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Unraveling continental volcaniclastic deposits from the Aptian Puesto La Paloma Member, Cañadón Asfalto Basin, Argentina

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ABSTRACT

The Aptian succession of the Puesto La Paloma Member was deposited in the present-day extra-Andean Patagonia, Argentina (Cerro Barcino Formation from the Cañadón Asfalto Basin), during a period of a significant volcaniclastic sediment supply from sources located nearly 200 km to the west. This study analyses the sedimentary palaeoenvironments and allocyclic controls operating in the Gorro Frigio depocentre based on facies analysis and the recognition of informal stratigraphic intervals. Overall, the recorded palaeoenvironmental evolution reflects a transition from: i) aeolian and lacustrine succession with 2D dunes, dry interdunes, and shallow lakes with surrounding mudflats and marginal sheet-floods (Interval I); to ii) a fluvial system dominated by sheet-floods with local feeder channels, laterally associated with fluvial channel and floodplain environments (Interval II). Ashfall deposits occur in both intervals, but are proportionally more abundant in Interval I. The palaeoenvironmental changes identified, both with respect to the underlying Bardas Coloradas Member and between the two informal stratigraphic intervals, were primarily controlled by spatio-temporal variations in volcaniclastic sediment supply.

Keywords: Aptian, Volcaniclastic system, Allocyclic controls, Patagonia

INTRODUCTION

During the Cretaceous, subduction processes along the western margin of Patagonia activated volcanic activity that delivered volcaniclastic sediments to several basins located to the east (Echaurren *et al.,* 2021; Figari and Hechem, 2021). The volcaniclastic materials reached the basins through either primary pyroclastic deposition or sedimentation in routing systems. In addition to arc-derived volcanic material, intraplate volcanic activity linked to episodes of

flat-slab subduction may have contributed subordinate volumes of volcaniclastic products (Navarrete, 2025). The Patagonian Aptian sedimentary record, in particular, is characterised by a significant volcaniclastic component associated with major palaeoenvironmental changes, as documented in the Cañadón Asfalto (Allard *et al.,* 2021a) and Golfo San Jorge (Paredes *et al.,* 2021) basins. This enhanced volcaniclastic input may be related to the eastward migration of a missing volcanic arc (Suárez *et al.,* 2023), which is currently represented only by exposures of its plutonic roots (Butler *et al.,* 2020).

The Aptian volcaniclastic-rich succession of the Cañadón Asfalto Basin, known as the Puesto La Paloma Member of the Cerro Barcino Formation, has been studied both at basinal (Umazano *et al.,* 2017; Krause *et al.,* 2020) and local (de la Fuente *et al.,* 2011; Sterli *et al.,* 2015; Melchor *et al.,* 2023, 2024; Villegas and Umazano, 2024) scales. This unit mainly records unconfined alluvial deposits, with subordinate channelled fluvial, lacustrine, and aeolian successions. Aeolian deposits include both dune and interdune facies, forming a geographically restricted stratigraphic interval in the western sector of the basin. These deposits have been linked to volcaniclastic oversupply (Umazano *et al.,* 2023; Villegas and Umazano, 2024) and to local wind patterns controlled by specific geomorphological and topographic conditions (Allard *et al.,* 2021a). The objectives of this contribution are: i) to reconstruct the sedimentary palaeoenvironment of the Puesto La Paloma Member in an area where aeolian deposits are particularly well developed (Gorro Frigio depocentre), based on a compilation of published data and new information; and ii) to identify the controls on sedimentation, with emphasis on the role of volcaniclastic sediment supply in the development of aeolian deposits.

GEOLOGICAL SETTING

The Cañadón Asfalto Basin is located in northern extra-Andean Patagonia and covers ~72,000 km^2 in Argentina (Figari *et al.,* 2015; Figari and Hechem, 2021; Fig. 1A). It is an intracontinental basin developed on a Palaeozoic-

Triassic plutonic and metamorphic basement (Allard *et al.,* 2021a). Basin development began during the Early Jurassic in response to extensional stresses and rifting. Although the Mesozoic tectonostratigraphic evolution of the basin is debated (Allard *et al.,* 2021b), the Jurassic-Cretaceous record has been classically subdivided into two Jurassic megasequences, designated as J1 and J2, and one Cretaceous megasequence, K, which includes the Chubut Group (Figari *et al.,* 2015; Fig. 1B). The latter begins with the Los Adobes Formation, an epiclastic alluvial succession deposited during reactivation of Jurassic half-grabens (Allard *et al.,* 2015; Villegas and Umazano, 2024), and continues with the volcaniclastic alluvial Cerro Barcino and Puesto Manuel Arce formations, accumulated under thermal subsidence with local syn-tectonic sedimentation associated with the reactivation of Jurassic extensional faults (Umazano *et al.,* 2017; Villegas *et al.,* 2019; Krause *et al.,* 2020; Foix *et al.,* 2024; Ruiz *et al.,* 2025; Villegas *et al.,* 2025a,b). The basin infill is completed by continental to marine successions associated with Atlantic Ocean transgressions (Foix *et al.,* 2021). Outcrops of megasequences J1 and J2 are generally discontinuous across the basin, whereas megasequence K is more extensively developed (Umazano *et al.,* 2017; Krause *et al.,* 2020). Locally, the megasequence K is overlain by intra-plate Cenozoic lava flows or intruded by necks and dykes (Haller *et al.,* 2020).

The study area corresponds to the Gorro Frigio depocentre, located in the western sector of the Cañadón Asfalto Basin (Figari *et al.,* 2015; Fig. 1C). This depocentre is a half-graben bounded to the west by a regional inverted normal fault, whose trace trends predominantly NNW-SSE with eastward-directed displacement. Towards its northern and southern terminations, the fault trace deflects to NE-SW and exhibits SE- and NW-directed transport, respectively. Internally, the depocentre includes a secondary inverted fault in its southern sector, and additional minor structures displaying normal and strike-slip kinematics. Associated folds include both anticlines and synclines with variable axial trends and locally plunging geometries.

