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Changing fluvial styles in volcaniclastic successions: A cretaceous example from the Cerro Barcino Formation, Patagonia

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ABSTRACT

The Cretaceous Puesto La Paloma (PLPM) and Cerro Castaño (CCM) members (Cerro Barcino Formation, Chubut Group) are pyroclastic-rich, alluvial successions deposited in the Somuncurá-Cañadón Asfalto Basin during sag and endorheic conditions. The PLPM comprises sheet-like tuffaceous sandstone strata, whereas the overlying CCM includes sheet-to ribbon-channel sandstone bodies intercalated within tuffaceous and fine-grained sediments. In this context, the goals of this contribution were: i) to make a detailed documentation of the contrasting sedimentary palaeonvironments; and ii) to infer the allocyclic controls that governed the sedimentation of both units. The study area is located in the western sector of the basin, where six localities, which were studied.

Six facies associations were defined including ash-falls, sheet-floods, shallow lakes, aeolian, fluvial channel-belts, and reworked debris-flows. We defined four stratigraphic intervals for the studied sections, denominated 1 to 4 in chronological order of deposition, which increase their thicknesses toward the Puesto Mesa-Cerro León site. The interval 1 (18–42 m thick) corresponds to the PLPM and includes numerous pedogenized sheet-flood deposits, carbonate-rich lacustrine, aeolian sandy facies, and ash-fall beds. The interval 1 is interpreted as an ephemeral and unconfined alluvial system that interacted with aeolian dunes and dry interdune zones. The interval 2 (20–47 m thick) represents the lower part of the CCM. It shows an alternation of fluvial channel-belt deposits and vegetated floodplain facies with sediments originated from sheet-floods, lakes, and few ash-falls and debris-flows. The mean palaeoflow was toward E-SE, except in the northernmost locality where the drainage was towards SW. Proportion of channel-belt bodies ranges from 10 to 36%, reaching higher values in the northern part of the study area, where they are also thicker. The interval 2 represents a permanent, meandering or locally low-sinuosity, fluvial system, and displays both an increase of lacustrine facies and a decrease of ash-fall deposits. The interval 3 (7.5–27 m thick) corresponds to the middle part of the CCM, and lacks channel-belt bodies. It has the highest participation of sheet-flood and ash-fall deposits. This interval entirely records a pedogenized floodplain setting. In relation to the interval 2, participation of debris-flow deposits remains constant and lacustrine facies subtly increases. The interval 4 (18–148 m thick) represents the upper part of the CCM. It comprises an alternation of channel-belt bodies and pedogenized floodplain facies, the last characterized by sheet-flood, lake, debris-flow, and volcanic ash rain deposits. The mean palaeoflow was toward E-SE, except in the two localities positioned further north where the drainage was towards NE and SSE. Proportion of channel-belt deposits ranges from 6 to 32%. It represents channelized and perennial fluvial systems with meandering and locally low-sinuosity styles. Increase in channel proportion and thicker channel bodies are in the northern part of the study area. Particularly, in Puesto

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Mesa-Cerro León locality this interval is the thickest and has the highest proportion of thicker channel-belt bodies.

We interpret these changes in facies architecture as the response to alternated periods of high (intervals 1 and 3) and low (intervals 2 and 4) primary pyroclastic sediment supply. Moreover, there was a climatic change to wetter conditions (intervals 1 to 2–4); as well as intrabasinal tectonic activity in northern area for intervals 2 and 4 inferred from palaeocurrent data.

1. Introduction

Commonly, the palaeoenvironmental changes in the depositional system of pre-Quaternary volcaniclastic fluvial successions that were deposited without an oceanic connection are evaluated in function of the spatial and temporal variation of the pyroclastic sediment supply. These types of successions are usually divided into syn and inter-eruptive stratigraphic intervals using the criterions proposed by Smith (1991); they include the sediment concentration of flows and resulting facies, the configuration of palaeochannels, the geometry of deposits, and the features of palaeosols, among others. Under this rationale, the remaining allocyclic controls were commonly considered of minor importance. Nevertheless, in the last years some contributions have focused in the understanding of the influence of tectonic activity (e.g. Paredes et al., 2015) and climatic changes (e.g. Umazano et al., 2008) on the sedimentation in volcaniclastic fluvial environments. Moreover, the basement morphology is an additional factor that can control the sedimentation in near vent positions (e.g. Umazano et al., 2014a). As a result, a more complete and precise understanding of this type of successions has been obtained.

The Cretaceous Cerro Barcino Formation is a continental, pyroclastic-rich succession widely distributed in the Somuncurá-Cañadón Asfalto Basin (Patagonia, Argentina). The formation, which is part of the more broadly distributed Chubut Group (*sensu* Codignotto et al., 1978), was the focus of several regional studies and compilations lacking a detailed sedimentary framework (Figari and Courtade, 1993; Cortiñas, 1996; Figari, 2005; Ranalli et al., 2011; Figari et al., 2015). Some local and relatively exhaustive palaeoenvironmental inferences have been included in sedimentological papers from partial sections of some stratigraphic intervals (Manassero et al., 2000; Cladera et al., 2004; Foix et al., 2012; Carmona et al., 2016), and in palaeontological contributions (Genise et al., 2010; de la Fuente et al., 2011; Argañaraz et al., 2013; Perez et al., 2013a,b; Passalia et al., 2015; Sterli et al., 2015). The palaeontological topic acquires significance, since the Cerro Barcino Formation has yielded some of the most complete titanosauriform remains (e.g., the titanosauriform *Chubutisaurus*; del Corro, 1975; Salgado, 1993; Carballido et al., 2011) and an undescribed gigantic basal titanosaur from Las Plumas zone, eastward from the study area (Carmona et al., 2016). The potential radiation of an endemic clade of gigantic titanosaur sauropods from the late Albian of Patagonia, is coincident with the establishment of the mid-Cretaceous Gondwanan fauna and the emergence of angiosperms in the continental ecosystems (Pol et al., 2016).

Recently, some preliminary results about regional palaeoenvironmental conditions of selected stratigraphic intervals were addressed (Allard et al., 2010a; Umazano, 2010; Umazano et al., 2012a; Umazano and Krause, 2013; Foix et al., 2014; Umazano et al., 2014b, 2016). According to observation by the authors, the lower part of the Cerro Barcino Formation (Puesto La Paloma Member) mainly records unconfined fluvial sedimentation with minor aeolian reworking. The overlying strata, denominated in ascending order Cerro Castaño, Las Plumas and Puesto Manuel Arce + Bayo Overo members, suggest a sedimentation dominated by channeled fluvial systems.

In this context, the contribution has two main goals. The first is to make a detailed documentation of the contrasting sedimentary palaeonvironments recorded in the Puesto La Paloma and Cerro Castaño members, as well as their spatial and temporal changes. The second is to infer the allocyclic controls that governed the sedimentation of both units, with emphasis in understanding the regional channelization of the fluvial systems towards the top of the succession.

2. Geological setting

2.1. Somuncurá-Cañadón Asfalto Basin

The Somuncurá-Cañadón Asfalto Basin covers a wide part of northern Patagonia Argentina (Fig. 1); but the Cretaceous deposits are restricted to the central part of the Chubut Province. The basin mainly developed over a Palaeozoic crystalline basement (Fig. 2) due to Jurassic extensional stress regime linked to the Gondwana breakup and opening of the South Atlantic Ocean (Figari and Courtade, 1993; Cortiñas, 1996; Figari, 2005; Ranalli et al., 2011; Figari et al., 2015). According to Figari et al. (2015), the fill of the basin can be divided into rift and postrift successions, the last one preceded by a tectonic reactivation stage with transtensive - transpressive stress and block rotation (Fig. 2). The rift stage record initiates with the early Jurassic fluvio-deltaic sediments of the Las Leoneras Formation (Nakayama, 1973; Chebli et al., 1976). Then, deposition of the volcanic-sedimentary Lonco Trapial Formation occurred (Lesta and Ferello, 1972). From middle Jurassic to late Jurassic (cf. Cúneo et al., 2013), several small troughs were originated and dominantly filled with lacustrine sediments of the Cañadón Asfalto and Cañadón Calcáreo formations (Proserpio, 1987; Cabaleri and Armella, 1999, 2005; Cabaleri and Benavente, 2013; Cabaleri et al., 2005, 2013; Volkheimer et al., 2008, 2009; Gallego et al., 2011).

The deposition of the postrift succession started in the Early Cretaceous (Fig. 2), when the basin experienced tectonic reactivation with transtensive – transpressive stress followed by thermal subsidence and high pyroclastic influx from the west. The postrift succession is initially represented by the Chubut Group, which is extensively distributed in central Patagonia (Gianni et al., 2015, 2016). It has been stratigraphically divided using two different schemes. According to Chebli et al. (1976), the Chubut Group is constituted of Gorro Frigio, Cañadón de Las Víboras and Puesto Manuel Arce formations. According to Codignotto et al. (1978), which is followed in this contribution, the Chubut Group is composed of the Los Adobes and Cerro Barcino Formations (see Fig. 2). The Los Adobes Formation (Barremian?) includes the Arroyo del Pajarito and Bardas Coloradas members. Both are characterized by conglomerates and sandstones with ribbon to sheet-like geometries, interbedded with tabular, fine-grained, mostly siliciclastic sediments. The Arroyo del Pajarito Member was deposited in alluvial fans and high-energy fluvial systems (Codignotto et al.,

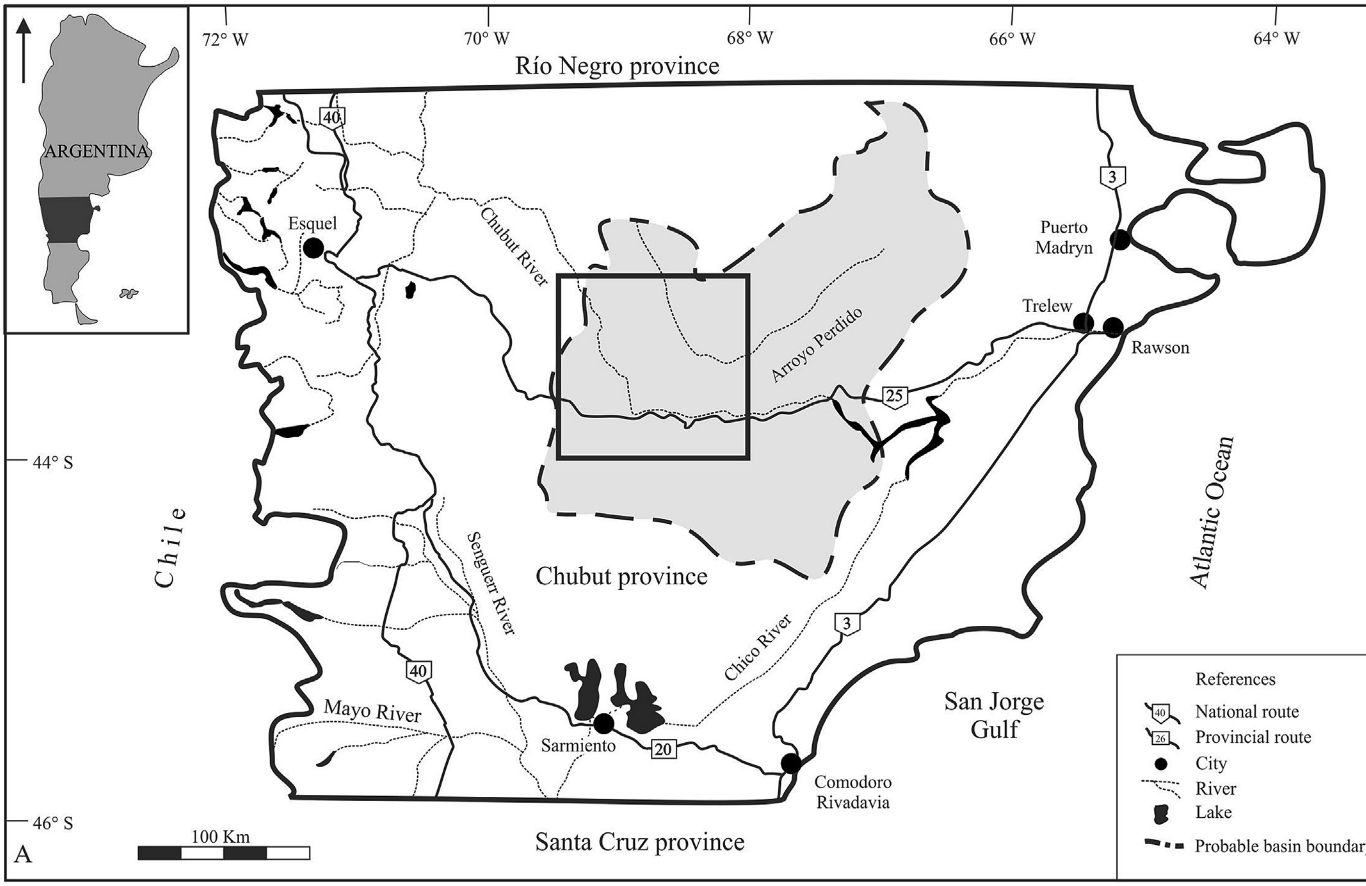

Fig. 1. Location of the Somuncurá-Cañadón Asfalto Basin (after Suarez et al., 2014) and study area (rectangle, which corresponds to Fig. 3).

