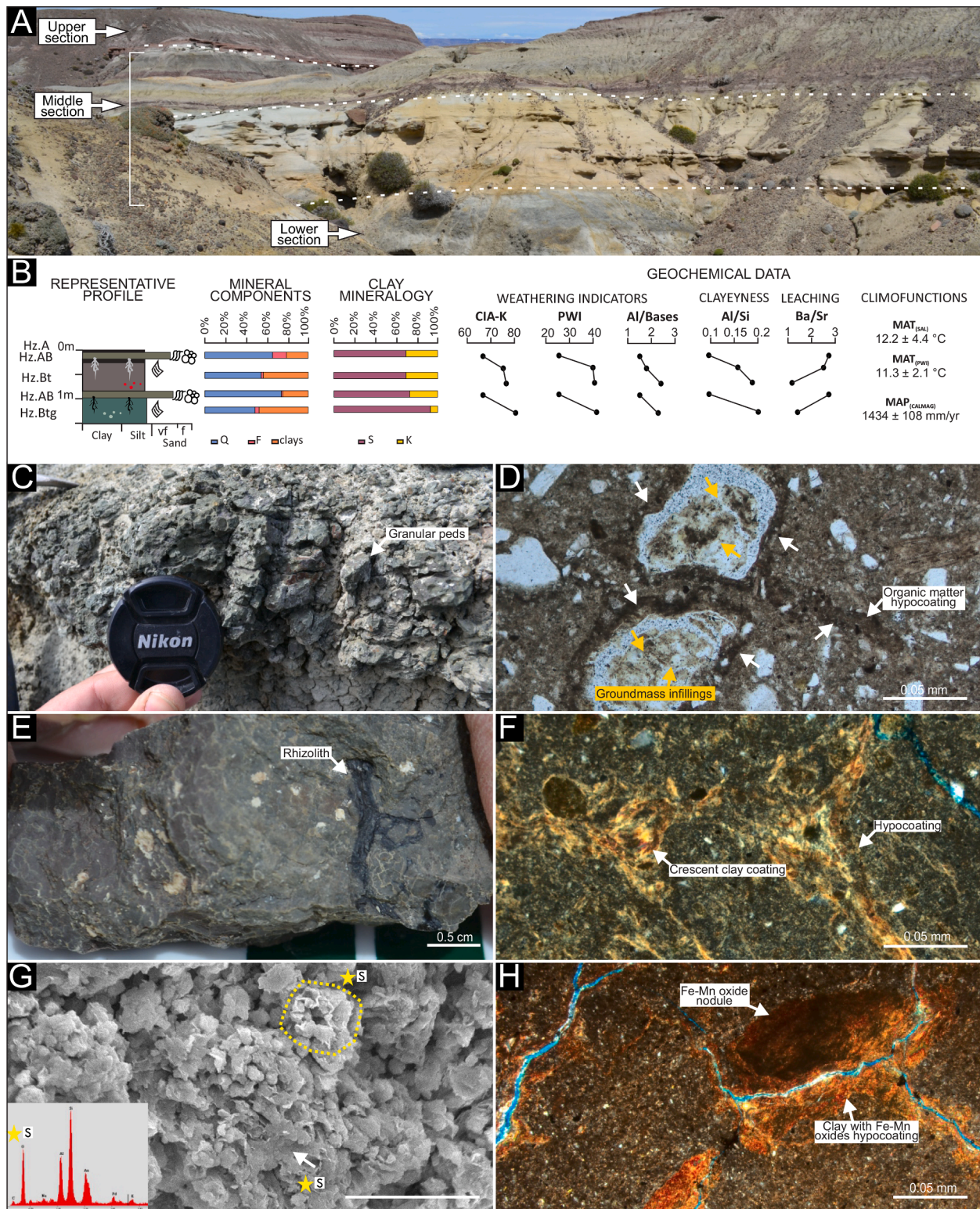


Fig. 4. A: General appearance of the middle section of the Puesto El Moro Formation. B: Representative profile, mineral components (Q: quartz; F: feldspars; clays) and clay mineralogy (S: smectite; K: kaolinite) determined by XRD, and geochemical data of La Lila pedotype. Climofunctions based on average values of Bt horizons. See key to Fig. 2 for macrofeatures. C-D: AB horizon. C: Granular peds and high bioturbation. D: Groundmass loose continuous infillings in cameras (yellow arrows) and organic matter hypocatings (white arrows; PPL, x5). E-G: Bt horizon. E: Detail of a black rhizolith. F: Crescent clay coating (left arrow) and clay hypocating (right arrow) (XPL, x5). G: Detail of a clay coating composed of smectite under SEM with curved leave morphologies (yellow arrows). The yellow dots indicate a rosette pattern. EDS peaks confirm a smectite composition. Scale bar: 10 μ m. H: Btg horizon with a Fe-Mn oxide nodule incorporate in a clay with Fe-Mn oxide hypocating (XPL, x5). PPL: plane polarized light; XPL: cross polarized light. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