The Puesto La Paloma Member constitutes the lower part of the Cerro Barcino Formation. It is assigned to the Aptian based on U-Pb dating of

zircons in tuffaceous strata (Krause *et al.,* 2020; Umazano *et al.,* 2025). At the Gorro Frigio depocenter, the Puesto La Paloma Member, up to 42 m thick, is

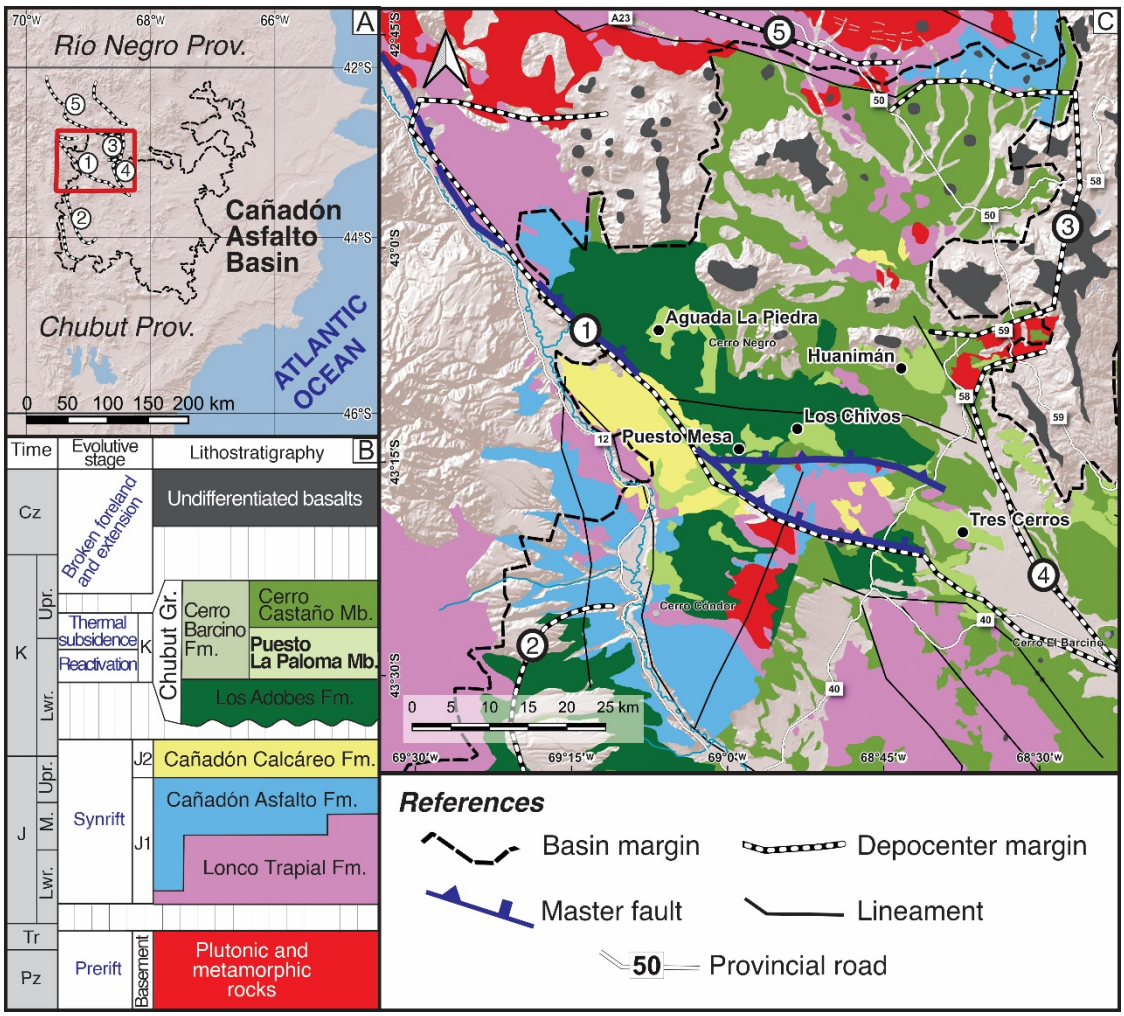


Figure 1. Location, stratigraphy and study area. a) Location map of the Cañadón Asfalto Basin (modified from Umazano *et al.,* 2025). The main western depocentres are indicated (cf. Figari *et al.,* 2015): 1) Gorro Frigio; 2) Paso de Indios; 3) Fossatti; 4) General Racedo; 5) Gastre. The red rectangle represents the study zone (Figure 1C). b). Stratigraphy of the Cañadón Asfalto Basin in the study area (modified from Figari *et al.,* 2015). c) Geological map of the study zone based on Umazano *et al.* (2025).

mainly composed of tabular volcaniclastic strata, consisting of interbedded sandstones and mudstones, with subordinate psephites, tuffs, and limestones. It conformably overlies and underlies the Bardas Coloradas and Cerro Castaño

members in transitional contact (Umazano *et al.,* 2017; Krause *et al.,* 2020; Villegas and Umazano, 2024). The lower contact coincides with a colour change from reddish to greenish hues, marking the onset of volcaniclastic sedimentation over epiclastic deposits, whereas the upper contact is defined by the reappearance of epiclastic sandstones and reddish-brown strata.

METHODOLOGY

Detailed sedimentological logs were compiled and updated for the Tres Cerros (TC), Huanimán (H), Cerro Los Chivos (LC), and Puesto Mesa (PM) localities (Figs. 1C and 2). A new section from the Aguada La Piedra locality (ALP; Figs. 1C and 2) is presented, together with supplementary data from specific strata in previously published sections. A representative sedimentological log was defined for each locality, except at LC, where three sections (LC1 to LC3) were considered. Localities H, LC1-LC3, and PM define a NE-SW transect parallel to the trace of the master fault in the southern sector of the depocentre, whereas ALP and TC are located to the north and south of this transect, respectively (Figs. 1C and 2).

Lithofacies were classified following the Miall (1996) code, adapted for volcaniclastic successions (Villegas and Umazano, 2024). For aeolian facies, an additional lowercase letter (a) was incorporated (Umazano *et al.,* 2017). The suffixes 1 and 2 were used to distinguish cross-laminations produced by unidirectional and oscillatory flows, respectively. Informal stratigraphic intervals were recognized from spatial variations in facies associations, correlation of sedimentological logs using key stratigraphic markers, and assessment of lateral continuity through photomosaics constructed from photographs acquired with an unmanned aerial vehicle.