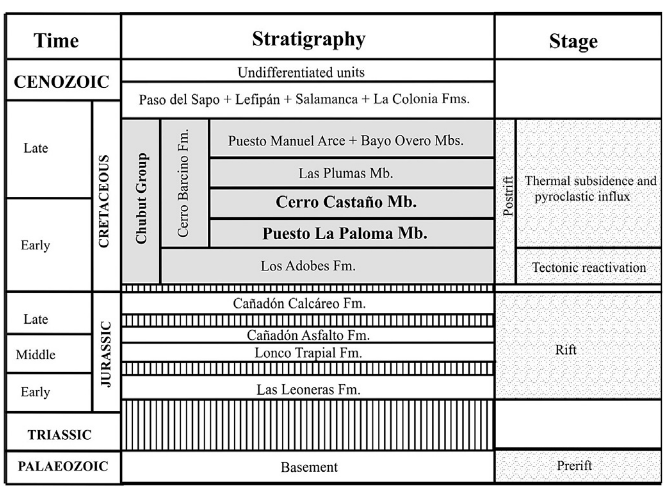

Fig. 2. Stratigraphy of the Somuncurá-Cañadón Asfalto Basin (modified from Figari et al., 2015). Units in bold are the focus of this study.

1978); whereas the Bardas Coloradas Member indicates a fluvial setting composed of channels, with different patterns and dimensions, crossing wide floodplains (Allard et al., 2009, 2010b, 2010c, 2011, 2012; Villegas et al., 2014; Brea et al., 2016). The Los Adobes Formation represents a continental depositional system, which regionally drained towards a big alkaline-saline lake emplaced in the nearby San Jorge Basin (Allard et al., 2015). The overlying Aptian-Campanian Cerro Barcino Formation (Figari et al., 2015) is more widely distributed and represents an alluvial, pyroclastic-rich succession. The volcanic source was the early Andes, located more than 150 km westward (Gianni et al., 2015; Echaurren et al., 2016). The Cerro Barcino Formation can be divided into members using the dominant coloration of the strata. From base to top, they are: the Puesto La Paloma (green), Cerro Castaño (reddish brown), Las Plumas (pinkish and reddish brown), and Puesto Manuel Arce (gray). In some parts of the basin, the Puesto Manuel Arce Member is replaced by greenish yellow tuffs of the Bayo Overo Member. The lower part of the Cerro Barcino Formation (Puesto La Paloma Member) is essentially composed of sheet-like alluvial strata (Allard et al., 2010a; Umazano, 2010; de la Fuente et al., 2011; Umazano and Krause, 2013; Umazano et al., 2014a; Sterli et al., 2015). The Cerro Castaño Member is mostly constituted by channeled sandstones interbedded with sheet-like and finer grained tuffaceous sediments (Manassero et al., 2000; Cladera et al., 2004; Allard et al., 2010a; Umazano et al., 2012a; Argañaraz et al., 2013; Umazano and Krause, 2013; Umazano et al., 2014a; Carmona et al., 2016). The remaining members are, in general, lithologically similar to the Cerro Castaño Member and also represent channeled fluvial systems (Codignotto et al., 1978; Manassero et al., 2000; Genise et al., 2010; Foix et al., 2012). At the eastern basin margin, Las Plumas Member records alluvial fan facies associated to master normal faults with evidence of synsedimentary activity (Allard et al., 2014a; Villegas et al., accepted a,b). In different parts of the basin, the Chubut Group was unconformably covered by Maastrichtian to Quaternary, marine and continental sediments, as well as by Cenozoic basalts (Fig. 2).

2.2. Study area

The study area is located in the north-central part of the Chubut province, about 190 km westward of the Trelew city (Figs. 1 and 3). Structurally, there are faults and lineaments with variable orientation, mostly related to outcrops of pre-Cretaceous rocks, which experienced fragile deformation (Anselmi et al., 2004). In addition, there are anticlines and synclines, in some cases with plunging axes, generally associated with outcrops of the Cretaceous Chubut Group or younger sediments, which suffered a ductile behaviour (Anselmi et al., 2004). Commonly, the flanks of both anticlines and synclines dip less than 15° and exhibit minor faults.

Outcrops of the Chubut Group are extensive and younger eastward (cf. Chebli et al., 1976; Codignotto et al., 1978). Particularly, the Los Adobes Formation is restricted to the central-western and southwestern parts of the study area, whereas the Cerro Barcino Formation is more widely distributed at a regional scale (Fig. 3). In this scheme, the Puesto La Paloma and Cerro Castaño members are the more extensively exposed units of the Cerro Barcino Formation; whereas the Bayo Overo and Las Plumas members crop out in the eastern and southeastern parts, respectively.

We worked in six localities denominated Huanimán, Tres Cerros, Puesto Mesa-Cerro León, La Payanca, La Madrugada and La Juanita (Fig. 3). The contact between Bardas Coloradas and Puesto La Paloma members was only reached in Puesto Mesa-Cerro León and, therefore, the Puesto La Paloma succession in this locality represents the unique complete section of this member. On the other hand, except for the Huanimán locality where the top of Cerro Castaño succession is missing by modern erosion, there are no conclusive evidence for erosion in the upper part of the analyzed sections. As generalization, in all localities the Puesto La Paloma Member (up to 42 m thick) shows sheet-like tuffaceous strata

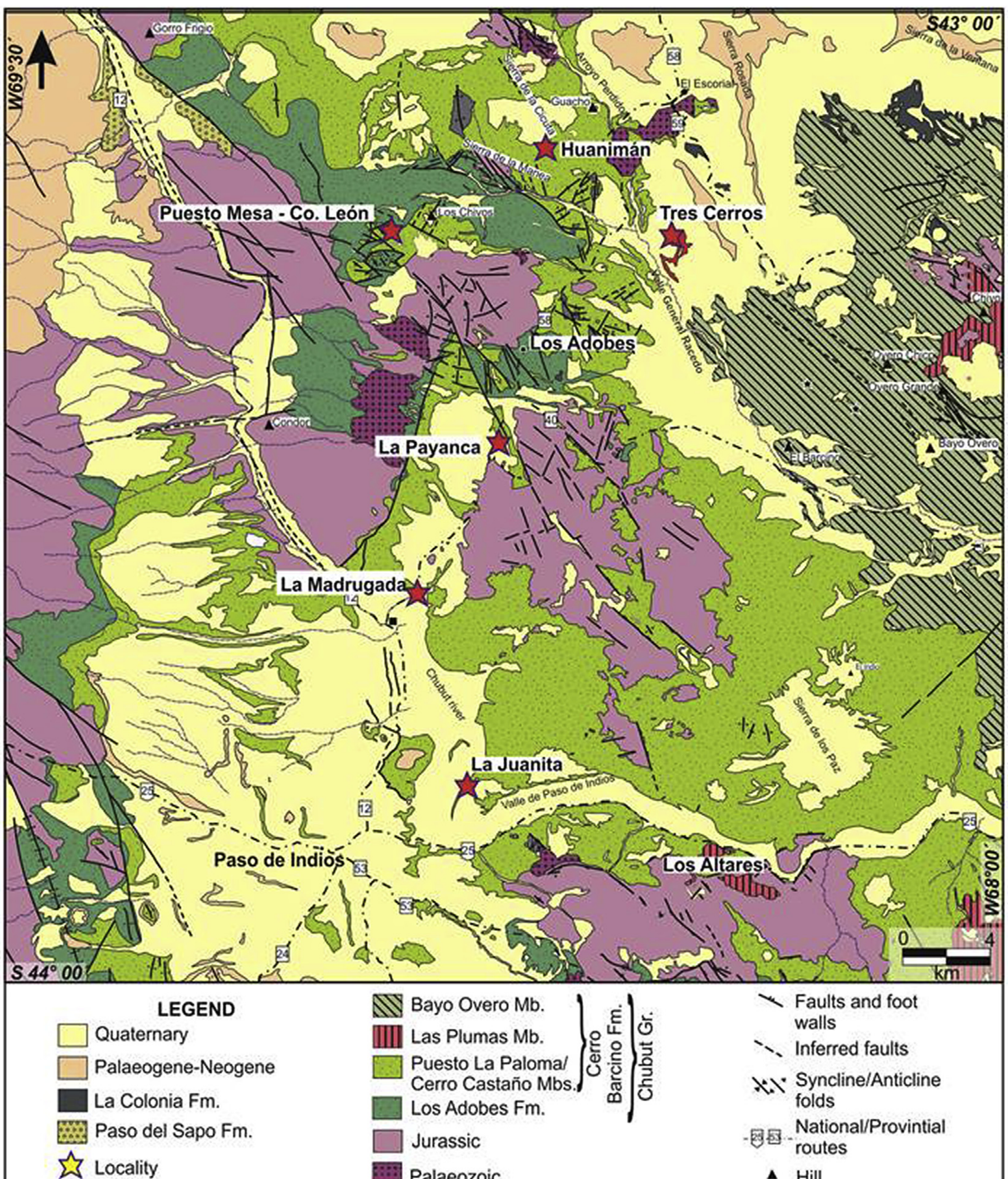

Fig. 3. Geological map of the study area and location of measured sections (after Krause et al., 2014).

dominated by sand-size sediments, whereas the Cerro Castaño Member (up to 215 m thick) includes channeled sandstone bodies interbedded with tuffaceous and finer grained sediments (Fig. 4). Except for the Tres Cerros locality, the sections define an approximately N-S oriented transect. Both units display a reduction in thickness northward and southward of Puesto Mesa-Cerro León locality (Fig. 5).

3. Methodology

Sedimentary logs were measured using standard techniques, considering the following basic attributes: thickness, features of bedding plane, lithology, grain-size, sorting, sedimentary structures, palaeocurrents and fossil content. The term tuff was reserved for primary pyroclastic rocks. The terms volcaniclastic conglomerate, tuffaceous sandstone and tuffaceous mudstone were respectively used for secondary pyroclastic of gravel-, sand- and mud-sized sediments, respectively (Umazano et al., 2012b).