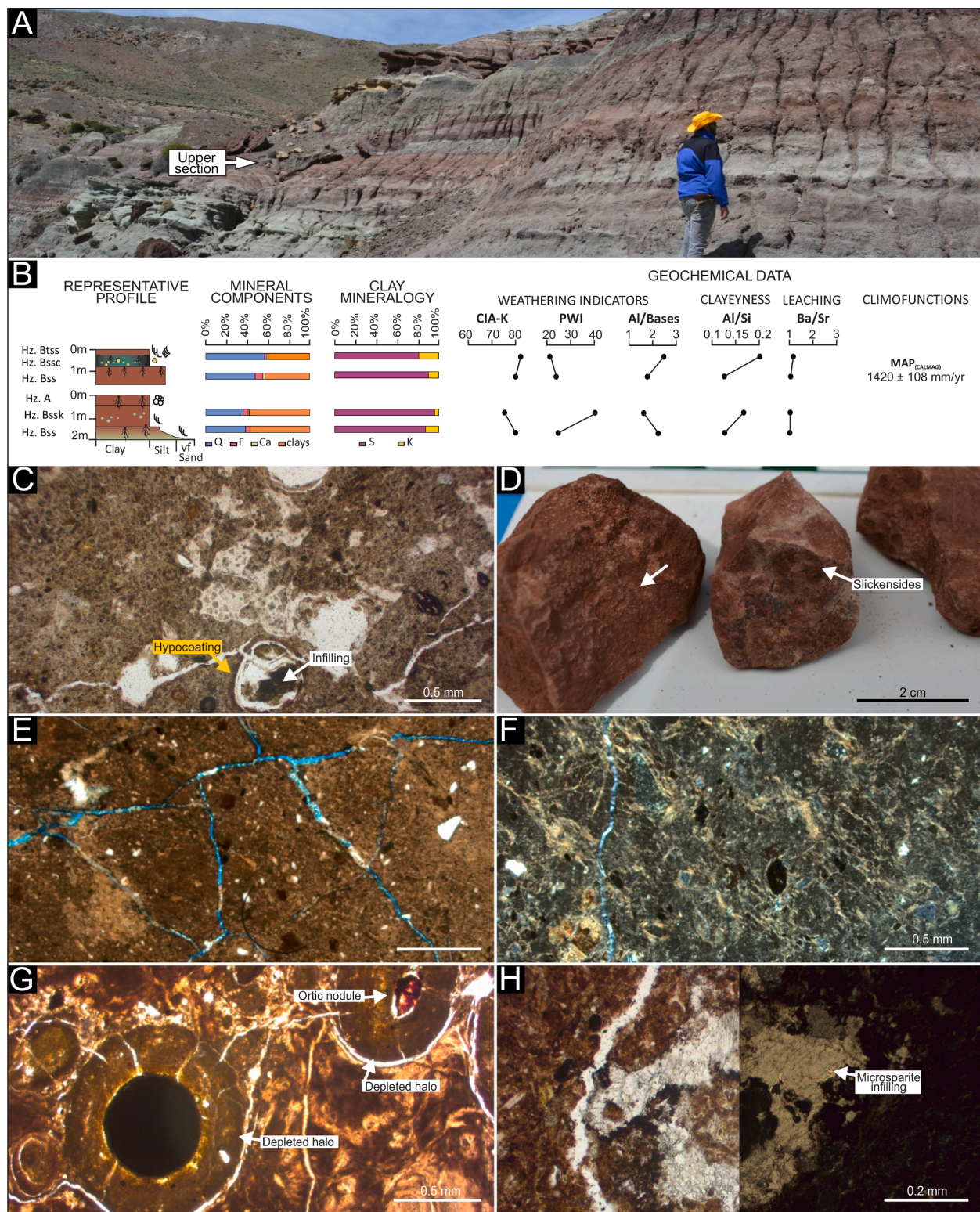


Fig. 5. A: General appearance of the upper section of the Puesto El Moro Formation. B: Representative profile, mineral components (Q: quartz; F: feldspars; Ca: calcite; clays) and clay mineralogy (S: smectite; K: kaolinite) determined by XRD, and geochemical data of La Lila pedotype. Climofunctions based on average values of Bss (and Bssc, Bssk, and Btss) horizons of the lower part of the upper section. See key to Fig. 2 for macrofeatures. C: Abundant chambers with loose discontinuous infillings of groundmass in A horizon (white arrow). Note the presence of organic matter hypocointing (yellow arrow; PPL x5). D-F: Bss horizon. D: Detail of slickensides defining angular blocky peds. E: Blocky peds defined by compound packing voids and planar voids (PPL, x5). F: Cross-striated b-fabric (XPL, x5). G: Bssc horizon cemented by Fe-Mn nodules and concretions. Note the ortic nodule with a depleted halo (PPL, x5). H: Bssk horizon with a dense complete infilling of microsparite (left: PPL, x10; right: XPL, x10). PPL: plane polarized light; XPL: cross polarized light. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

is $\sim 81.55\%$ on average, the PWI is ~ 40.4 on average, and the $Al/\Sigma Bases$ is $\sim 1.35\%$ on average. The clayeyness (Al/Si) is $\sim 0.097\%$ on average and the leaching (Ba/Sr ratio) is $\sim 1.35\%$ on average. Finally, the Ti/Al ratio is $\sim 0.056\%$ on average (Fig. 4B).

The C horizon is massive or preserves relict sedimentary structure. The coarse fraction (coarse-loamy to fine sandy texture) is composed mainly of quartz, feldspars, and sedimentary and volcanic lithics.

4.3. The paleosols of the upper Puesto El Moro Formation – La Bernarda pedotype

This pedotype (Fig. 5A–H) is lithified and it is developed within the fine-grained deposits of the upper section of the Puesto El Moro Formation. The representative profile is characterized by stacked Bss horizons with Bssc, Bssk, and Btss horizons. In some cases, A and C horizons are preserved (Fig. 5B).

The A is a black to dark red (5G 2.5/2 to 10R 3/2) horizon that is 0.20 m-thick. Macroscopic features include rhizoliths and granular peds. The coarse fraction ($>31\ \mu m$) is composed of quartz and volcanic lithics while the micromass ($<31\ \mu m$) is mainly composed of clays with a light brown color. The c/f ratio ranges from 5 to 15 % of the coarse fraction with an open to double-spaced porphyric c/f related distribution pattern. Chambers and vughs are very abundant and in general, are connected by channels. B-fabric is cross-striated. A granular micro-structure is observed. Loose discontinuous infillings of groundmass inside chambers and vughs are abundant, which in some cases are surrounded by organic matter hypocoating (Fig. 5C). A few Fe-Mn oxide nodules, poorly impregnated, are also observed.

The Bss is gray to olive green and red to dark brown (10Y 5/1 and 10R 4/2 to 10R 3/2) horizon that is 0.20–0.60 m-thick. Macroscopic features include rhizoliths, Fe-Mn oxide mottles and nodules, and slickensides that divide angular blocky peds (Fig. 5D). The coarse fraction ($>31\ \mu m$) is composed mainly of quartz while the micromass ($<31\ \mu m$) is mainly composed of clays with a reddish color with white zones, due to low impregnation with Fe-Mn oxides. The c/f ratio ranges from 3 to 15 % of the coarse fraction with an open to double-spaced porphyric c/f related distribution pattern. Compound packing voids and planar voids are defined as blocky peds (Fig. 5E). Vughs and channels are also observed. B-fabric is cross-striated (Fig. 5F). Amiboidal nodules, moderately to very well impregnated, and typical coatings, both composed of Fe-Mn oxides, are the most conspicuous pedofeatures. Bssc, Bssk, and Btss are similar to Bss horizons and the differences are in their micropedofeatures. Bssc horizons are strongly cemented by Fe-Mn nodules and concretions. Nodules present typical or amiboidal and digitated morphologies, moderately to very well impregnate. Ortic nodules with a depleted halo are also observed. Is common the presence of planar voids fracturing the nodules (Fig. 5G). Bssk horizons show dense complete and incomplete infillings of microsparite and sparite (Fig. 5H). Btss horizons present crescent and laminated clay coatings. The mineral components identified by XRD in Bss, Bssc, Bssk, and Btss horizons are abundant to very abundant quartz (~ 50 – 60%), abundant clays (~ 50 – 95%), scarce feldspars ($<10\%$). In the Bssk are also scarce calcite ($<10\%$). The clay mineral association is dominated by very abundant (~ 70 – 95%) smectite and scarce to abundant (5 – 30%) kaolinite. The weathering indicators show that the CIA-K value is $\sim 80\%$ on average, the PWI is $\sim 33.7\%$ on average, and the $Al/\Sigma Bases$ is $\sim 2.36\%$ on average. The clayeyness (Al/Si) is $\sim 0.174\%$ on average and the leaching (Ba/Sr ratio) is $\sim 0.97\%$ on average. Finally, the Ti/Al ratio is $\sim 0.059\%$ on average.