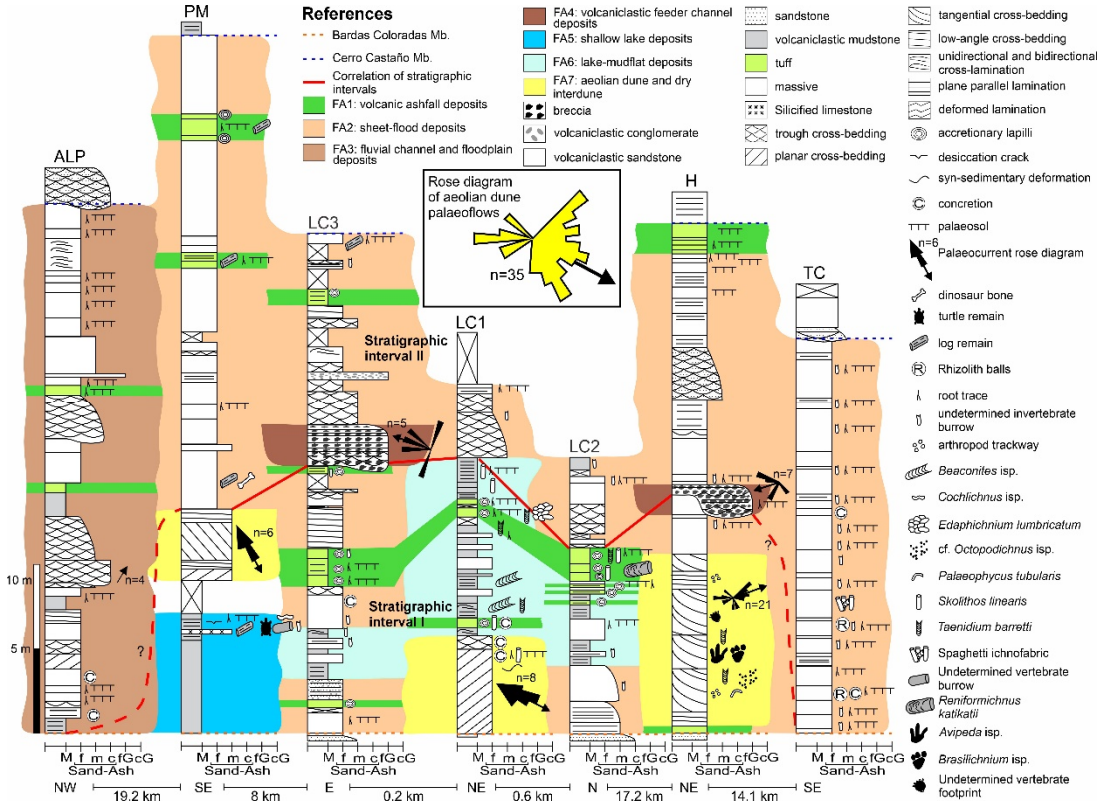


Figure 2. Detailed sedimentary logs of the Puesto La Paloma Member of the studied localities in the Gorro Frigio depocentre. ALP: Aguada La Piedra (new information). PM: Puesto Mesa (Umazano *et al.,* 2017; Krause *et al.,* 2020). LC1-LC2-LC3: Los Chivos 1 to 3 (Krause *et al.,* 2020; Melchor *et al.,* 2023, 2024; Villegas and Umazano, 2024). H: Huanimán (Umazano et al., 2017; Krause *et al.,* 2020). TC: Tres Cerros (Umazano *et al.,* 2017; Krause *et al.,* 2020). The facies associations are indicated in each locality.

RESULTS

Facies associations (FAs)

FA1. Volcanic ashfalls. FA1 includes well-sorted, fine-grained tuffs with occasional accretionary lapilli, occurring as massive (Tm) or parallel laminated (Th) deposits (Figs. 2 and 3A). Root traces and vertebrate and invertebrate burrows are locally present, including Skolithos linearis, Taenidium barretti, Edaphichnium lumbricatum and Reniformichnus

katikatii. This FA forms mantle-bedded bodies up to 3.2 m thick with non-erosive bases.

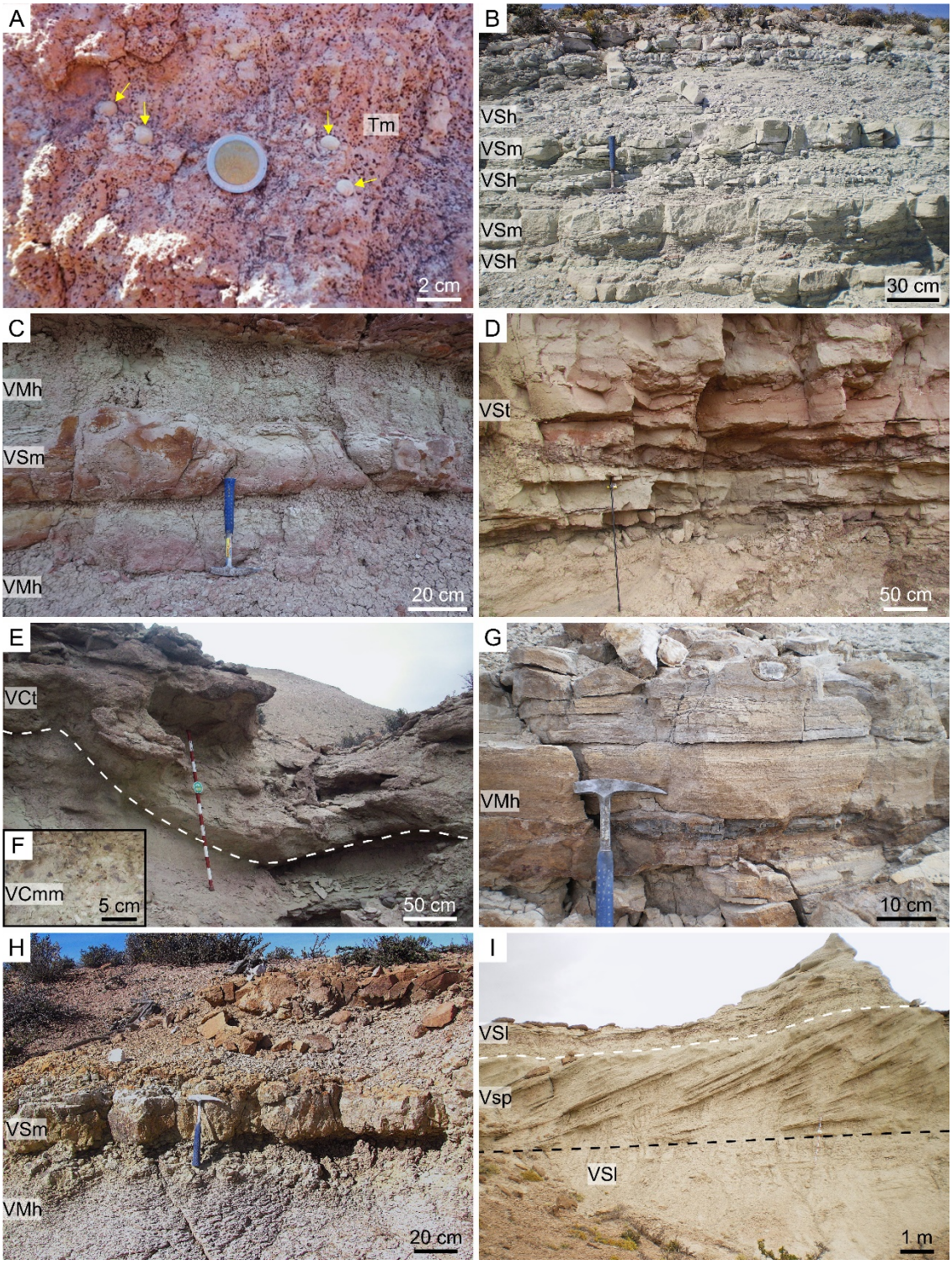


Figure 3. Examples of facies and facies associations. a) Volcanic ashfall deposits (FA1). The yellow arrows indicate accretionary lapilli. b) Sheet-flood deposits (FA2). c-d) Fluvial channel and floodplain deposits (FA3). e-f) Feeder channel deposits (FA4). g) Shallow lake deposits (FA5). h) Lake-mudflat deposits (FA6). i) Aeolian dunes and dry interdune deposits (FA7). Coin is 2.5 cm in diameter. Geological hammer is 33 cm long. Jacob staff is 150 cm long. See facies nomenclature in the text.