Facies nomenclature agrees with the general approach made by Miall (1978), but adapted to similar volcaniclastic fluvial successions (Umazano et al., 2012b). For the aeolian facies, an additional small letter (a) was employed to highlight its origin. For description of geometry of facies associations, we applied the classification proposed by Bridge (1993) which is based in the parameters width (W), length (L) and thickness (T); in this classification the W/T ratio is used to differentiate ribbons ($W/T \leq 15$) from sheets ($W/T \geq 15$). Hierarchy of bounding surfaces of channeled bodies follows Allen (1984); a more detailed classification of these surfaces (e.g. Bridge, 1993) cannot be performed because the major order stratasets are commonly unclear. The minimum and maximum true width of fluvial channel-belt deposits was estimated using the empirical formulas of Bridge and Mackey (1993) and Bridge and Tye (2000), which are based on thickness of cross-bedded sets.

4. Facies associations

Twenty two sedimentary facies were distinguished; a summary of their descriptions and interpretations is presented in Table 1. These facies were grouped in the following six associations: ash-fall deposits (FA1), sheet-flood deposits (FA2), shallow lake deposits (FA3), aeolian deposits (FA4), fluvial channel-belt deposits (FA5) and reworked debris-flow deposits (FA6) (Table 2). The stratigraphic position of each facies association at every locality is shown in Figs. 6–9. Fig. 10 displays the participation of each facies association within both members.

4.1. Ash-fall deposits

4.1.1. Description

FA1 is mainly composed of vitric, fine-grained, well-sorted tuffs with plane parallel lamination or massive aspect, facies Th and Tm respectively, arranged in bodies with mantle bedding (Fig. 11A). Occurrence of accretionary lapilli and burrows is common in both facies. It is also common the presence of levels bearing scarce root traces (facies P). Individual beds have non erosive bases, are 0.2–0.5 m thick, and exhibit a lateral continuity of up to 2 kms. In some places, individual deposits are stacked forming sheet-like bodies up to 3 m thick. In thin section, the tuffs are dominated by vitroclasts including glass shards and pumice fragments and show scarce participation of crystaloclasts (plagioclase, quartz and biotite) and lithoclasts (volcanic lithic fragments). The samples classify as vitric tuffs (Schmid, 1981), with a homogeneous composition near the V apex. This FA is recorded in both members, at Puesto Mesa-Cerro León, La Payanca and La Madrugada localities, where it can reach 18% of the measured thickness (Fig. 10). On the other hand, in Huanimán section this FA is only represented in the Puesto La Paloma Member; whereas at La Juanita and Tres Cerros localities, it occurs only in the Cerro Castaño Member (Fig. 10).

4.1.2. Interpretation

Thin and fine-grained tuff strata arranged in bodies with mantle bedding, with no evidence of erosion in their bases, preservation of glass shards indicating low abrasion and absence of current/tractive structures are consistent with settling of primary volcanic ash (Walker, 1973; Cas and Wright, 1987; Houghton et al., 2000). The massive tuff facies (Tm) indicates volcanic eruptions with relatively uniform intensity and slow settling or fallout; whereas the laminated facies (Th) represents temporal variability in eruption intensity. Presence of accretionary lapilli, a structure formed by ash aggregation in the troposphere with low potential of preservation (Gilbert et al., 1991; Gilbert and Lane, 1994; James et al., 2003), suggests sub-aerial conditions. Sub-aerial exposure and low or null sediment accumulation are inferred by the presence of root traces (facies P).

4.2. Sheet-flood deposits

4.2.1. Description

FA2 consists of sheet-like bodies, laterally traceable by several hundred of meters, mostly composed of massive or plane parallel laminated, medium to fine-grained, moderate to well-sorted

Fig. 4. Panoramic photo showing the Puesto La Paloma and Cerro Castaño members of the Cerro Barcino Formation at Tres Cerros locality. See text for explanation.

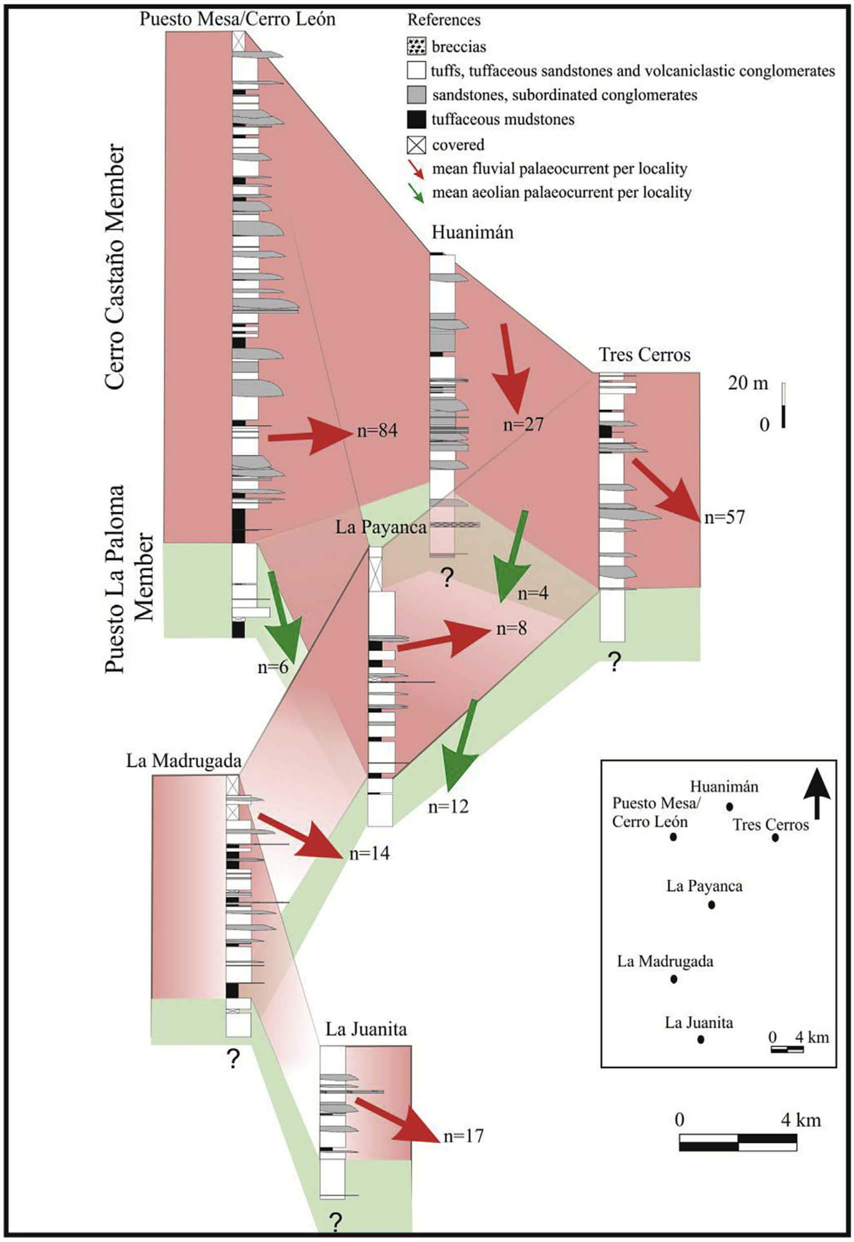

Fig. 5. Panel diagram, synthetic sedimentary logs, and mean palaeocurrent directions of fluvial and aeolian deposits.

tuffaceous sandstones, facies TSm and TSh, respectively (Fig. 11B). Bases of beds are subtly erosive. These facies commonly show a vertical transition from TSm to TSh. There is subordinated participation of sandstones and tuffaceous sandstones with trough cross-bedding (facies TSt and St), rippled tuffaceous sandstone (facies TSr) and massive sandstone (facies Sm). Occurrence of centimeter thick-sandstones with root traces, mottles, nodules and ped structure (facies P) is also reduced. Facies P from the Puesto La Paloma sections in Tres Cerros and La Juanita localities, show both hydromorphic and calcic features (Krause et al., 2014). Decimeter- to meter-thick beds are commonly stacked and amalgamated forming packages up to 23 m thick. In the field, strata of this FA pass laterally to shallow lake deposits (FA3) and fluvial channel-belt deposits (FA5). Petrographic composition is very similar to that of FA1. Scarce palaeocurrent data indicate a palaeoflow direction towards ≈ N and ≈S, which are oblique to near perpendicular with the associated fluvial channel-belt deposits. Except for the succession of Puesto La Paloma Member at La Payanca locality, this FA is the most abundant in both members (Fig. 10). Participation of FA2 per locality ranges between 23% and 100% in Puesto La Paloma Member; and between 48% and 74% in Cerro Castaño Member.

4.2.2. Interpretation

A genesis as sheet-floods that commonly remobilized pyroclastic deposits is envisaged from the sheet-like geometry and dominance of tuffaceous sandstones (Cas and Wright, 1987; Martina et al., 2006; Fisher et al., 2007; Hampton and Horton, 2007; Nichols and Fisher, 2007; Umazano et al., 2008, 2012b). The massive (TSm and Sm) and laminated (TSh) facies indicate dilute flows with high sediment concentration, and deposition in plane bed phase, respectively. Transition from facies TSm to TSh suggests a dilution phenomenon (Fisher, 1983), which probably occurred towards distal positions of the floods. More dilute flows, probably in even more distal sectors, favored the migration of

Table 1
Description and interpretation of the sedimentary facies. White rows: primary pyroclastic facies, dark gray rows: fluvial facies, intermediate gray rows: aeolian facies, light gray rows: palaeosoils.

Facies code	Lithology and texture	Sedimentary structures	Fossil content	Interpretation
Tm	Well-sorted, fine-grained, vitric tuff	Massive, some levels with accretionary lapilli, concretions or mottles	Invertebrate burrows	Subaerial ash-fall event without variability in eruptive intensity
Th	Well-sorted, fine-grained, vitric tuff	Plane parallel lamination, some levels with accretionary lapilli	Invertebrate burrows	Discontinuous subaerial settling of volcanic ash
Bh	Poorly-sorted, clast-supported, intraformational breccia	Diffuse horizontal stratification, rare imbrication	-	Fluvial channel lag
VCm	Poorly-sorted, matrix-supported, volcaniclastic conglomerate	Massive, rare normal grading	Invertebrate burrows	Debris-flow deposits
Sm	Moderately well-sorted, medium to fine-grained sandstone	Massive, common basal scours, rare concretions	Invertebrate burrows	Dilute water flow with high concentration of sediments
TSm	Moderately well-sorted, medium to fine-grained, vitric tuffaceous sandstone	Massive, common scours at base, rare concretions and liessegang rings	Invertebrate burrows, dinosaur bones, dinosaur eggs, logs and rhizolith balls	Reworking of pyroclastic substrates by dilute flows with low water-sediment ratio
Sh	Moderately well-sorted, coarse to fine-grained sandstone	Plane-parallel lamination, synsedimentary folds	-	Water stream in conditions of upper-stage plane bed streamflow. Later physical disruption of the sediments
TSh	Moderately well-sorted, medium to fine-grained, vitric tuffaceous sandstone	Plane-parallel lamination, occasional deformed laminae, rare concretions	Invertebrate burrows	Reworking of pyroclastic substrates by stream flows with development of plane beds
St	Moderately well-sorted, coarse to fine-grained sandstone	Trough cross-bedding, rare concretions	Invertebrate burrows and dinosaur bones	Subaqueous migration of 3D sand dunes
TSt	Well-sorted, fine-grained, vitric tuffaceous sandstone	Trough cross-bedding, very rare synsedimentary folds	Invertebrate burrows	Reworking of pyroclastic substrates by water flows with development of 3D dunes
Sp	Moderately well-sorted, medium-grained sandstone	Planar cross-bedding	-	Subaqueous migration of 2D sand dunes
Sr	Moderately well-sorted, medium to fine-grained sandstone	Asymmetrical ripples	-	Subaqueous migration of ripples
TSr	Fine-grained tuffaceous sandstone	Asymmetrical ripples	-	Reworking of pyroclastic substrates by low energy water currents
TMh	Tuffaceous mudstone	Plane-parallel lamination, rare desiccation cracks, deformed laminaes and synsedimentary folds	Turtle remains, logs and invertebrate burrows	Settling of suspended sediments in standing water
TMm	Tuffaceous mudstone	Massive	Abundant unidentified trace fossils and logs	Deposition of fine grained substrate in a lake and posterior intense bioturbation
TMr	Tuffaceous mudstone	Asymmetrical ripples with occasional climbing	Logs	Weak unidirectional water flows with reduced participation of settling from suspension
L	Silicified limestone	Massive	Ostracods	Inorganic carbonate precipitation in alkaline waters; subsequent silicification during diagenesis
TSpa	Very well-sorted, fine-grained tuffaceous sandstone	Thick sets (up to 2.5 m) of planar cross-bedding with direct and reverse intralamina grading	-	Migration of 2D aeolian dunes by processes of grain fall and grain flow
TSta	Very well-sorted, fine-grained tuffaceous sandstone	Thick sets (up to 2.2 m) of tangential cross-bedding with direct and reverse intralamina grading	Invertebrate burrows, rounded and tridactyl footprints and arthropod trackways	Migration of some sinuous 2D aeolian dunes with regressive ripples
TSla	Very well-sorted, fine-grained tuffaceous sandstone	Low angle cross-bedding (subcritically climbing translatent strata)	Invertebrate burrows and root traces	Migration of wind ripples without preservation of slipfaces
TSra	Very well-sorted, fine-grained tuffaceous sandstone	Rippleform laminae	-	Migration of wind ripples with preservation of slipfaces
P	Fine-grained tuff, tuffaceous sandstone or tuffaceous mudstone	Massive, rarely with relict lamination. Macro and microscopic pedofeatures	Root traces and invertebrate burrows	Soil development in primary or reworked pyroclastic deposits