The C horizon has little or no evidence of pedogenesis. The coarse fraction (fine to medium sandy texture) is composed of mainly of quartz, feldspars, and sedimentary and volcanic lithics.

4.4. Paleotemperature and paleoprecipitation of the Puesto El Moro Formation

Geochemical data from the paleosols of the Puesto El Moro were used to obtain climofunctions.

The MAT estimates were calculated only for the middle section of the Puesto El Moro Formation using both the SAL proxy and the PWI proxy. In the lower section the majority of carbonaceous material and the hydromorphic features that resembles to a waterlogging soil prevent us from using the SAL proxy. In the upper section the presence of carbonate features also prevent us from using the SAL proxy.

The Bt horizons of the middle section of the Puesto El Moro Formation show a $MAT_{(SAL)}$ estimated of $12.2 \pm 4.4\ ^\circ C$ and a $MAT_{(PWI)}$ estimated of $11.3 \pm 2.1\ ^\circ C$ (Fig. 4B). Thus, these conditions are classified as temperate based on the terminology proposed by Zhang et al. (2016) (Fig. 4B and Fig. 6).

The MAP estimates were calculated using only the CALMAG proxy for the paleosols of the entire Puesto El Moro Formation. This is because it was developed as a weathering index specifically for paleosol profiles with vertic features (Nordt and Driese, 2010), and hence the entire succession is characterized by this type of features, the CALMAG index is presumed to be a useful and appropriate weathering index to be applied.

The Bg horizons of the lower section of the Puesto El Moro Formation show a $MAP_{(CALMAG)}$ estimated of $1392 \pm 108\ mm/yr$ (Fig. 3B). The Bt horizons of the middle section of the Puesto El Moro Formation show a $MAP_{(CALMAG)}$ estimated of $1434 \pm 108\ mm/yr$ (Fig. 4B). The Bss (and Bssc, Bssk, and Btss) of the lower part of the upper section of the Puesto El Moro Formation show a $MAP_{(CALMAG)}$ estimated of $1420 \pm 108\ mm/yr$ (Fig. 5B). The average values of MAP for the entire Puesto El Moro Formation have an average of $1424 \pm 108\ mm/yr$ (Fig. 6). Thus, these conditions are classified as humid based on the terminology proposed by Bull (1991) (Fig. 6).

5. Discussion

5.1. Deep-time critical zone reconstruction in mid-cretaceous Southern Patagonia

5.1.1. Pedosphere

The sedimentological analysis conducted by Varela et al. (2019) resulted in the subdivision of the Puesto El Moro Formation into three informal sections, each characterized by a distinct type of paleosol. The lower section of the Puesto El Moro Formation is identified by estuary bay deposits and estuarine coastal plain deposits formed in a littoral estuarine environment (Varela et al., 2019). Under these conditions, paleosols with preserved organic matter and hydromorphic features of the Kachaie pedotype were developed. The contact between the lower and middle sections was marked by the presence of continuous outcrops of a braided fluvial system (Varela et al., 2019). The middle section continued as a high-sinuosity meandering fluvial system with moderately well-developed paleosols of the La Lila pedotype. Finally, the upper section was dominated by unconfined flow deposits that were interpreted as part of a distributive fluvial system (Varela et al., 2019), where paleosols of the La Bernarda pedotype were found.

The paleosols of the Lower Puesto El Moro Formation (Kachaie pedotype) present a relatively well-developed horizon sequence (O-A/B-C horizons) indicating a moderately developed paleosol. The high content of organic matter and the preservation of organic horizons are mainly linked to the sedimentary environment in which this type of paleosols are developed, which is associated with waterlogged conditions, probably in the margins of an estuary (coastal plain) environment. Here, the decomposition of the organic matter is inhibited due to the lack of oxygen (Buol et al., 2011), and their preservation indicates anoxic and reducing conditions resulting from high watertable as it typically occurs in hydromorphic soils (e.g., Wright et al., 2000; Kraus and Hasiotis, 2006; Raigemborn et al., 2023). Besides, this pedotype is