The massive (Tm) and laminated (Th) tuffs are interpreted as volcanic ashfall deposits accumulated under relatively steady and fluctuating eruptive conditions, respectively (Mazzoni, 1986). The occurrence of accretionary lapilli indicates fallout through a moisture-rich atmosphere and deposition under subaerial conditions. Root traces record episodes of pedogenesis following deposition, whereas the burrows reflect bioturbation by invertebrates and vertebrates.

FA2. Sheet-floods. FA2 is dominated by tabular strata composed of moderately well-sorted, medium- to fine-grained volcaniclastic sandstones (Figs. 2 and 3B). The participation of sandstones is very subordinate. Individual beds are typically decimetre thick and form successions up to 28 m thick, laterally continuous for hundreds of meters, with evidence of lateral amalgamation. The sandstones contain tuffaceous, gravel-sized intraclasts and are massive or horizontally laminated (VSm/Sm and VSh/Sh). Transitional contacts between massive and laminated beds are locally observed. Subordinate facies include massive, poorly-sorted, matrix (sand)-supported volcaniclastic conglomerates (VCmm), and sandstones with trough cross-stratification (VSt/St), low-angle cross-stratification (VSl), and uni- and bidirectional cross-lamination (VSr1 and VSr2). Root traces and invertebrate burrows (*Skolithos linearis*, *Taenidium barretti* and *Edaphichnium lumbricatum*) are common, whereas rhizolith balls and particular ichnofabric consisting of a complex network of burrows with massive or meniscate fill and occasional wall occur less frequently.

The predominance of laterally extensive tabular volcaniclastic bodies with subtle erosional bases, intraclasts, and limited channelization supports deposition by volcaniclastic sheet-floods (McKee *et al.,* 1967; Umazano *et al.,* 2012). The abundance of massive beds suggests rapid deposition from sediment-laden, highly-concentrated flows (VSm and Sm). In contrast, intervals with parallel lamination and cross-stratification (VSh/Sh, VSl, VSt/St) indicate episodes of more diluted flows, allowing the development of plane beds, low-relief bedforms, and 3D dunes. The presence of asymmetric and symmetric ripple cross-lamination (VSr1 and VSr2) reflects unidirectional and oscillatory flow conditions, respectively. Rare occurrences of oscillatory structures suggest the development of shallow, ephemeral lentic areas following the waning or cessation of sheet-flood events. The isolated occurrence of a non-cohesive debris-flow deposit (VCmm) indicates occasional, higher-concentration gravity-flow processes. Transitions between massive and laminated beds reflect fluctuations in sediment concentration and flow rheology, likely related to dilution and/or bulking processes. Root traces and invertebrate burrows indicate periods of subaerial exposure. The particular ichnofabric has been attributed to earthworm activity (Massa *et al.,* 2018), whereas rhizolith balls may reflect fungiculture-related structures produced by social insects (Genise *et al.,* 2010).

FA3. Fluvial channels and floodplain. FA3 comprises poorly to moderately well-sorted volcaniclastic sandstone bodies with both channelised and tabular geometries (Figs. 2 and 3C-D). Channelised bodies are up to 2.8 m thick, display irregular erosional bases, and are characterised by single-storey fills that fine upward from coarse- or medium- to fine-grained volcaniclastic sandstones with trough cross-stratification (VSt). The palaeocurrent data indicate flow towards the NE. Laterally associated, tabular volcaniclastic sandstone bodies have subtle erosional bases and are typically fine-grained and massive, locally displaying root traces (VSm). Less commonly, they exhibit parallel lamination (VSh), or cross-stratification, including planar (VSp), trough (VSt) and low-angle types (VSl), as well as unidirectional ripple cross-lamination (VSr1). Individual beds are decimetre thick and form successions up to 11.4 m thick. Subordinate facies include tabular bodies of

massive or parallel laminated volcaniclastic mudstones (VMh), which are clay-dominated and up to 1.4 m thick and with non-erosive bases.

FA3 records a volcaniclastic fluvial system comprising channels and associated floodplain environments (Miall, 1996; Bridge, 2006; Paredes, 2022). Channelised sandstone bodies dominated by trough cross-stratification (VSt), together with their simple internal architecture indicate deposition by migrating 3D dunes within relatively short-lived channels. The predominance of single-storey channel fill suggests limited channel reoccupation. Tabular sandstone bodies represent pedogenised floodplain deposits. Massive facies (VSm) indicate rapid deposition from sediment-laden, suspension-dominated flows, whereas laminated and cross-stratified facies (VSh, VSp, VSt, VSl, VSr1) reflect more diluted flow conditions, allowing the development of bedforms. The later deposits are interpreted as proximal floodplain accumulations. Mudstone facies (VMh) records suspension settling in low-energy, standing-water conditions at distal floodplain settings.

FA4. Feeder channels. FA4 comprises two channelled bodies with concave-up erosional bases, planar tops, and infills dominated by poorly-sorted volcaniclastic breccias displaying a subtle upward fining trend (Figs. 2 and 3E-F). Both bodies reach up to 10 m in lateral extent and ~2.3 m in thickness. Clasts, up to 12 cm long, are composed mainly of tuff fragments, with subordinate basaltic, andesitic, and granitic lithologies. The matrix consists of fine-grained ash. The architecture is characterised by alternating volcaniclastic breccias with trough cross-stratification (VCt), massive matrix-supported deposits (VCmm), and levels with diffuse horizontal stratification and imbricated clasts (VCh). Locally, the uppermost part of these bodies grades into moderately well-sorted volcaniclastic sandstones with trough cross-stratification (VSt). Palaeocurrent data indicate flow towards the SW and W-NW.