Table 2
Summary of description and interpretation of facies associations.

Facies association	Facies	Lower bounding surface	Geometry	Interpretation
FA1	Tm and Th, common presence of P	Non-erosive	Mantle bedding	Ash-fall deposits
FA2	TSm and TSh, minor participation of TSt, St, TSr, Sm and P	Plane and locally erosive	Sheet	Sheet-flood deposits
FA3	TMh and TMm, occasional occurrence of TMr, TSt, TSr, TSm and P	Non-erosive	Sheet or ribbon	Shallow lake deposits
FA4	Common alternance of TSpa, TSta and TSla, local participation of TSra and P	Plane and commonly non-erosive	Sheet	Aeolian deposits
FA5	Bh and St are common. Sr, Sh and Sm are less common. Rare participation of Sp and TMh	Erosive, irregular or concave-upward	Sheet or ribbon	Fluvial channel belt deposits
FA6	VCm, locally TSt and TSm	Irregular and locally erosive	Sheet or plane-convex	Reworked debris-flow deposits

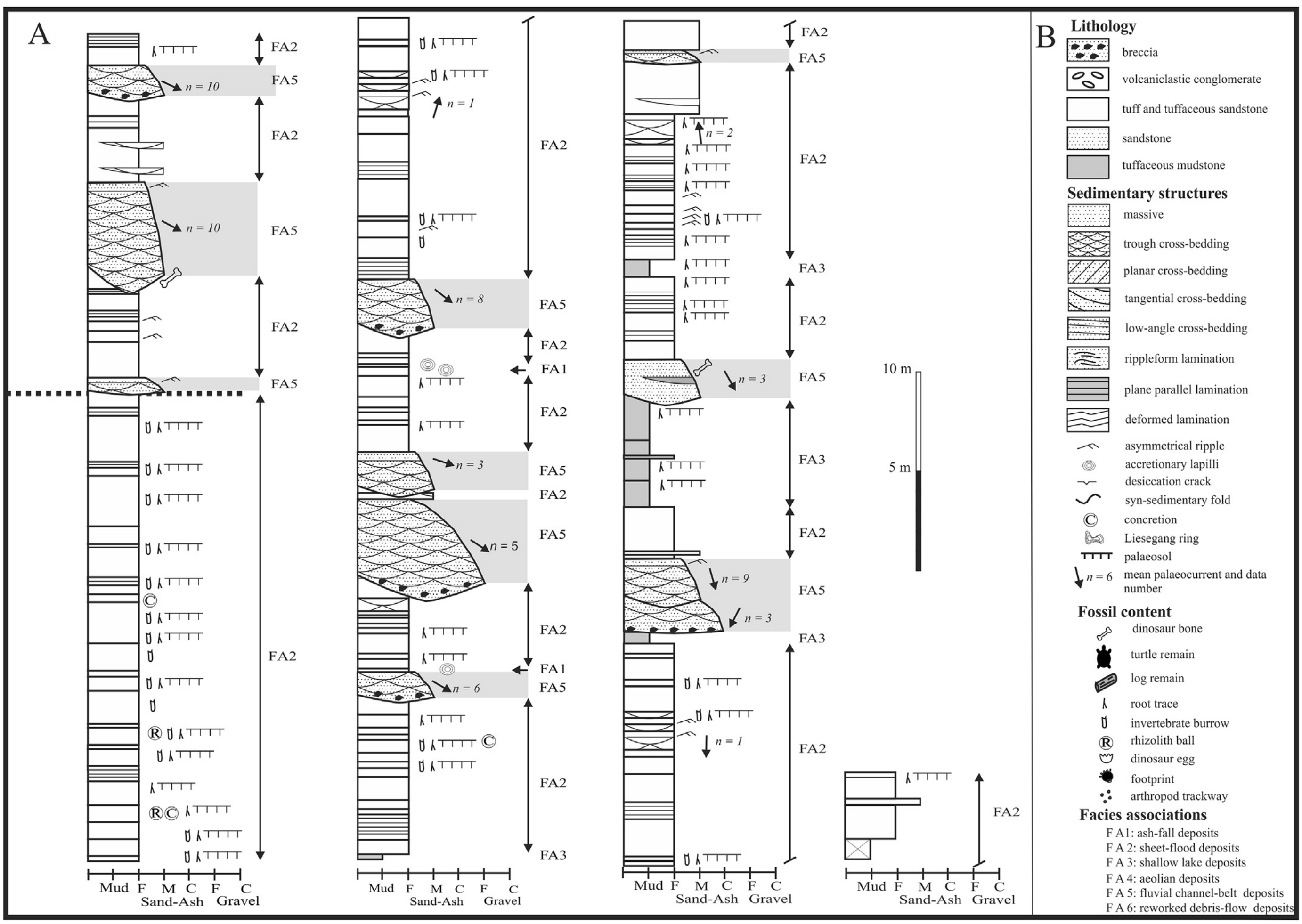

Fig. 6. Detailed sedimentary log of the Tres Cerros locality (A) and references for all sedimentary logs (B). Stratigraphic position of each facies association is shown. Data are arranged in ascending stratigraphic order from left to right. The contact between the Puesto La Paloma and Cerro Castaño members is indicated by a dotted line.

dunes with discontinuous curved crests (facies TSt and St) and asymmetrical ripples (facies TSr). Some of these deposits were modified by incipient pedogenesis (facies P).

4.3. Shallow lake deposits

4.3.1. Description

FA3 comprises sheet to ribbon-like bodies with non erosive bases, mainly composed of tuffaceous mudstones with plane parallel lamination (facies TMh) or massive due to bioturbation (facies TMm; Fig. 11C). These 0.3 m–9.8 m thick bodies are laterally extended by several hundred meters. Occasionally they show thin levels of tuffaceous mudstones with asymmetrical ripples and rare climbing ripples (facies TMr), subhorizontal root traces (facies P); and tuffaceous sandstones with trough cross-bedding (facies TSt), current ripples (facies TSr) or massive aspect (TSm). One body exhibits a centimetre thick intercalation of silicified micritic limestones with ostracod remains (facies L). Silica commonly occurs as micro-quartz replacing carbonate grains or zebra-like chalcedony filling pores. This FA was only recorded at Puesto Mesa-Cerro León locality (17%; Fig. 10) of the Puesto La Paloma Member; whereas it was observed in all sections of the Cerro Castaño Member, where it accounts for 6%–22% of the measured section (Fig. 10).

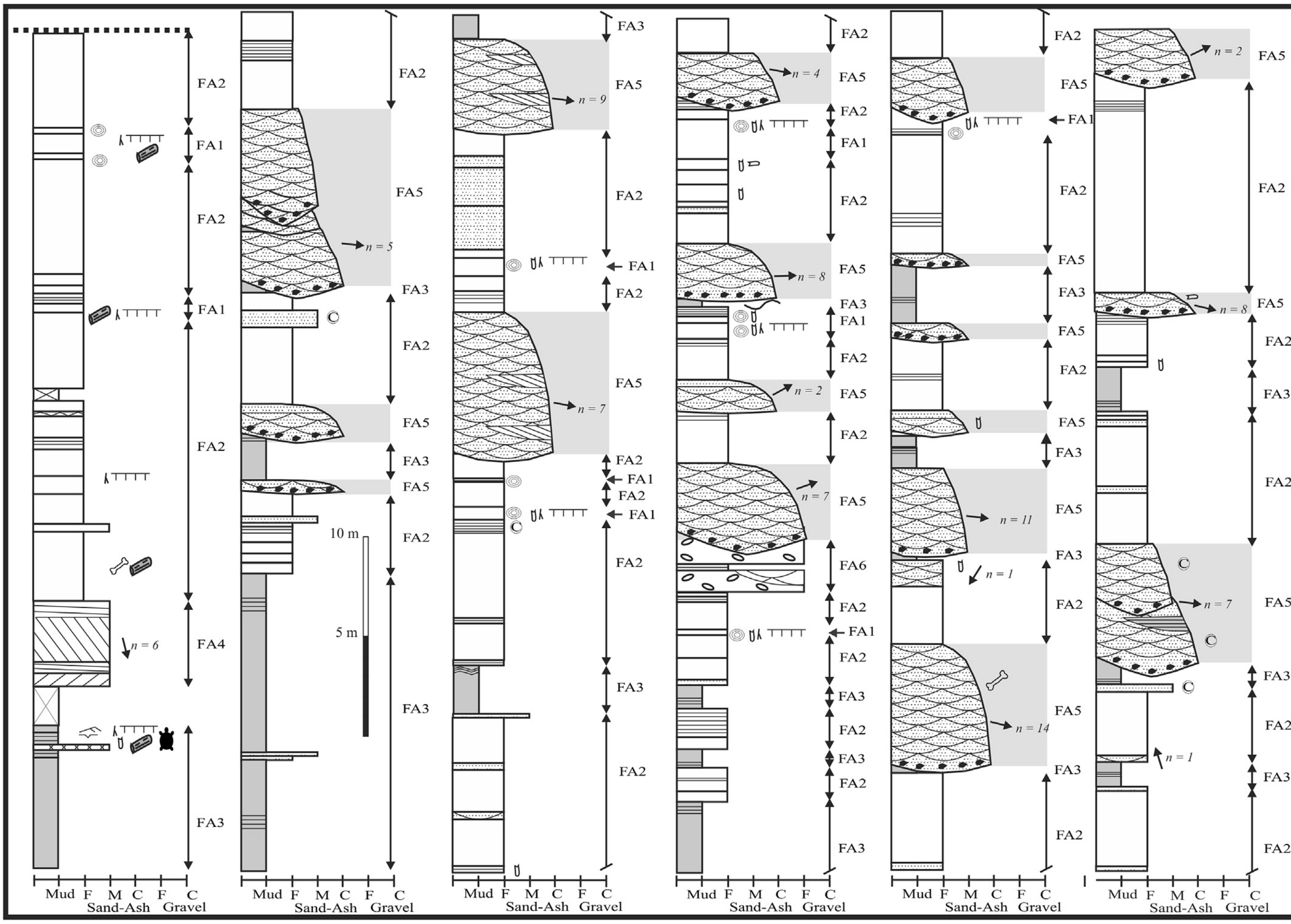

Fig. 7. Detailed sedimentary log of the Puesto Mesa-Cerro León locality. Stratigraphic position of each facies association is shown. Data are arranged in ascending stratigraphic order from left to right. The contact between the Puesto La Paloma and Cerro Castaño members is indicated by a dotted line. See references in Fig. 6.