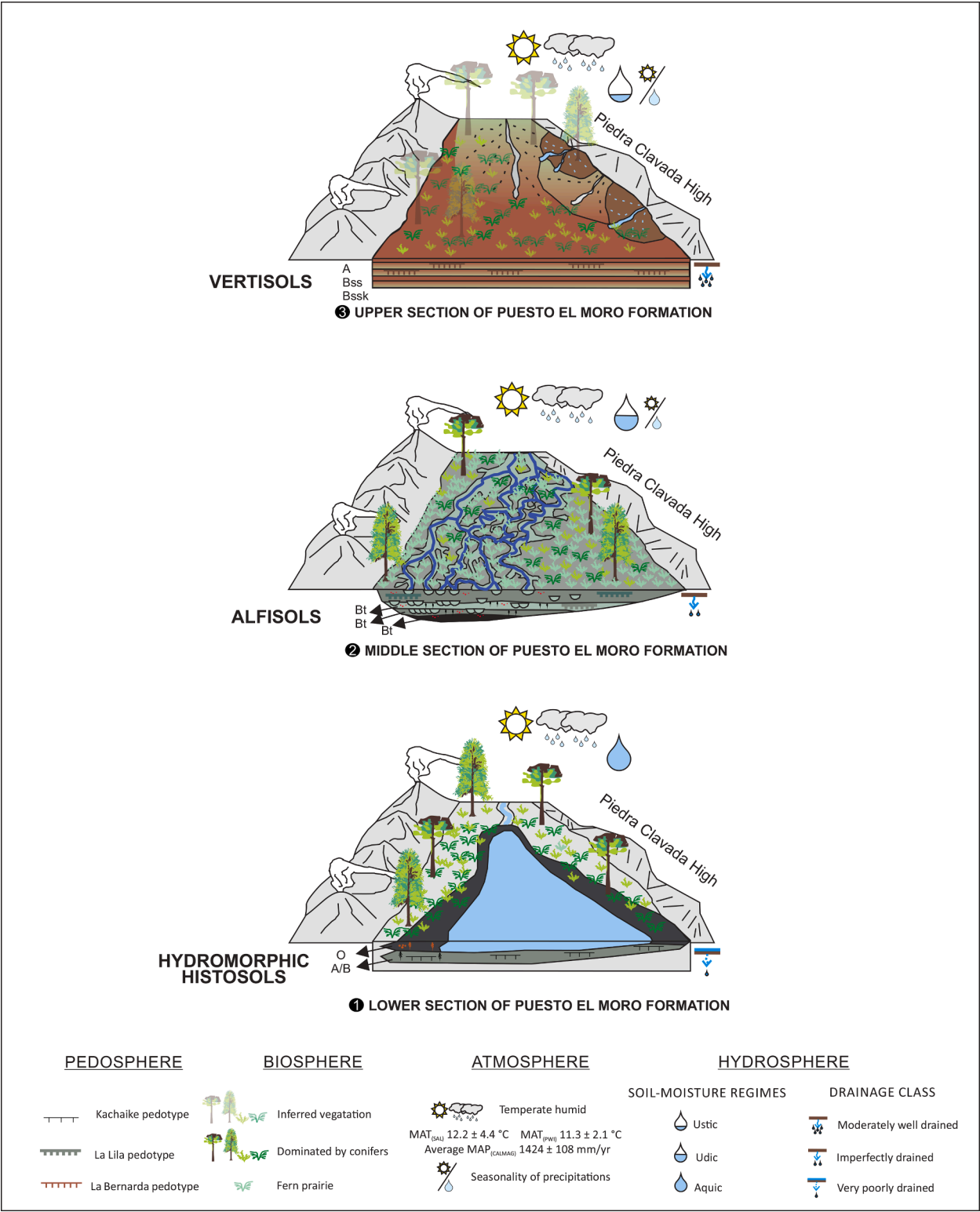


Fig. 6. Schematic reconstruction of the deep-time Critical Zone for the Puesto El Moro Formation based on the paleoenvironmental interpretations made by [Varela et al. \(2019\)](#). The pedosphere reconstruction is based on the three pedotypes defined for each section. The hydrosphere was illustrated with drainage class and the soil-moisture regime for each pedotype. The biosphere reconstruction based on the paleoflora reported from the unit. The atmosphere reconstruction based on the paleoclimate reconstruction. MAT and MAP values are the average values for the entire Puesto El Moro Formation.

dominated by hydromorphic features related to poor drainage conditions and extended periods of water saturation (e.g., [Therrien et al., 2009](#); [Lindbo et al., 2010](#); [Vepraskas, 2015](#); [Vepraskas and Craft, 2016](#); [Vepraskas et al., 2018](#); [Raigemborn et al., 2023](#)). These conditions can be interpreted as episaturation conditions, where the soil was saturated

with water in one or more layers in the soil surface and also had one or more unsaturated layers, below the saturated layer ([Soil Survey Staff, 2015](#)). The presence of slickensides at macroscale, the development of a b-fabric at microscale together with the moderate to very abundant smectite indicate shrink-swell processes due to vertization (e.g., [Ahmad,](#)

1983; Ahmad and Mermut, 1996; Mermut et al., 1996; Retallack, 2001; Varela et al., 2018; Lizzoli et al., 2021). Rhizoliths, channels and chambers, and infillings of groundmass and organic matter (fecal pellets) indicate bioturbation. The Al/Bases ratio and the Ba/Sr ratio indicate moderate hydrolysis and leaching, while the low values of the Al/Si ratio indicate a low abundance of clays. The high percentage of clays from the XRD are therefore interpreted as belonging to the sedimentary environment (detrital clays). Considering that CIA values in the range of 60–80 are indicators of moderate weathering (Nestbitt and Young, 1982; McLennan, 2001), the overall CIA and CIA-K obtained indicated moderate weathering of these levels. The abundance of macro- and micromorphological features prove that subaerial exposure was moderate, and the main pedogenic processes that took place in this pedotype were, in decreasing order of importance, hydromorphism, bioturbation, and vertization.

The Kachaikite pedotype is similar to modern Histosols (Soil Survey Staff, 2022) and thus, they may be classified as hydromorphic Histosol-like paleosols, and as a gleyed Histosol following Mack et al. (1993). The occurrence of an organic horizon with abundant carbonaceous material resemble to modern Histosols (Soil Survey Staff, 1999, 2022). This type of soil occurs in topographically low areas with very poor drainage conditions. While these soils are characterized by the presence of a histic and/or folistic epipedon, identified due to a high organic carbon content, fossil Histosols are defined as paleosols that contained a layer of concentrated organic matter that accumulated in situ (e.g., Mack et al., 1993; Kahmann et al., 2008; Tabor et al., 2017; Varela et al., 2018; Raigemborn et al., 2023). Paleosols generally contain notably less organic matter than their modern equivalents due to effective biotic decomposition and burial dissolution (Sheldon, 2003). Due to coal layers undergo significant compaction as they transition into the rock record, no minimum thickness is necessary for coal to qualify as a Histosol (Tabor et al., 2017).

The paleosols of the Middle Puesto El Moro Formation (La Lila pedotype) present a moderately well-developed horizon sequence (AB-Bt or AB-Btg-C horizons) indicating a well-developed paleosol. The AB horizon is defined based on the shared characteristics between an A and a B horizon, with an A horizon, they both share the abundant bioturbation, burrows, rhizoliths, and granular peds, and with a B horizon, they both share the presence of clay coatings. The latter could also be a criterion to define a superficial Bt horizon. The argilluviation is the dominant processes in the development of these paleosols, where Bt horizon have an enrichment in illuvial clay, evidenced by clay coatings (composed of smectite and kaolinite identified by XRD) and by the increment of the Al/Si ratio from the superficial to the subsuperficial horizons. Hydromorphism is also a dominant process, evinced both in the intrusive hydromorphic features as in the impregnative hydromorphic features (nodules). Slickensides, striated b-fabric, and smectite in the clay fraction show that vertization was also active in the development of these paleosols. Rhizoliths, channel and chambers, and infillings of groundmass and organic matter (interpreted as fecal pellets) indicate bioturbation. Considering that CIA values in the range of 60–80 and 80–100 are indicators of moderate and intense weathering, respectively (Nestbitt and Young, 1982; McLennan, 2001), the overall CIA and CIA-K obtained indicated moderate/intense weathering range. Based on macro-, micro-, and nanomorphological features as well as clay mineralogy and geochemical data, the main pedogenic processes that took place in this pedotype were, in decreasing order of importance, argilluviation, hydromorphism, vertization, and bioturbation.

The La Lila pedotype is similar to modern Alfisols (Soil Survey Staff, 2022) and thus, they may be classified as Alfisol-like paleosols, and as an Argillisol following Mack et al. (1993). The pedofeatures and the geochemical data suggest a well-developed profile with moderate/intense weathering. The increase of clayeyness (ratio Al/Si) with deep, the evidence of illuvial clay (clay coating on peds and oriented clay in vughs or planes), and the overall thickness of the profile allow us to classify them as Bt horizons, typical of Alfisols (Retallack, 2001;

Gallagher and Sheldon, 2013).