The geometry of the bodies, including concave-up erosional bases and channelled morphology, together with their coarse-grained volcaniclastic infill, supports interpretation as fluvial channels (Miall, 1996; Bridge, 2006;

Paredes, 2022). The facies arrangement indicates deposition from a range of high-energy, gravelly volcaniclastic flows. Trough cross-stratified breccias (VCt) record migration of 3D bedforms under dilute tractional conditions, whereas massive matrix-supported facies (VCmm) are consistent with non-cohesive debris flows. Levels with imbricated clasts and diffuse stratification (VCh) reflect high-energy tractional transport. Upward transitions to sandy facies with trough cross-stratification (VSt) indicate a progressive decrease in flow competence during channel infill. The restricted spatial distribution of these bodies supports their interpretation as local feeder channels supplying coarse volcaniclastic material to unconfined depositional areas.

FA5. Shallow lake. FA5 consists of a 7.1 m thick succession with ribbon-like geometry and no erosional features, dominated by massive volcaniclastic mudstones that locally display horizontal parallel lamination, desiccation cracks, undetermined vertebrate burrows, and *Cochlichnus* isp. (VMh) (Figs. 2 and 3G). The succession is laterally continuous for several hundred meters. Subordinate facies include centimetre-thick intercalations of silicified micritic limestones containing ostracods (L) and volcaniclastic siltstones with unidirectional ripple cross-lamination and root traces near the top of the FA (VMr1). Turtle remains assigned to *Chubutemys copelloi* are present near the top of the interval assigned to this FA (de la Fuente *et al.,* 2011).

The predominance of massive to laminated volcaniclastic mudstones (VMh), arranged in laterally extensive bodies with non-erosive bases, supports deposition by settling from suspension in shallow lacustrine settings (Nakayama and Yoshikawa, 1997; Benavente and Bohacs, 2024). Ostracod-bearing micritic limestones (L) indicates periods of calcium carbonate precipitation under relatively alkaline conditions. Interbedded volcaniclastic siltstones with unidirectional ripple cross-lamination (VMr1) are interpreted as littoral deposits formed under weak tractional currents in shallow marginal areas of the lake. Desiccation cracks and root traces indicate periodic subaerial exposure related to fluctuations in lake level, shoreline retreat, and progressive shallowing of the system.

FA6. Lake-mudflat. FA6 comprises tabular to sheet-like bodies with non-erosive bases, dominated by volcaniclastic mudstones with thin intercalations of moderately well-sorted, fine-grained volcaniclastic sandstones (Figs. 2 and 3H). Mudstones are typically massive or display horizontal parallel lamination (VMh) and locally exhibit symmetrical ripple cross-lamination (VMr2). Volcaniclastic sandstones are predominantly massive (VSm), and less commonly parallel laminated (VSh). Root traces and invertebrate burrows including, *Taenidium barretti* and *Beaconites* isp., are present, particularly within facies VMh. Individual beds range from centimetres to metres in thickness and form successions up to 10 m thick, with lateral extent of up to ~100 m.

The predominance of fine-grained volcaniclastic deposits, together with subordinate tuffaceous sandy intercalations, indicates deposition in standing water and associated occasional flows (Benavente and Bohacs, 2024). The lateral relationship with the preceding FA5, along with the evidence of pedogenic features, supports interpretation as ponded areas in lake-mudflat environments. Massive and laminated mudstones (VMh) record suspension settling in shallow water bodies occupying topographic depressions within the lake mudflat. The occurrence of symmetrical ripple cross-lamination (VMr2) indicates oscillatory wave activity in shallow-water settings, probably generated by wind action. Interbedded volcaniclastic sandstones (VSm and VSh) reflect episodic influxes of sediment-laden dilute flows, deposited either from suspension-dominated flows or alternating phases of low-energy flow and suspension settling, respectively. Root traces and trace fossils indicate recurrent colonization by plants and burrowing invertebrates during intervals of reduced sedimentation and subaerial exposure.

FA7. Aeolian dunes and dry interdunes. FA7 is mainly composed of alternating, well-sorted, medium- to fine-grained volcaniclastic sandstones with planar (VSpa), tangential (VSaa), and low-angle cross-stratification (VSla) (Figs. 2 and 3I). Cross-stratified sets of facies VSpa and VSaa have variable thicknesses between 0.7 and 5 m displaying foresets dipping up to 30°, together with normal and inverse grading. Reactivation surfaces and local soft-

sediment deformation structures are also present. Locally, the upper part of this FA includes well-sorted, fine-grained volcaniclastic sandstones with trough cross-stratification (VSta). Facies VSla exhibits inverse intralamina grading across stratigraphic intervals 0.5 to 1 m thick. FA7 ranges from 4.25 to 10.6 m in thickness, extends laterally for more than 100 m, and displays plano-convex to sheet-like geometries. Trace fossils of vertebrates, including *Avipeda* isp., *Brasilichnium* isp. and undetermined footprints, are common in facies VSpa and VSaa. Invertebrate traces include *Skolithos linearis*, *Taenidium barretti*, *Palaeophycus tubularis*, cf. *Octopodichnus* isp., and undetermined arthropod trackways, together with scarce root traces. Palaeocurrent data are unimodal toward the SE at PM and LC1 localities, but more variable at H locality (Fig. 2).

Large-scale cross-sets composed of well-sorted volcaniclastic sandstones indicate deposition by tractional aeolian processes (Kocurek, 1996; Mountney, 2006; Pye and Tsoar, 2009). In particular, volcaniclastic sandstones with planar and tangential cross-stratification (VSpa and VSaa), characterised by foresets dipping up to 30° and showing both normal and inverse intralaminar grading, are interpreted as deposits formed by dune migration by grainfall and grainflow processes, forming 2D dunes oriented perpendicular to the prevailing wind direction. The local occurrence of a reactivation surface overlain by volcaniclastic sandstones with trough cross-stratification (VSta) indicates a change in wind direction and/or intensity, followed by the migration of crescentic aeolian dunes. Soft-sediment deformation structures recorded in facies VSpa are interpreted as the result of landslides or sand avalanches on the leeward side of the dunes. Volcaniclastic sandstones with low-angle cross-stratification (VSla) are interpreted as dry interdune deposits. The ichnological content indicates colonization by a variety of vertebrates and invertebrates, and the limited occurrence of root traces suggests shifting and ephemeral substrates.

Stratigraphic intervals

Along the studied transect, two informal stratigraphic intervals, designated I and II, were recognized, refining the stratigraphic framework previously proposed for the LC area by Villegas and Umazano (2024) (Figs. 2 and 4). Both intervals are present in the central sector of the study area (PM, LC1–LC3, and H localities), whereas only interval II is recorded at the peripheral localities (ALP and TC).