4.3.2. Interpretation

Mudstone bodies with non erosive bases, and the dominance of laminated or massive beds is compatible with lacustrine conditions (Talbot and Allen, 1996; Nakayama and Yoshikawa, 1997). Facies TMh was generated by settling from suspension in a subaqueous setting. Massive tuffaceous beds (facies TMm) with high degree of bioturbation suggest well-oxygenated lake bottoms. Subordinated tractive sandy facies (TSt, TSr and TMr) are related to littoral migration of dunes and ripples. Sheetflows with high sediment concentration occasionally reached the marginal zone of the lakes (facies TSm). Limestone levels (facies L) were formed by carbonate precipitation in alkaline shallow lakes that supported ostracods; deposits were subsequently silicified during diagenesis (Boggs, 1992). Intercalation of incipient palaeosols (facies P) points out to short-lived subaerial exposure and soil-forming processes of lake deposits and progradation of marginal facies over basinal ones.

4.4. Aeolian deposits

4.4.1. Description

FA4 includes sheet-like tuffaceous sandstone bodies, which mostly show an alternation of planar or tangential cross-bedding (facies TSpa and TSta, respectively), and low angle cross-bedding (facies TSla, Fig. 11D). Facies TSpa and TSta compose decimeter to meter thick sets and have foreset dip angles up to 30°. Both facies exhibit laminae with normal and inverse grading. Thickness of this FA ranges between 4 m and 16 m. FA4 commonly overlies primary pyroclastic deposits (FA1) and underlies sheet flood deposits (FA2). In the La Payanca locality, where the FA4 dominates the measured section of the Puesto La Paloma Member (73%; Fig. 10), there are intercalations of tuffaceous sandstones with rippleform laminae (*sensu* Hunter, 1977; facies TSra). In addition, this FA is represented in sections of Puesto La Paloma Member from Puesto Mesa-Cerro León (9%) and Huanimán (30%) localities (Fig. 10). Particularly, the top of FA4 deposits from Huanimán (Fig. 8A) is highly bioturbated by root traces and therefore shows massive aspect (facies P). Palaeocurrent data measured from facies TSpa and TSta suggest wind directions from the NE and NW (Fig. 5).

4.4.2. Interpretation

The presence of tuffaceous sandstones with thick cross-bedded sets showing high foreset dip angles with a scarcely variable palaeocurrent direction is interpreted as transverse aeolian dunes (Kocurek, 1996; Mountney, 2006; Pye and Tsoar, 2009). While facies TSpa reflects transverse dune migration by processes of grain fall and grain flow; facies TSta suggests development of regressive aeolian ripples at foreset toe. The rooted palaeodune from Huanimán indicates a relative environmental stability. Among the remaining facies, TSra represents sedimentation in a dry interdune zone (Kocurek, 1996; Mountney, 2006; Pye and Tsoar, 2009); where

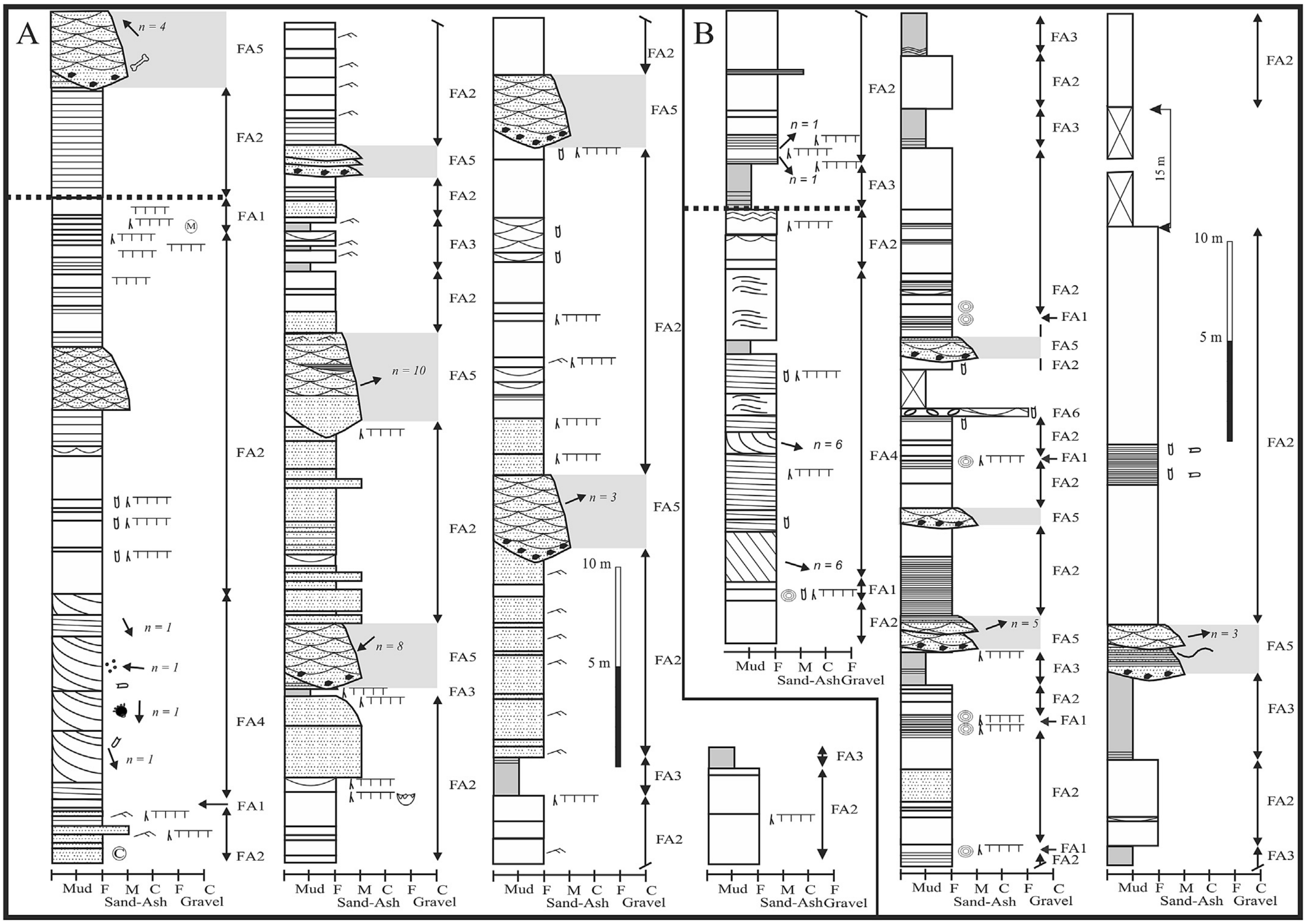

Fig. 8. Detailed sedimentary logs of the Huanimán (A) and La Payanca (B) localities. Stratigraphic position of each facies association is shown. Data are arranged in ascending stratigraphic order from left to right. The contact between the Puesto La Paloma and Cerro Castaño members is indicated by a dotted line. See references in Fig. 6.

the migration of aeolian ripples with and without preservation of slipfaces occurred (facies TSla and TSra, respectively).

4.5. Fluvial channel-belt deposits

4.5.1. Description

FA5 is commonly represented by isolated, sandstone-dominated bodies with channel or ribbon shapes. Each body shows an erosive and irregular or concave-upward base; the top is usually plane or, rarely, slightly convex-upward. Bodies commonly exhibit a fining-upward trend, beginning with laterally discontinuous breccias with horizontal stratification and rare imbrication (facies Bh), passing upward into trough cross-bedded sandstones (facies St, Fig. 11 E). Commonly, the upper part of the bodies is a sandstone with asymmetrical ripples, plane-parallel lamination or massive aspect (facies Sr, Sh and Sm, respectively). In some cases, discontinuous intercalations of laminated tuffaceous mudstones (facies TMh) and sandstones with planar cross-bedding (facies Sp), plane-parallel lamination (facies Sh) or massive (facies Sm) were recorded. Sandstone facies are mostly classified as feldspathic litharenites and, less commonly, as litharenites (Rosso et al., 2012). The framework grains are dominated by effusive volcanic lithic fragments, volcanic glass shards and pumice, and plagioclase. This FA is commonly interbedded with either sheet-flood deposits (FA2), shallow lake deposits (FA3) or both; more rarely, it overlies debris-flow deposits (FA6) or is covered by ash-fall strata (FA1). FA5 is only recorded in the Cerro Castaño Member in all studied localities, where it accounts for 11%–28% of the measured sections (Fig. 10). The thickness of individual FA5 deposits ranges from 0.4 m to 8.5 m; with the thicker bodies occurring in the three northernmost localities (Table 3). Minimum true width varies from 37 m to 1719 m; whereas the maximum true width ranges from 134 m to 2155 m; both parameters show the maximum values in Puesto Mesa-Cerro León locality (Table 3). Mean palaeocurrents per locality suggest a palaeodrainage mostly toward the E; except for Huanimán and Tres Cerros localities, where the flow was toward SE (Fig. 5). At local scale, the mean palaeocurrent of individual bodies along the sections is mostly homogeneous. Two stratigraphic intervals from Huanimán and Tres Cerros localities are excluded of this generality because they show adjacent FA5 deposits with near orthogonal mean palaeocurrents (Figs. 6 and 8).

4.5.2. Interpretation

The FA5 deposits are considered fluvial channel-belts according with their cross-sectional geometries, erosive bases and fining-upward trend (Allen, 1964; Miall, 1996; Bridge, 1993, 2003, 2006; Gibling, 2006). A more detailed interpretation of these deposits is made in the following Section 5 employing architectural element analysis. Deposition mainly occurred from dilute flows by migration of three and two-dimensional dunes (facies St and Sp), ripples