The paleosols of the Upper Puesto El Moro Formation (La Bernarda pedotype) present a relatively well-developed horizon sequence with stacked Bss horizons (A-Bss or Bssc/Bssk/Btss-C horizons) indicating a moderately developed paleosol. The presence of slickensides, the dominance of smectite in the groundmass, the striated b-fabric, and the planar voids associated to the fracture of nodules and infillings, suggest that the main pedogenic process was vertization. The Ba/Sr ratio and the Al/Bases ratio indicate moderate hydrolysis and leaching. These paleosols also present hydromorphic features, where hydromorphism was associated to vertization. Fe-Mn oxide nodules and hypocoatings of Bss horizons might be associated with a fluctuating water table or a short duration of water saturation. The development of concentric nodules and halos nodules of Bssc horizons is associated with multiple cycles of wetting and drying of the soil, or to a higher fluctuation of water table. The presence of carbonate features on the Bssk horizon indicated that the drier periods were long enough for their development. The coexistence of both carbonate and hydromorphic features reveals the oscillatory character of the Eh conditions in these paleosols, where carbonate was precipitated during dry periods while the hydromorphic features were developed during the wetter ones (Soares et al., 2020). These recurring wetting–drying changes in the clay-rich groundmass in combination with the swell-shrink potential of expansive clays were likely responsible for the development of the cross and granostriated b-fabrics (e.g., Kovda and Mermut, 2010).

The presence of crescent and laminated clay coatings in the Btss horizon indicate argilluviation. Unlike the previously described Alfisols, the abundance of clays with smectite composition generated a predominance of vertic features over the development of illuvial features. Rhizoliths, voids as channel and chambers, and infillings of groundmass and organic matter, indicate bioturbation. Based on macro-, micro-, and nanomorphological features as well as clay mineralogy and geochemical data, the main pedogenic processes that took place in this pedotype were, in decreasing order of importance, vertization, hydromorphism, calcification, argilluviation, and bioturbation.

The La Bernarda pedotype is similar to modern Vertisols (Soil Survey Staff, 2022) and thus, they may be classified as Vertisol-like paleosols, and as a Vertisol following Mack et al. (1993). The classification was based on evidences of shrinkage and swelling of expandable clays (wedge-shaped peds, slickensides and smectite as the main clay mineral).

5.1.2. Lithosphere

The main parent material for the paleosols of the Puesto El Moro Formation are mainly mudstones (Varela et al., 2019). Further mineralogical and micromorphological analysis of the deeper horizons (C horizons), it is possible to infer the composition resembling of the parent material. In the Puesto El Moro Formation there are differences between the lower section and the middle and upper sections. The lower section is composed of quartz, feldspars, volcanic lithics, carbonate shell remains, glauconite, and biotite. The middle and upper section are composed mainly of quartz, feldspars, and volcanic and sedimentary lithics. These differences are possibly linked to the sedimentary environment in which each section has been developed, since the lower section has an estuarine influence while the middle and upper sections are clearly continental.

Molar ratio of provenance (Ti/Al) contributed to a better understanding between the alteration of deposits (parent material) and pedogenic evolution (e.g., Da Silva et al., 2019). The Ti/Al ratio is particularly useful as an indicator of provenance because the content of Ti can be quite variable among the different types of rocks, whereas the Al levels are relatively constant (Sheldon and Tabor, 2009). The Ti and Al elements are very stable during geochemical weathering, and along the alteration profile, the relationship between these oxides must be continuous through the paleosols if the parent material is the same (Sheldon, 2006). In the paleosols of Puesto El Moro Formation,

differences in the Ti/Al ratio are evident between the lower (average of 0.040) and the middle and upper sections (average of 0.058). This variation aligns with the mineralogical and micromorphological differences previously mentioned, reinforcing the link between provenance and paleosol characteristics.

Although Alfisols and Vertisols of the middle and upper sections share the same mineralogical composition and the molar ratio of provenance, there are certain differences to consider. The parent material plays a crucial role in determining the resulting type of paleosol. Alfisols of the middle section exhibit a coarser grain size compared to the Vertisols of the upper section, resulting in a lower percentage of clays and a higher permeability. In addition, the composition of the clay mineralogy changes from smectite and kaolinite in the Alfisols to smectite-dominated for the Vertisols. These differences may explain the development of Alfisols in the middle section and Vertisols in the upper section.

5.1.3. Hydrosphere

Reconstructing terrestrial hydrospheres include, in addition to climate parameters from geochemical analysis, information extracted from paleosols and the affiliated environments of deposition (Nordt and Driese, 2013). Drainage class can be inferred from hydromorphic features and faunal traces related to water table levels, ponding, and flooding (Kraus and Hasiotis, 2006). In terms of the soil moisture regime, the CALMAG index can be used (Nordt and Driese, 2010). Therefore, for each section of the Puesto El Moro Formation both the soil-moisture regimes and the drainage class are analyzed.

The hydromorphic Histosols of the Kachaiké pedotype are developed on a coastal plain environment with impeded drainage conditions. Therefore, the presence of hydromorphic features is common as well as the development of an organic horizon. This pedotype is interpreted as a very poorly drained paleosol (*sensu* Kraus and Hasiotis, 2006) formed in low and flooded site (Fig. 6). Regarding the soil-moisture regime, aquic conditions are inferred since these paleosols were found without oxygen as they were saturated with water for most part of the year (Fig. 6).

Alfisols of the La Lila pedotype are characterized by gray to greenish gray colors with abundant hydromorphic features. These features indicate waterlogging conditions and fluctuations of the water table. However, the presence of clay coatings allows us to infer alternating conditions and moments where the horizons were dry. Therefore, it can be interpreted as an imperfectly drained argillic paleosol (following Kraus and Hasiotis, 2006), with evidence of endosaturation due to hydromorphic features in the subsurface horizons (Fig. 6). Regarding the soil-moisture regime, the average value of CALMAG index is 81.59, therefore it corresponds with udic soils, and it is inferred as paleosols that must have had more than 90 wet cumulative days but at least one dry episode per year (Soil Survey Staff, 2022) (Fig. 6).