Interval I (up to 16.3 m thick) comprises the lower part of the Puesto La Paloma Member at the PM, LC1–LC3, and H localities (Figs. 2 and 4). This interval extends from the contact with the underlying Bardas Coloradas Member to the level where sheet-flood deposits become regionally dominant or, where present, to the base of the feeder channel deposits. In these localities, interval I is dominated by aeolian dune and dry interdune deposits (FA7, 35.4–72.4 %), which pass vertically and laterally into sheet-flood (FA2, 24.8–60.7 %), shallow lake (FA5, 60.7 %), lake mudflat (FA6, 19.1–54.4 %), and volcanic ashfall (FA1, 2.8–23.8 %) deposits. Within the LC1-LC3 sector, below the laterally correlative FA1 deposits (cf. Villegas and Umazano, 2024), aeolian dune and dry-interdune deposits (FA7) show a clear lateral relationship with sheet-flood and lake-mudflat deposits (FA2 and FA6, respectively). These FA's can, in turn, be traced laterally towards the shallow lake deposits (FA5) exposed at the PM locality.

Interval II (up to 31.4 m thick) comprises the upper part of the Puesto La Paloma Member at the PM, LC1-LC3, and H localities and extends upward to the contact with the Cerro Castaño Member. In these localities, this interval is dominated by sheet-flood deposits (FA2, 75.2–100 %), with local occurrences of volcanic ashfall deposits (FA1, 7.2–10.1 %) and isolated feeder-channel deposits at its base (FA4, 12.9–17.6 %) (Figs. 2 and 4). At the TC locality, interval II is composed exclusively of sheet-flood deposits (FA2, 100%), whereas at ALP it is dominated by fluvial channel and floodplain deposits (FA3, 96.1 %), with minor intercalations of volcanic ashfall deposits (FA1, 3.9 %) (Figs. 2 and 4).

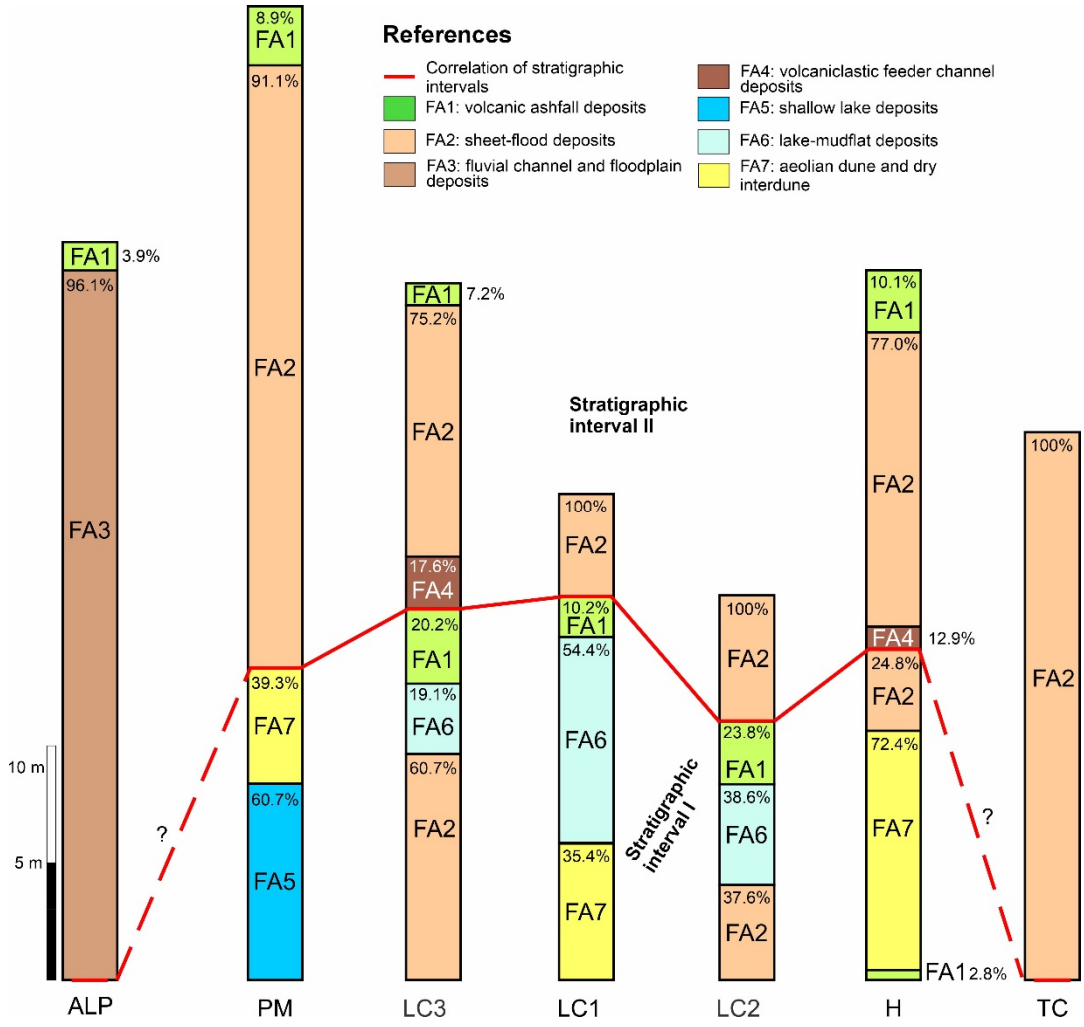


Figure 4. Percentages of facies associations for each stratigraphic interval and locality. ALP: Aguada La Piedra. PM: Puesto Mesa. LC1-LC2-LC3: Los Chivos 1 to 3. H: Huanimán. TC: Tres Cerros.

DISCUSSION

Palaeoenvironmental setting

Sediments composing stratigraphic interval I were initially delivered by episodic ash fallouts (FA1) sourced from volcanic centres located nearly 200 km to the west, in the present-day Andean region (Umazano *et al.*, 2017; Allard *et al.*, 2021a; Villegas and Umazano, 2024). Following deposition, primary volcaniclastic materials underwent extensive pedogenesis and/or resedimentation by different transport agents and flow types across a variety

of depositional environments. In the central sector of the studied transect (localities PM to H, Fig. 2), interval I records an interaction between 2D aeolian dunes that migrated in the range between NE and SE quadrat and associated dry interdunes (FA7), together with a shallow lake (FA5), fringing lake-mudflats (FA6), and marginal sheet-floods (FA2) (Fig. 5). At LC1, dune deposits were either stabilized by pedogenesis or affected by reactivation processes related to changes in wind direction and/or velocity (Kocurek, 1996). Depressed areas represented subaqueous lacustrine deposits sourced by sheet floods. The lacustrine deposits were surrounded by subaerially exposed mudflats, where scattered aeolian dunes and low relief areas (dry interdune) developed. The sediment supply required for dune development may have originated from subaerially exposed deposits of the shallow lake and adjacent lake-mudflats (Paredes *et al.,* 2025), primary ash fall deposits and/or from previously accumulated sheet-flood sediments (Umazano *et al.,* 2014, 2021). At LC1-LC3, pedogenised tuffaceous strata developed on volcanic ashfall deposits. The ichnological assemblage preserved in this palaeosol indicates soil formation under semi-arid, seasonal climatic conditions (Melchor *et al.,* 2023, 2024). Trace fossils recorded at H section indicate colonization of the dunes by desert fauna (Ahlbrandt *et al*., 1978) and suggest some degree of substrate cohesion, probably related to moisture availability through groundwater rise, rainfall, or dew formation (Espinoza *et al.,* 2026).