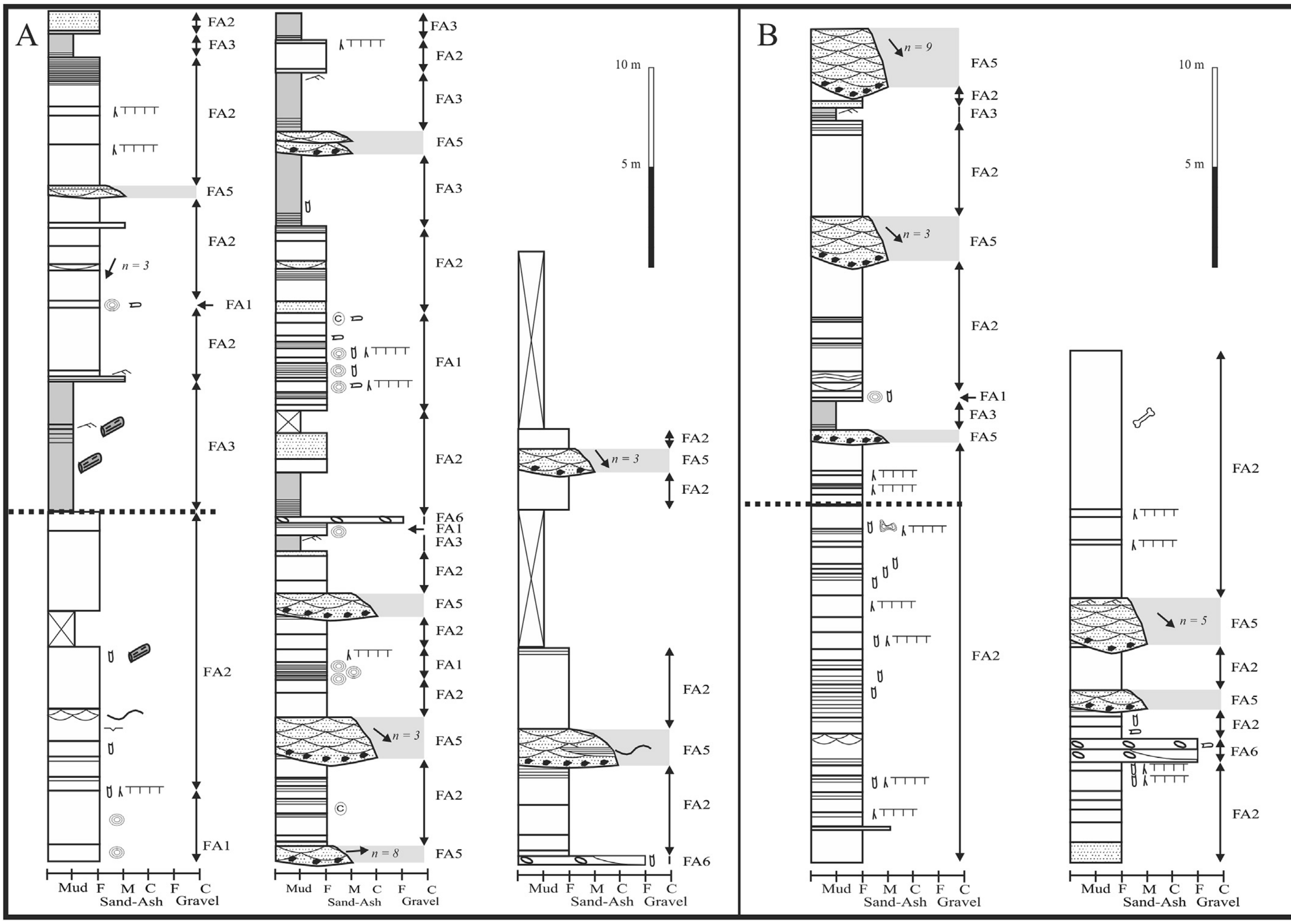

Fig. 9. Detailed sedimentary logs of the La Madrugada (A) and La Juanita (B) localities. Stratigraphic position of each facies association is shown. Data are arranged in ascending stratigraphic order from left to right. The contact between the Puesto La Paloma and Cerro Castaño members is indicated by a dotted line. See references in Fig. 6.

(facies Sr), and under plane bed conditions (facies Sh); as well as from more concentrated streamflows lacking generation or preservation of bedforms (facies Sm; Smith and Lowe, 1991). Breccias with horizontal stratification (facies Bh) are interpreted as channel lag deposits. All bodies represent perennial fluvial channel-belts because there is no evidence for subaerial exposure in the lower part of the bodies, like rhizoliths, soil structures or footprints of non-aquatic animals (Bridge et al., 2000; Bridge, 2003, 2006; Melchor et al., 2012). However, intercalations of tuffaceous laminated mudstones (facies TMh) indicate strong decrease or transient stoppage of water discharge. In addition, the massive sandstones (facies Sm) suggest important changes in the sediment concentration.

4.6. Reworked debris-flow deposits

4.6.1. Description

FA6 includes sheet-like to plano-convex strata with irregular and locally erosive bases that commonly comprise massive volcaniclastic fine conglomerates (facies VCm) and, in some places, lenses of trough cross-bedded or massive tuffaceous sandstones (facies TSt and TSm respectively, Fig. 11 F). Conglomerates are matrix-supported and, very rarely, with normal grading; the clasts are subrounded to subangular fragments of tuffs and, less commonly, effusive volcanic rocks. The matrix is composed of vitric fine-grained tuff. Individual beds range in thickness from less than 1 m–3 m, and show a lateral extension greater than 200 m. FA6 deposits are commonly enclosed by FA2 deposits or have their tops eroded by FA5 deposits. In some places, a physical connection with FA5 deposits was observed. Except for Huanimán and Tres Cerros localities, this FA was recorded in low proportion (2%–3%; Fig. 10) in the Cerro Castaño sections.

4.6.2. Interpretation

The massive and matrix-supported nature of facies VCm indicates deposition from debris-flows (Shultz, 1984; Smith and Lowe, 1991; Best, 1992; Nakayama and Yoshikawa, 1997). The tuffaceous clasts, as well as the locally erosive bases, suggest that the debris-flows partially eroded the underlying deposits. The dominance of ungraded and matrix-supported beds over those with normal grading is mostly compatible with pseudoplastic debris-flows (Miall, 1996). After episodes of *en masse* sedimentation, deposits were commonly reworked by dilute flows with low and high sediment concentration (facies TSt and TSm respectively). These streams could represent an independent flow or the late stage of a single debris-flow event (Nemec and Steel, 1984).

5. Architecture of fluvial channel-belt deposits

Two channeled river patterns were recognized using the

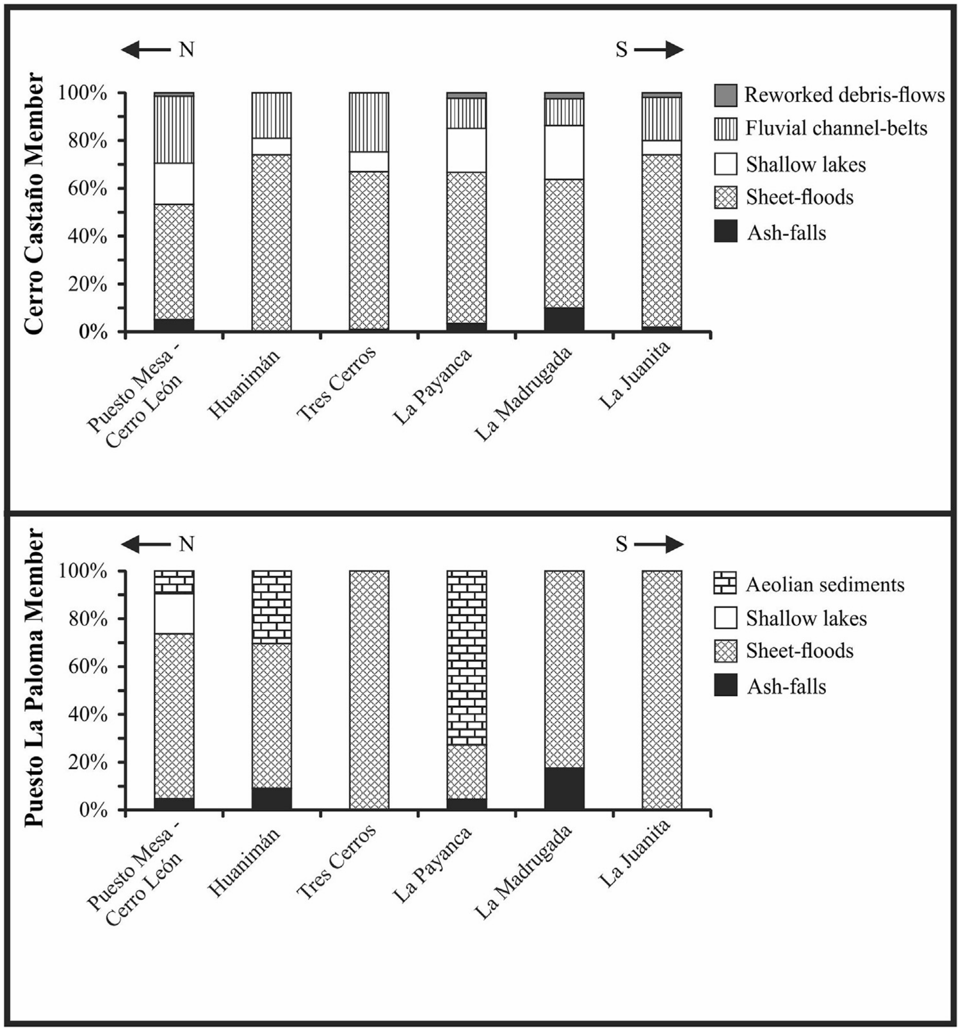

Fig. 10. Histograms showing the percent participation of each facies association per locality and lithostratigraphic member.

morphology and arrangement of second order surfaces of FA5 deposits in views near orthogonal to the mean palaeocurrent. They are: i) meandering fluvial system, and ii) low sinuosity fluvial system (Sections 5.1 and 5.2, respectively).

5.1. Meandering fluvial system

5.1.1. Description

A meandering fluvial system characterizes the Cerro Castaño Member at Huanimán, La Payanca, La Madrugada and La Juanita localities. The channeled bodies of this fluvial style have second order surfaces that show two distinctive features: i) they dip up to 15° in approximately the same direction; and ii) they define a laterally stacked pattern in views near orthogonal to the mean palaeocurrent (Fig. 12). The tops of the lenticular sets limited by second order surfaces (hereafter denominated stratasets) dip at high-angle in relation to the palaeoflow data of associated cross-bedded sandstones (Fig. 12). The stratasets are 0.4 m–1.55 m thick, have a fining-upward trend and generally exhibit the following vertical transition of facies: Bh, St and Sr. In several bodies, the uppermost strataset is fully composed of tabular sandstone facies including Sm, Sh and Sr.

5.1.2. Interpretation

The morphology and arrangement of second order surfaces in views near orthogonal to the palaeocurrent data, as well as the high angular value between the dip directions of the strataset tops and palaeoflow inferred from associated cross-bedded sandstones, indicate single-channel rivers with lateral migration of a point bar and an adjacent thalweg (e.g. Georgieff and González Bonorino, 2002; Perez et al., 2013c), probably within a single fluvial channel-belt. After abandonment, those bodies with the uppermost strataset totally composed of tabular sandstone facies were, probably, fully filled from overbank flows related to active channels. There are no conclusive evidences of reoccupation of channels after avulsion.