Vertisols of the La Bernarda pedotype are characterized by reddish colors with vertic, hydromorphic, and carbonate pedofeatures. Reddish colors indicate the presence of hematite, which associated with carbonate pedofeatures imply that the paleosols were at least moderately well drained and oxidized (Kraus and Hasiotis, 2006; Fig. 6). Also, the presence of vertic features is consistent with seasonal wetting and drying. Therefore, these paleosols are interpreted as a moderately well drained paleosol (*sensu* Kraus and Hasiotis, 2006) due to the presence of hydromorphic features, such as concretions of oxides of Fe-Mn, and carbonate features. Regarding the soil-moisture regime, the average value of CALMAG index is 81.81, therefore, it corresponds to udic conditions (Fig. 6). However, the presence of vertic and carbonate pedofeatures can be associated with a marked dry season, and xeric conditions can also be inferred.

5.1.4. Biosphere

The Puesto El Moro Formation presents evidence of bioturbation both from flora and fauna. Rhizoliths (*sensu* Klappa, 1980) are mainly composed of preserved organic matter in the hydromorphic Histosols of

the Kachaiké pedotype. As for fauna, there was no evidence of trace fossils at macroscale, but there are identified at microscale as chambers and channels and as infillings of the groundmass. These are interpreted as groundmass transported by organisms that inhabit the paleosols, probably associated with worms and insect larvae (Stoops et al., 2010, 2018).

Plant species are generally low in diversity and restricted to such waterlogged sites for Histosols. They support bogs, swamps, and marches (Retallack, 2001). This type of vegetation is probably assumed for the hydromorphic Histosol-like paleosols of the Kachaiké pedotype (Fig. 6). Alfisols usually have vegetation that ranges from grassy woodland to open forests (Retallack, 2001), similar to the ones inferred for the La Lila pedotype (Fig. 6). Vertisols usually have vegetation that ranges from grassland to open woodland (Retallack, 2001), similar to the ones inferred for the La Bernarda pedotype. Due to its stratigraphic correlation with the Mata Amarilla Formation, a similar flora reconstruction can be inferred. The flora of the Mata Amarilla Formation, based on palynological, leaves, and wood findings (Iglesias et al., 2007; Santamarina et al., 2018, 2020, 2022; Varela et al., 2021), was interpreted as a gymnosperm-dominated forest with an understory composed by ferns and bryophytes.

Santamarina et al. (2023) studied palynofloras from the lower and middle section of the Puesto El Moro Formation. In the lower section of the unit, palynological assemblages are dominated by gymnosperm pollen grains (*Classopollis* pollen related to Cheirolepidiaceae), with spores representing a subordinate group (Fig. 6). In this section are also abundant freshwater algae related to Zygnemataceae and Botryococcaeae (Zippi, 1998) and megaspores of Salviniales (water ferns) indicating the presence of freshwater environments and ponds, wetlands or flooded places (Kramer and Green, 1990; Scafati et al., 2009). Conversely, in the middle section, there is a higher representation of spores (Cyatheaceae, Dicksoniaceae, Dipteridaceae or Matoniaceae) and pollen grains of Pococarpaceae and progressing towards the upper levels of the middle section, the relative abundance of *Classopollis* decreases (Fig. 6). The relative abundance of these group support high levels of humidity on this section. The lack of internal stratigraphic control in the Puesto El Moro Formation prevents us to make more detailed correlations with the Mata Amarilla Formation (Santamarina et al., 2023). However, future palynological studies of the Puesto El Moro Formation will provide a more accurate reconstruction of its flora and will offer the possibility of a detailed comparison between the palynofloras of the both two units.

5.1.5. Atmosphere

Advances in paleo-atmospheric sciences were based on reconstruction of ancient pedospheres for reconstructing climate, especially mean annual precipitation and mean annual temperatures (Nordt and Driese, 2013). Macro- and micromorphology, clay mineral composition, pedogenic processes, and climofunctions, have been used for reconstructing climate (Tabor and Myers 2015, Hyland and Sheldon, 2016, Tabor et al., 2017, among others). Paleosols within the Puesto El Moro Formation can offer insights into the climatic conditions that existed in Southern Patagonia during the mid-Cretaceous.

The main pedogenic processes observed are hydromorphism and vertization, both indicated seasonality of precipitations during soil formation. Modern Vertisols are not associated with a particular climate, and can occur with mean annual precipitations between 500 and 1000 mm (Kovda, 2020; Basilici et al., 2022; Raigemborn et al., 2023). However, temperature and pronounced periodic precipitations, which control well-defined wet and dry cycles, are needed for their genesis and development (Ahmad, 1983; Basilici et al., 2022). The clay mineralogy, dominated by smectite, indicated the shrinking and swelling of the expandable clays during alternating wet and dry periods. The formation of slickensides that lead to separation of wedge-shaped or angular blocky peds, are originated from overburden pressure and stress associated with the alternating phases of swelling and shrinking (e.g.,

Basilici et al., 2022).

The development of Bt-horizons, with illuvial clays conforming coatings, suggests prolonged phases of weathering and paleosol formation (Srivastava et al., 2018). Modern Alfisols are developed in subhumid to humid conditions with wetting and drying cycles. Also, clay coatings form in a relatively well drained soil above the water table (Tabor and Myers, 2015). The combination of clay coatings with hydromorphic features (both in the Bt and Btg horizons) also reflect periodic to complete saturation of the soil profile (Tabor and Myers, 2015).

Pedogenic carbonate may form in environments with high precipitation in which the drying of the soil took place for a sufficient period of time to develop their precipitation. Therefore, the presence of carbonate is a reliable indicator of seasonal precipitation (e.g. Tabor and Myers, 2015; Raigemborn et al., 2018; Lizzoli et al., 2021).

For a quantitative paleoclimate reconstruction, based on geochemical data, certain considerations must be taken, since not all paleosols would reflect the paleoclimate conditions that prevailed at the time of their formation. It is well known that the development of a soil is conditioned by the five soil-forming factors (climate, biota, topographic relief, time, and parent material), as that they do not act as separate but all together for the development of the soil (e.g., Wright, 1992; Kraus, 1999; Retallack, 2001; Da Silva et al., 2019; Lizzoli et al., 2021). In spite of that, the development of a soil may be more or less influenced by one or more of the soil-forming factors. Thus, zonal soils would be the ones that are dominated by the climate and biota during their formation and could allow us to infer the paleoclimate conditions that prevailed at the time of its formation (Alexander, 2009). Intrazonal soils are those where the topography or the parent material dominated their formation and might be indicating local paleoclimate conditions (Alexander, 2009). Finally, azonal soils are those where the time conditioned their formation and would not be good paleoclimate indicators (Alexander, 2009).