In contrast, stratigraphic interval II is dominated by sheet-flood deposits (FA2), interpreted as the product of resedimentation of episodic distal ashfall deposits (FA1) (Fig. 5). This pattern occurs throughout the study area except at ALP, where a channelised fluvial system with sandy bedload and associated floodplain environments persisted (FA3). At this locality, proximal floodplain deposits were formed by dilute type I and II flows (Smith and Lowe, 1991), whereas more distal sectors record suspension settling under low-energy standing-water conditions. Most sheet-flood deposits accumulated from dilute type I flows, although the flows locally evolved towards higher sediment concentration, acquiring characteristics of type II dilute flows and even debris flows. These changes reflect fluctuations in sediment concentration and flow rheology (Fisher, 1983). At the LC3 and H localities, gravelly feeder channels

developed (FA4), recording alternations of dilute flows and debris flows draining towards the NW and SW, respectively. The occurrence of clasts derived from granitoids and effusive volcanic rocks indicates an additional sediment supply from the basement and units of megasequence I, respectively, as previously recognised in the overlying Cerro Castaño Member (Umazano *et al.*, 2025). Pedogenesis of sheet-flood and floodplain deposits was recurrent during interval II, indicating reduced sedimentation rates, repeated episodes of subaerial exposure, and temporary landscape stability.

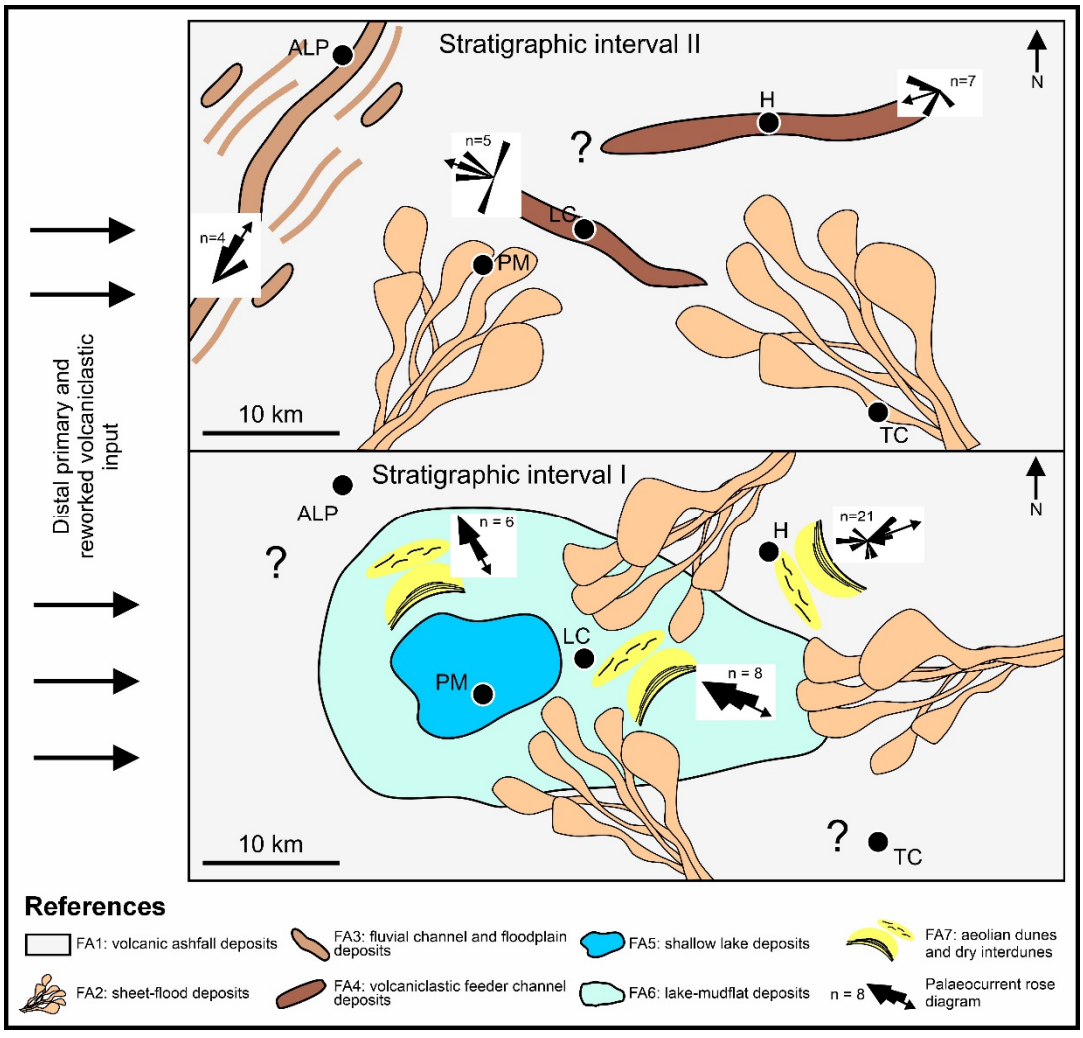


Figure 5. Reconstruction of Aptian sedimentary palaeoenvironments of the Puesto La Paloma Member in the Gorro Frigio depocentre.

Overall, the Puesto La Paloma Member in the study area records a volcaniclastic sedimentary system (Fig. 5) broadly comparable to that interpreted at the basin scale (Umazano *et al.,* 2017). Specifically, the palaeoenvironmental evolution previously proposed for the LC sector by Villegas and Umazano (2024) can be extended to other areas of the Gorro Frigio depocentre, although important spatial and temporal variations are recognized.