5.2. Low sinuosity fluvial system

5.2.1. Description

A low sinuosity fluvial system is typical of the Cerro Castaño Member at localities Puesto Mesa-Cerro León and Tres Cerros. In views near orthogonal to the palaeoflow, the second order surfaces are essentially parallel between them, show a near horizontal disposition and, very rarely, exhibit erosive lateral superposition (Fig. 13). The dip directions of strataset tops and palaeoflow data

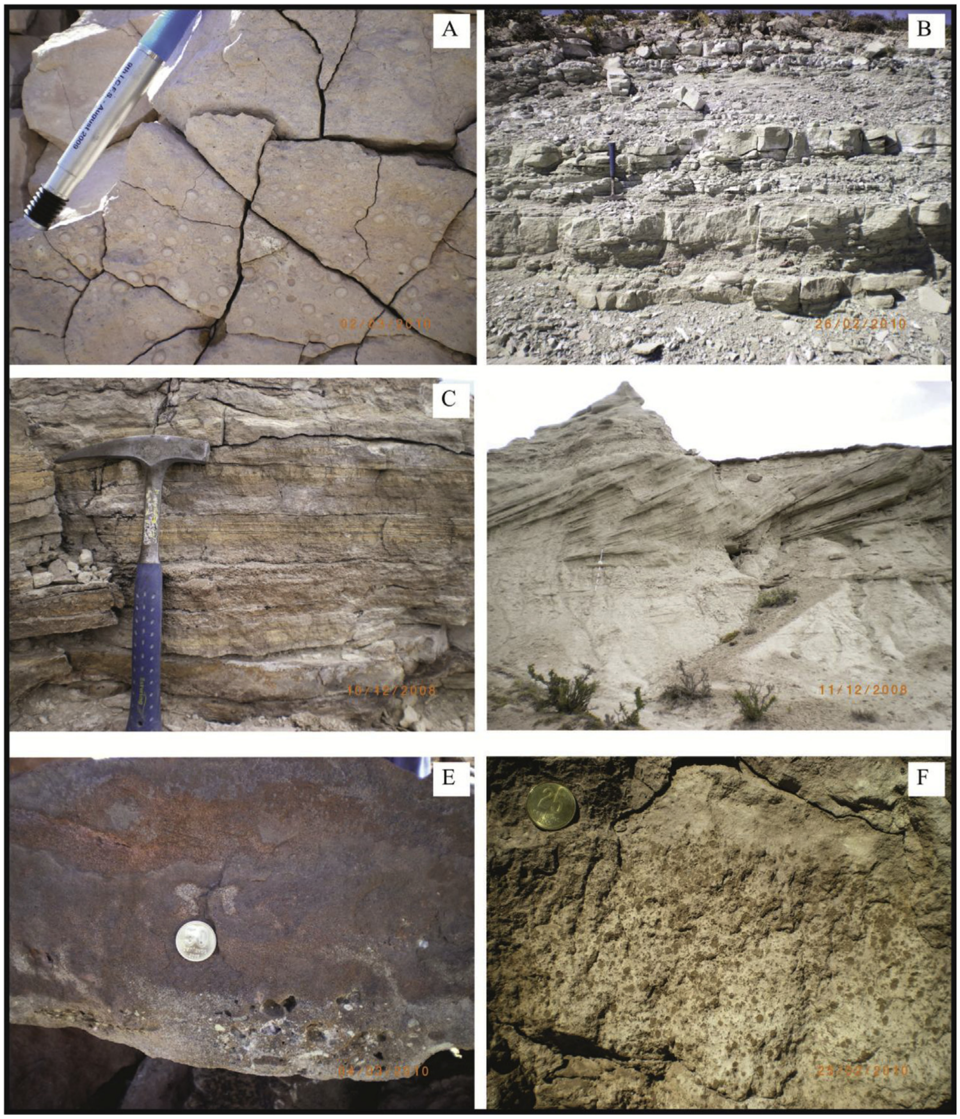

Fig. 11. Examples of facies and facies associations. (A) Massive tuff with accretionary lapilli, pen is 14 cm long (FA1). (B) Alternation of massive and laminated tuffaceous sandstones, hammer is 33 cm long (FA2). (C) Laminated tuffaceous mudstones, hammer is 33 cm long (FA3). (D) Tabular cross-bedded sets of tuffaceous sandstones, Jacob staff is 1.50 m long (FA4). (E) Breccia with diffuse horizontal stratification that passes upward to trough cross-bedded sandstones, coin is 3 cm in diameter (FA5). (E) Massive and matrix-supported volcaniclastic conglomerate, coin is 3 cm in diameter (FA6).

Table 3
Mean properties from fluvial channel-belt deposits (FA5); the ranges are indicated between parentheses. Information is showed per locality. Void rows represent localities in which data not qualify for calculations using empirical formulas (see restrictions explicated by Bridge and Mackey (1993) and Bridge and Tye (2000)).

Parameter (in m)	Tres Cerros	Huanimán	Puesto Mesa-Cerro León	La Payanca	La Madrugada	La Juanita
Mean thickness	**3.2** (0.8–4.8) n = 9	**2.95** (1.4–4.5) n = 6	**3.17** (0.5–8.5) n = 18	**1.36** (0.7–2.4) n = 4	**1.13** (0.4–1.9) n = 7	**1.54** (0.65–2.8) n = 5
Mean cross-set thickness (Sm) and standard deviation (StD)	–	–	**0.41** ± 0.25 (0.16–0.58) n = 12	–	**0.14** ± 0.07 (0.10–0.18) n = 3	**0.21** ± 0.12 (0.17–0.22) n = 4
StD/Sm	–	–	**0.61**	–	**0.58**	**0.57**
Mean flow depth (d) $d = 11.6 \times hm^{0.84}$ where $hm = 2.22(Sm/1.8)^{1.32}$	–	–	**4.41** (1.55–6.46) n = 12	–	**1.31** (0.77–1.74) n = 3	**0.18** (0.15–0.23) n = 4
Mean minimum true width (cbw min) $cbw\ min = 59.9 \times d^{1.8}$	–	–	**923** (131–1719) n = 12	–	**104** (37–163) n = 3	**236** (154–355) n = 4
Mean maximum true width (cbw max) $cbw\ max = 192 \times d^{1.37}$	–	–	**1502** (349–2155) n = 12	–	**284** (134–411) n = 3	**541** (393–743) n = 4

The bold is used to highlight the average values.

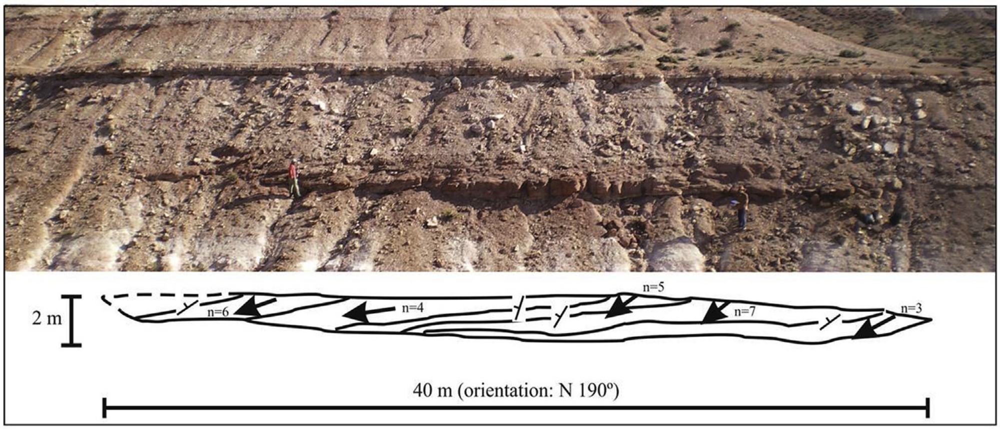

Fig. 12. Tracing of second order surfaces, palaeocurrent data, and strike and dip of strataset tops in deposits of a meandering fluvial system; the river migrated from right to left. The pictured body belongs to the Cerro Castaño Member at La Madrugada.

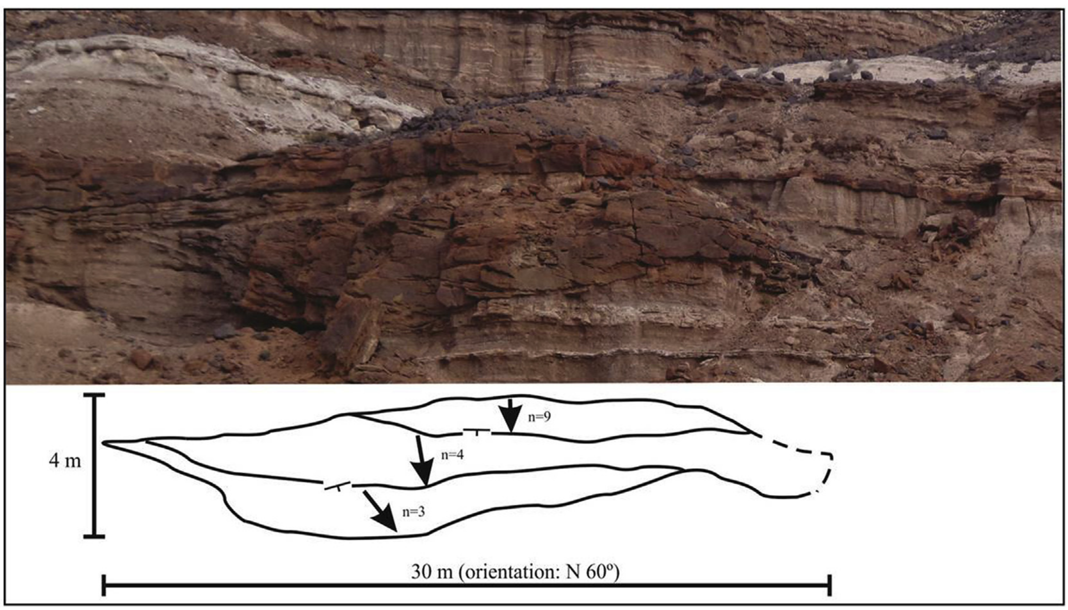

Fig. 13. Arrangement second order surfaces, palaeocurrent data, and strike and dip of strataset tops in deposits of a low sinuosity fluvial system. The pictured body belongs to the Cerro Castaño Member at Tres Cerros.

from associated cross-bedded sandstones have similar values (Fig. 13). The stratasets, which record uniform palaeocurrent data, are 0.5 m–3.1 m thick, and show a subtle fining-upward trend. Internally, the stratasets are commonly composed of laterally discontinuous stratified breccias (facies Bh), which underlies trough cross-bedded sandstones (facies St). At Tres Cerros locality, the latter facies is covered by rippled sandstones (facies Sr). In minor amount, there are bodies with the uppermost strataset exclusively composed of massive tabular sandstones (facies Sm). Alternatively, some lenticular intercalations of sandstones with planar cross-bedding (facies Sp) and laminated tuffaceous mudstones (facies TMh) were also observed.

5.2.2. Interpretation

Coarse parallelism between second order surfaces in views near orthogonal to the palaeocurrent data, which have similar values from adjacent stratasets, and the similarity between dip directions of strataset tops and associated cross-bedded sandstones, suggest a low sinuosity river (e.g. Gibling, 2006; Foix et al., 2013; Paredes et al., 2016). The absence of second order surfaces morphologically compatible with central or attached-margin bars, allows inferring that the channels were probably unique. The absence of point bars implies laterally stable channels related with vegetated to coherent banks (Bridge, 1993); or with important topographic slopes (Paredes et al., 2015), although there are no additional evidence supporting such a situation. The presence of mudstones settled from a suspension in the channel fill is linked to important fluctuations or stoppage in water flow. The bodies with the uppermost strataset fully composed of massive sandstones could represent the final stage of filling of inactive channels. As in 5.2.1, there are no evidence of abandonment and later reoccupation of channels.

6. Facies architecture and stratigraphy

The studied sections were divided into stratigraphic intervals

according to the distribution of facies associations, and correlated by using the Puesto La Paloma-Cerro Castaño contact and other two additional marker beds. A regional cross-section, using as datum the lithostratigraphic contact between both members is shown in Fig. 14. Both additional markers exhibit good continuity in the studied area, and can be observed along several kilometers between the logged sections. They are commonly massive and/or laminated, rarely rippled, whitish to pinkish, sand-sized tuffaceous beds that are up to 5 m thick, which belong to floodplain facies (facies associations 1, 2, 3, 4, and 6). They are included in the Cerro Castaño Member, although in some sections only one of these marker beds is reliable: the upper one in Puesto Mesa-Cerro León and La Payanca localities, the lower one in La Madrugada and La Juanita localities. In average, the lower and upper markers are located 20 m and 80 m, respectively, above the boundary between both members; except in Puesto Mesa-Cerro León locality, where the upper marker is positioned approximately 125 m above the mentioned boundary.