The hydromorphic Histosol-like paleosols (Kachaik pedotype) of the lower section of the Puesto El Moro Formation were interpreted as intrazonal paleosols due to their development under very poorly-drainage conditions in a topographically low area. For this reason, it is not considered appropriate the use of climofunctions. However, the presence of vertic and hydromorphic features mentioned above allow to infer seasonality of climate during soil formation. However, paleo-Alfisols (La Lila pedotype) and Vertisols (La Bernarda pedotype) of the middle and upper section of the Puesto El Moro Formation, respectively, were interpreted as zonal paleosols. Besides, the Ti/Al ratio between Alfisols and Vertisols have no significant variations, which suggest that no provenance change occurred (see above). Therefore, quantitative paleoclimate reconstruction can be applied. Estimates on MAT for the paleosols of the middle and upper sections of the studied unit suggest temperate conditions, while estimates on MAP suggest humid ones.

Due to all the evidence expresses above, the paleoclimate conditions interpreted for the Puesto El Moro paleosols are temperate and humid with a marked seasonality of the precipitations. Although based on our data the paleoclimate conditions remains more or less unchanged throughout the succession, in relative terms, changes in the seasonality might be inferred being more marked for the upper section, in which Vertisols take place (Fig. 6).

5.2. Paleoclimate implications of the Puesto El Moro paleosols in mid-Cretaceous global climate reconstructions

There are wide bibliography focus on paleosols used as paleoclimate proxies to generate paleoclimate reconstructions (e.g., Li et al., 2016; Hyland et al., 2016; Srivastava et al., 2018; Varela et al., 2018; Lizzoli et al., 2021; Raigemborn et al., 2018, 2022, 2023; among others). Mid-Cretaceous global climate reconstructions came from both Northern and Southern Hemispheres for (1) low-paleolatitudes (0–30° N and S) such as those of the Southeastern Tibetan Plateau in China (Shang et al., 2016) and the Rukwa Rift Basin in Eastern Africa (Orr et al., 2021), (2) mid-paleolatitudes (30–50° N and S) such as those of the Lower Tuscaloosa

Formation and Dakota Rosee Cret Pit Formation in the Western Interior Basin (WIB) from United States (Ufnar et al., 2002, 2005, 2008) and the Neuquén Basin in Argentina (Lizzoli et al., 2021), and (3) for mid-high paleolatitudes (50–60° N and S) such as those of Dunvegan Formation in the WIB from United States (Ufnar et al., 2002, 2005, 2008) and the Austral-Magallanes Basin from Argentina (Varela et al., 2018). From the reconstruction of the atmospheric conditions of the Puesto El Moro paleosols, we provide a new Southern Hemisphere data to add to the mid-Cretaceous global climate reconstruction at mid-high paleolatitudes (Fig. 7).

In the Northern Hemisphere, Cenomanian paleosols from the Southeastern Tibetan Plateau in China (~15° paleo-N) shown arid conditions with a high summer soil temperature, with an average of ~35° C (Shang et al., 2016), while paleosols from Lower Tuscaloosa Formation in the southwest of Mississippi of the WIB (~25° paleo-N) shown humid conditions (MAP values of 1400 mm/yr), and paleosols from Dakota Rose Creek Pit in Farbury Nebraska of the WIB (~35° paleo-N) also shown humid conditions (MAP values of 1600 mm/yr) (Ufnar et al., 2008). These localities are situated in the Northern Hot Arid belt (NHA) following Chumakov et al. (1995) and Hay and Floegel (2012) (Fig. 7). Paleosols from the Dunvegan Formation in the east of British Columbia of the WIB (~55° paleo-N) shown temperate and perhumid conditions (MAT values of 19° C and MAP values of 3100 to 3600 mm/yr) (Ufnar et al., 2008). It should be noted that the values obtained by Ufnar et al. (2008) represent the potential precipitation rate (PPR), and therefore represent significantly higher values indicating the amount of rainfall that would occur on average if the atmosphere were to completely exhaust its moisture supply. This locality is situated in the Northern Mid-latitude Warm humid belt (NMW) following Chumakov et al. (1995) and Hay and Floegel (2012) (Fig. 7).

In the Southern Hemisphere, Cenomanian paleosols from the Rukwa Rift Basin of the Galula Formation in East Africa (~10–15° paleo-S) shown temperate conditions with a shift from semi-arid to sub-humid climatic conditions with rainfall seasonality (MAT values that varies from 10.3 to 13.9° C and MAP values that varies from 454 to 987 mm/yr) (Orr et al., 2021). This locality is situated in the Equatorial Humid belt (EH) following Chumakov et al. (1995) and Hay and Floegel (2012) (Fig. 7). Paleosols from Neuquén Basin in Argentina indicate that seasonal temperate arid and semi-arid conditions prevailed with a trend towards subhumid conditions (Lizzoli et al., 2021). This locality is situated in the limit between the Southern Hot Arid Belt (SHA) and the Southern Mid-latitude Warm humid belt (SMW) following Chumakov et al. (1995) and Hay and Floegel (2012) or the proposed made by Lizzoli et al. (2021) of a Cretaceous Hot Semi-arid Belt for those paleolatitudes (Fig. 7). Paleosols from Austral-Magallanes Basin in Argentina indicate that temperate humid with seasonal rainfall conditions prevailed (with MAP of 12 ± 2.1° C and MAT of 1404 ± 108 mm/yr) (Varela et al., 2018). This locality is situated in the limit between the Southern Mid-latitude Warm humid belt (SMW) and the Southern High-latitude Temperate humid belt (SHT) following Chumakov et al. (1995) and Hay and Floegel (2012) (Fig. 7).

The global paleoclimate reconstructions suggest that the study area (~54° paleo-S following van Hinsbergen et al., 2015) was located in the Southern mid-latitude Warm Humid Belt (SMW) following Chumakov et al. (1995) and Hay and Floegel (2012) (Fig. 7). Following the global paleoclimate reconstructions from Burgener et al. (2023), the study area was in the Cenomanian paleo-Köpen climate zone temperate humid subtropical (Ca). During Cenomanian times, almost fifty percent of land area was occupied by this climate zone. Our paleoclimate data correspond to temperate and humid with a marked seasonality of the precipitations, and confirm that at ~54° paleo-S the paleo-Köpen climate zone was within the Temperate humid (Burgener et al., 2023) and within the Southern mid-latitude Warm Humid Belt (Chumakov et al., 1995; Hay and Floegel, 2012).