Sedimentary controls

Classically, palaeoenvironmental changes recorded in volcaniclastic alluvial successions, including those affected by aeolian processes, have been related to allocyclic controls such as syn-depositional tectonic activity, eustatic fluctuations, climatic changes, and variations in volcaniclastic supply (Smith, 1991; Miall, 1996; Bridge, 2006; Catuneanu, 2026). In the study area, the Puesto La Paloma Member was deposited in an endorheic depocentre lacking evidence of marine connection; accordingly, eustatic control can be excluded as primary driver of the observed palaeoenvironmental changes. Furthermore, no evidence of syn-sedimentary tectonic activity was identified to account for the observed modifications. Therefore, the most plausible controls on the observed changes are variations in volcaniclastic supply, climate or both.

Volcaniclastic supply. The markedly volcaniclastic nature of the studied succession suggests that volcaniclastic input, whether supplied directly by tephra fallout or through secondary processes, may have acted as a major allocyclic control (e.g., Smith, 1991; Critelli *et al.,* 2023). In particular, the transitional contact with the underlying Bardas Coloradas Member, associated with an increased abundance of volcaniclastic strata and a shift from channelised fluvial conditions below to predominantly unconfined depositional settings above (Umazano *et al.,* 2017; Krause *et al.,* 2020; Villegas and Umazano, 2024), is consistent with a dominant control exerted by volcaniclastic supply. In agreement with our inferences, charophyte assemblages recorded in lentic environments of the Puesto La Paloma Member

have been linked to stress associated with volcaniclastic influx relative to the underlying Bardas Coloradas Member (De Sosa Tomas and Martin-Closas, this volume). Particularly, the reduction in fluvial confinement recorded during interval I (when compared with underlying strata) can be related to an increase in volcaniclastic sediment influx, leading to oversupplied conditions. In this context, the geographically restricted occurrence of aeolian dune and dry interdune deposits in a mudflat around a shallow lake suggests local availability of volcaniclastic sediments above the water table and, therefore, susceptible to aeolian transport (Edgett and Lancaster, 1993).

In Interval II, the marked predominance of sheet-flood deposits with intercalations of ashfall strata across all localities except ALP suggests that volcaniclastic influx remained a primary control. Particularly, the dominance of sheet-flood deposits and the absence of aeolian deposits may reflect higher rates of water-driven sediment transport or aggradation (Manville *et al.,* 2009; Pierson and Major, 2014), together with reduced sediment availability for aeolian reworking. Compared to the underlying interval, the lower proportion of ashfall deposits may reflect either a decrease in volcaniclastic influx or reduced preservation of primary ashfall deposits due to enhanced erosion and sediment remobilisation. The latter possibility could be associated with increased water availability and/or drainage integration, promoting the bypass and redistribution of primary ash deposits, even if volcaniclastic supply remained broadly similar between the two intervals. Likewise, feeder-channel deposits, recorded locally at the base of Interval II and consistent with the axial drainage of the studied depocentre, might be linked to episodes of fluvial recovery (Smith, 1991) or respond to the spatial organization of the drainage system (Paredes, 2022). On the other hand, the occurrence of fluvial channel and floodplain deposits at ALP indicates a lower local influx of volcaniclastic sediment, probably related to its more peripheral and upland position within the studied depocentre.

Climate. Qualitatively, the presence of deposits produced by sheet-floods, commonly amalgamated and pedogenized, together with the occurrence of aeolian and shallow lacustrine successions containing calcium

carbonate,suggests that deposition of stratigraphic interval I took place under semi-arid to arid climatic conditions (Parrish, 1998). The sheet-flood deposits represent the characteristic depositional events of the unit at the basin scale, whereas carbonate-bearing lacustrine and aeolian deposits are geographically restricted, suggesting local environmental controls in both the studied depocentre and the adjacent Paso de Indios depocentre (Brea *et al.,* 2016; Umazano *et al.,* 2017; Krause *et al.,* 2020; Allard *et al.,* 2021a). Available palaeoclimatic information from the underlying Bardas Coloradas Member also indicates semi-arid to arid conditions with marked seasonality during deposition. These interpretations are based on quantitative palaeohydrological estimates of mean annual precipitation derived from fluvial channel deposits (Allard *et al.,* 2021a), the occurrence of palaeosols containing calcium carbonate, gypsum, and hydromorphic features in floodplain deposits, and the presence of particular charophyte assemblages in lacustrine deposits (De Sosa Tomas, 2025; De Sosa Tomas *et al.,* 2022; De Sosa Tomas and Martin-Closas, this volume). Based on the sedimentological, palaeopedological, palaeohydrological, and micropalaeontological evidence discussed above, the marked palaeoenvironmental differences between the Los Adobes and Cerro Barcino formations do not appear to reflect major climatic changes.

The persistence of amalgamated and pedogenized sheet-flood deposits in stratigraphic interval II is compatible with continued semi-arid to arid climatic conditions. Although the absence of aeolian deposits and calcium carbonate-bearing lacustrine deposits could suggest relatively more humid conditions (e.g., Lam *et al.,* 2025), quantitative palaeoclimatic estimates based on major-element geochemistry of palaeosol samples from the upper part of the Puesto La Paloma Member at TC indicate mean annual precipitation and temperature values ranging between 200–700 mm/year and 7–9 °C, respectively (Krause *et al.,* 2014). In addition, the macro- and micromorphological features of these palaeosols include the coexistence of calcic and hydromorphic characteristics, indicating significant temporal variations in soil moisture availability. Furthermore, the local development of volcaniclastic aeolian dunes has been reported in fluvial environments under climates with a mean annual precipitation exceeding 2,500 mm; this suggests

that the use of local aeolian dune deposits as a paleoclimatic indicator should be approached with caution (Umazano *et al.*, 2014). Overall, the currently available information does not support major climatic differences between the informal stratigraphic intervals recognized within the Puesto La Paloma Member.

CONCLUSIONS

The detailed palaeoenvironmental study of the Aptian volcaniclastic succession of the Puesto La Paloma Member in the Gorro Frigio depocentre (Cañadón Asfalto Basin, Argentina), including facies analysis and the recognition of two informal stratigraphic intervals, allowed the following main conclusions to be obtained.

Interval I, recorded in the central zone of the study area, represents a shallow lacustrine environment surrounded by mudflat zones with episodic influx of sheet-floods and ashfalls, in which aeolian dunes and dry interdune zones developed, locally dominating the succession.

In the depositional area of Interval I, the overlying Interval II mostly records sheet-floods with intercalations of ashfall events and, locally, feeder channels. Toward the NW and SE extremes of the study area, this interval represents fluvial channels and floodplains with occasional volcanic ashfalls, and sheet-floods, respectively.

The palaeoenvironmental changes detected both in relation to the underlying Bardas Coloradas Member and between intervals were mostly governed by spatio-temporal variations in the supply of volcaniclastic sediments.

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Artificial Intelligence (IA) use statement. The authors only used AI to improve the English phrasing of certain passages.

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