The previously presented data and the findings of the present study agrees that, during mid-Cretaceous, greenhouse conditions with a high

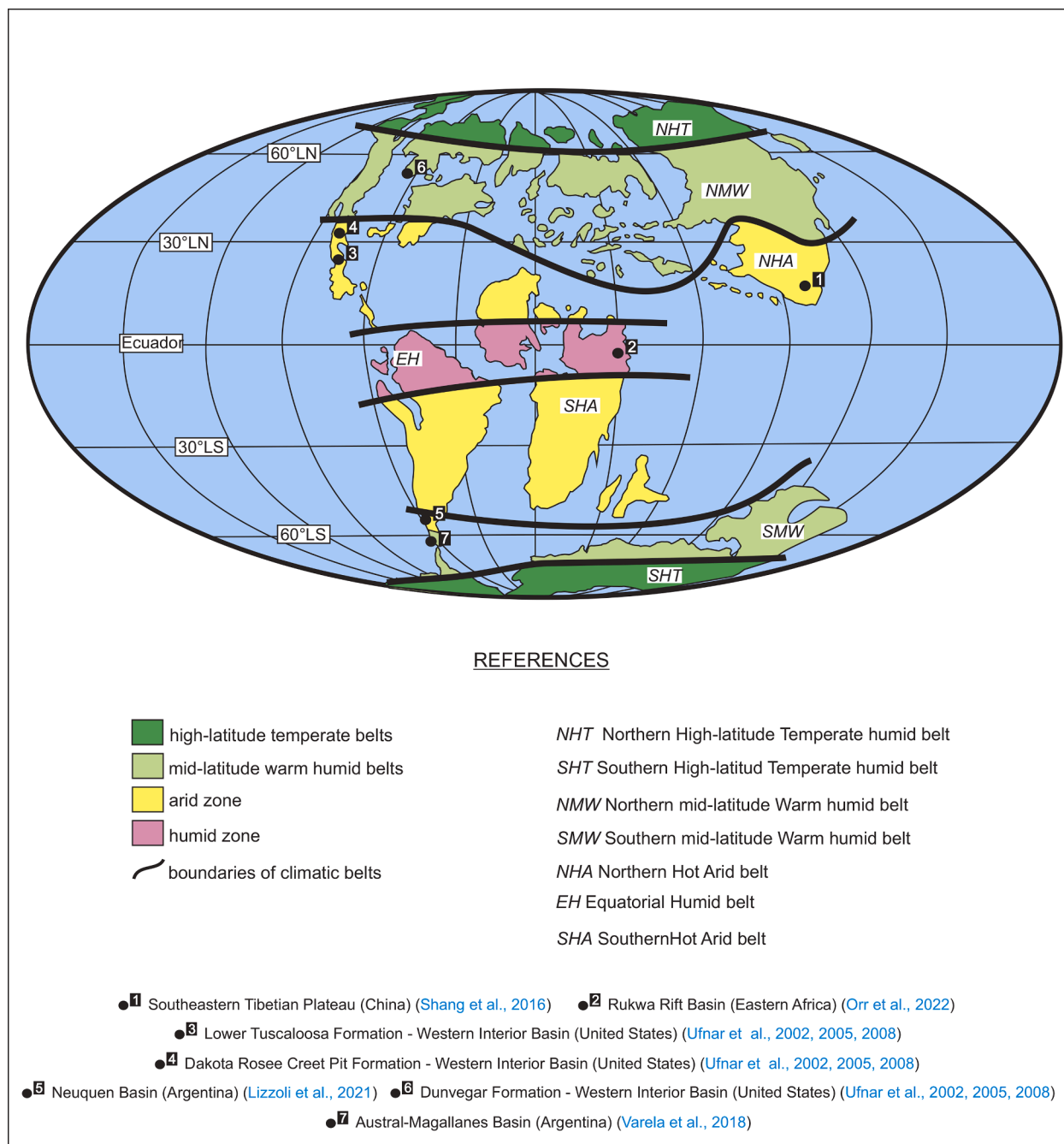


Fig. 7. Mid-Cretaceous global paleogeographic reconstruction from Scotese (1991) and global paleoclimate reconstruction from Chumakov (1995) modified by Spicer and Skelton (2003).

precipitation rate through poles, prevailed. As a result, a latitudinal distribution of the paleoclimatic belts occurred from arid zones at low-paleolatitudes towards warm humid and temperate belts at high-paleolatitudes. Thus, the use of paleosols as paleoclimate proxies agrees with model results and provides data from mid-high paleolatitudes of the Southern Hemisphere to polish the current mid-Cretaceous climate reconstructions in the context of a greenhouse world. Ultimately, it is important to note that the development of these maps of the past provides a natural case study, offering insights into understanding global climate change during warm periods like the mid-Cretaceous.

6. Conclusions

In summary, we show that the mid-Cretaceous Puesto El Moro Formation in the southern of the Austral-Magallanes Basin (~54° paleo-S) contain paleosols which are hydromorphic Histosol-like paleosols (Kachaike pedotype), Alfisol-like paleosols (La Lila pedotype), and Vertisol-like paleosols (La Bernarda pedotype). The conjunction of the analyzed paleosols enables us to infer the four scientific spheres (lithosphere, hydrosphere, biosphere, and atmosphere) and provides a deep-time Critical Zone reconstruction. Distinct mineralogical and micro-morphological differences along with different molar ratios of provenance contribute to understanding the alteration of deposits and pedogenic evolution. Soil-moisture regimes and drainage classes allow for the reconstruction of the hydrosphere, from very poorly drained

paleosols with aquic conditions to moderately well-drained paleosols with both udic and xeric conditions. The atmospheric reconstruction points towards a relatively unchanged temperate and humid climate with a marked seasonality of the precipitations throughout the succession. The paleoclimate reconstruction obtained here, during the global mid-Cretaceous greenhouse, provides new data from mid-high paleolatitudes and agrees with the current mid-Cretaceous climate reconstructions in the context of a greenhouse world. Overall, the development of past climate maps provides a natural case study, offering insights into understanding global climate change during warm periods like the mid-Cretaceous.

CRedit authorship contribution statement

Sabrina Lizzoli: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Augusto N. Varela:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **M. Sol Raigemborn:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Conceptualization. **Sebastian M. Richiano:** Resources, Project administration, Funding acquisition. **Patricio Santamarina:** Writing – review & editing, Writing – original draft. **Valeria S. Perez Loinaze:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This research was funded by Agencia Nacional de Promoción Científica y Tecnológica (PICT 2012-0828 awarded to A.N. Varela and PICT 2013-1298 awarded to S. Richiano), Subsidio Jóvenes Investigadores de la UNLP 2013 (La Plata University Exp. Cod.100 N°19333/2/13 awarded to A.N. Varela). The authors would like to thank the S de Cultura de la Provincia de Santa Cruz and landowners Noble, Díaz and Piccinini for their permission to carry out fieldwork, as well as the workers of Estancia La Lila, La Federica and Kachaike. We are grateful to Associated Editor, Jaroslaw Waroszewski, Co Editor-in-Chief, Eleonora Bonifacio, and two anonymous reviewers, for their constructive comments and suggestions that improve the original manuscript. We also want to thank to the technicians of the CIG (Centro de Investigaciones Geológicas) for preparing thin sections and X-ray diffractions.

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