Four stratigraphic intervals, denominated 1 to 4 in chronological order of deposition, were recognized (Fig. 14). In general, all stratigraphic intervals increase in thickness toward the Puesto Mesa-Cerro León locality. Stratigraphic interval 1 (18–42 m thick) corresponds to the Puesto La Paloma Member and includes numerous sheet-flood deposits, as well as lacustrine and aeolian facies (dunes and dry interdune zones) and ash-fall strata (Fig. 14). Stratigraphic interval 2 (20–47 m thick) represents the lower part of the Cerro Castaño Member and includes the lower marker (Fig. 14). It shows an alternation of fluvial channel-belt deposits and sediments originated from sheet-floods, lakes, and few ash-falls and debris-flows. Vertical proportion of channel-belt bodies is 10–36% reaching higher values in the northern part of the study area (Table 4), where they are also thicker. In comparison with the underlying stratigraphic interval, there is occurrence of channel-belt bodies, an evident increase of lacustrine facies and diminution of ash-fall deposits. Stratigraphic interval 3 (7–27 m thick) represents the middle part of the Cerro Castaño Member and lacks channel-belt bodies (Fig. 14). It has the highest participation of sheet-flood and ash-fall deposits. In relation to the stratigraphic interval 2, participation of debris-flow deposits remains constant and lacustrine facies subtly increases. Stratigraphic interval 4 (18 m-148 m thick) represents the upper part of the Cerro Castaño Member and includes the upper marker (Fig. 14). It comprises an alternation of channel-belt bodies and sediments generated from sheet-floods, lakes, debris-flows and volcanic ash rains. Proportion of channel-belt deposits ranges from 6 to 32% (Table 4). As in the stratigraphic interval 2, the higher proportion and thicker channel bodies are found in the northern part of the study area. Particularly, in Puesto Mesa-Cerro León locality this stratigraphic interval is the

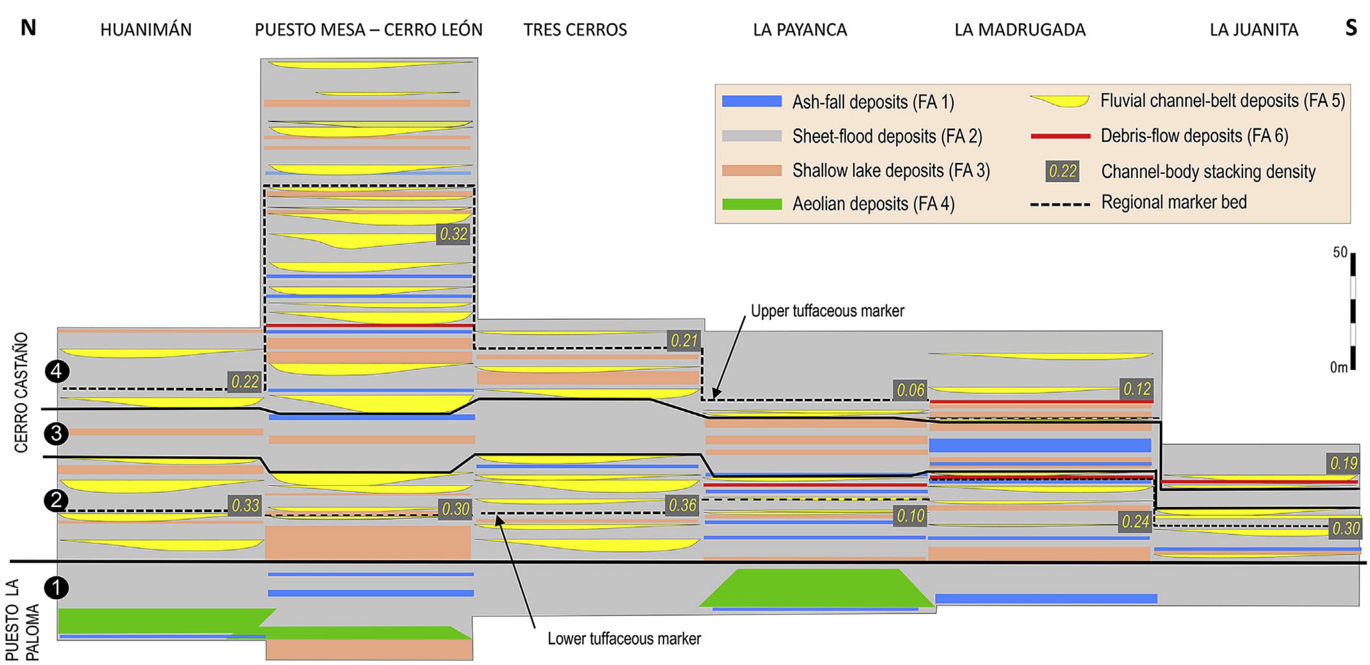

Fig. 14. Facies architecture of the Puesto La Paloma and Cerro Castaño members; stratigraphic intervals were defined according with the occurrence and amount of different facies associations.

Table 4
Proportion and number of channel-belt deposits per stratigraphic interval for the Cerro Castaño Member.

Stratigraphic interval	Huanimán	Puesto Mesa-Cerro León	Tres Cerros	La Payanca	La Madrugada	La Juanita
4	**22.09%** 2 bodies	**31.67%** 15 bodies	**20.73%** 3 bodies	**5.95%** 1 body	**12.31%** 3 bodies	**18.75%** 2 bodies
3	**without channel-belts**					
2	**33.23%** 4 bodies	**30.26%** 4 bodies	**35.90%** 7 bodies	**10.34%** 3 bodies	**24.34%** 4 bodies	**29.37%** 3 bodies
1	**without channel-belts**					

The bold is used to highlight the average values.

thickest and has the highest proportion of thicker channel-belt bodies. In comparison with the stratigraphic interval 2, which also records an alternation of channel-belt and floodplain facies, there is lower participation of channeled bodies and ash-fall deposits, as well as major amount of lacustrine facies; whereas participation of debris-flow deposits is similar.

In summary, the following aspects are highlighted: i) the sheet-flood and ash-fall deposits are notoriously more abundant in the stratigraphic intervals 1 and 3, the first one accompanied by participation of aeolian facies; ii) the stratigraphic intervals 2 and 4 are characterized by abundant channel-belt bodies; iii) the participation of lacustrine sediments increases from stratigraphic intervals 1 to 4; and iv) the stratigraphic intervals 2 to 4 record debris-flow deposits without a vertical trend in their abundance.

7. Depositional model

Sediments of the Puesto La Paloma Member (stratigraphic interval 1) were essentially deposited by unconfined fluvial systems with recurrent influx of volcanic ash-rains (Fig. 15A). Atmospheric settling of volcanic ash uniformly mantled the topography (cf. Wright et al., 1980; Houghton et al., 2000) and, the resulting deposits (FA1) were commonly reworked by sheet-floods (FA2), or modified by soil-forming processes. These sheet-floods were dilute and laterally experienced a diminution of the sediment concentration, changing from flows that not allow the generation/preservation of tractive sedimentary structures (type 2 flow *sensu* Smith and Lowe, 1991) to typical stream flows (type 1 flow *sensu* Smith and Lowe, 1991). At Puesto Mesa-Cerro León locality, the sheet-

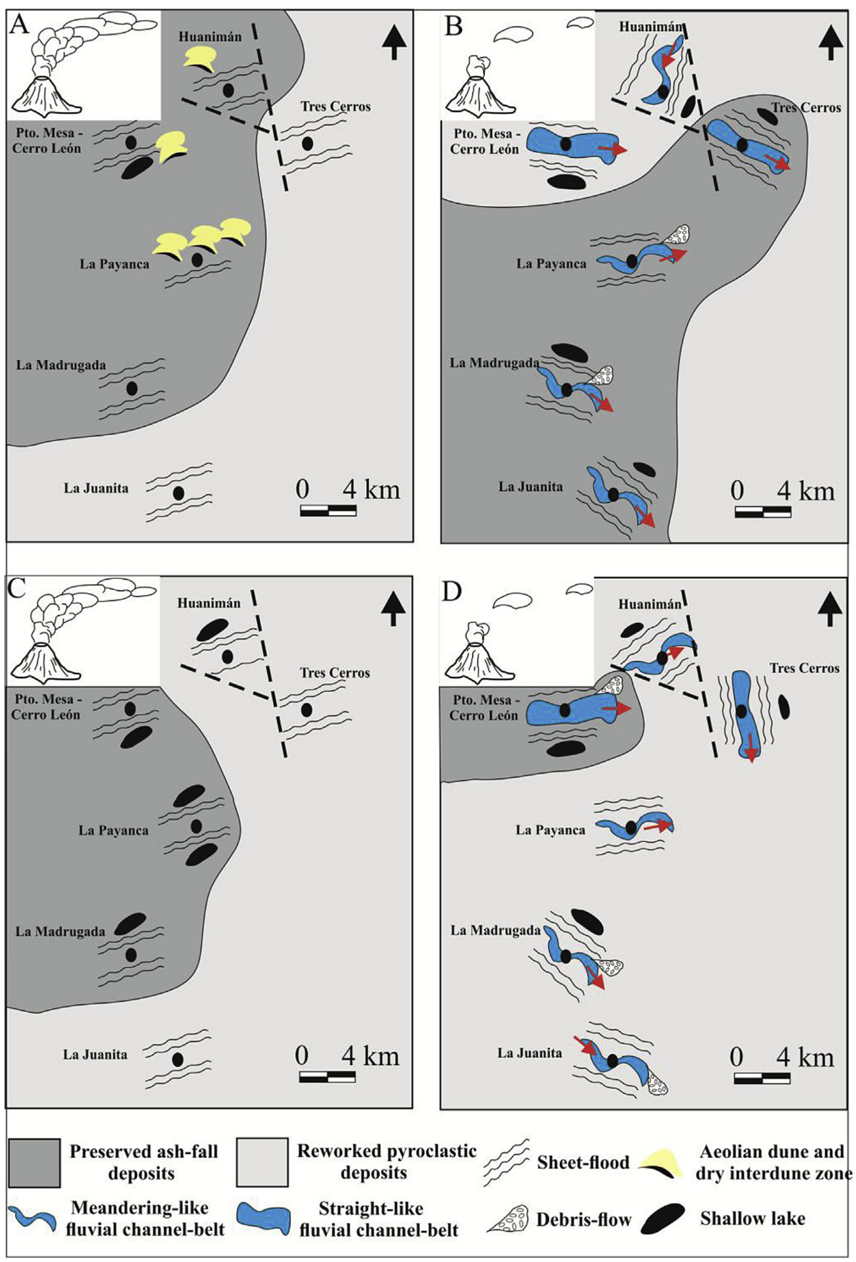

Fig. 15. Palaeoenvironmental reconstruction of the studied lithostratigraphic units. (A) Stratigraphic interval 1 (Puesto La Paloma Member). (B-C-D) Stratigraphic intervals 2, 3 and 4 corresponding to lower, middle and upper part, respectively, of the Cerro Castaño Member. The red arrows indicate the mean palaeoflow per locality in each stratigraphic interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

floods flowed into a shallow lake, where settling of suspended sediments and carbonate precipitation were the main depositional processes (FA3). Lacustrine sedimentation can also result from the damming of sheet-flood deposits. In some localities (Huanimán, Puesto Mesa-Cerro León and La Payanca), there were transverse aeolian dunes separated by dry interdune zones (FA4), which were active during deposition of the lower part of the succession. The common presence of hydromoprhic palaeosols and calcic pedofeatures of this unit suggests that sedimentation of FA1, FA2 and FA3 deposits was interrupted very frequently but by short lapses of time, and fluctuations in water table occurred (Krause et al., 2014). In particular, the evidence of soil development in the sheet-flood deposits, as well as the variation in the sandstone sheet dimensions (thickness), suggest an ephemeral unconfined fluvial system (Nichols, 1987; Fisher et al., 2007).

The lower part of the Cerro Castaño Member (stratigraphic interval 2) represents a channelized fluvial system also affected by ash-falls (FA1; Fig. 15B). Fluvial channel-belts (FA5) were perennial and mostly flowed towards the E and SE; except in Huanimán locality where the flow was towards the S-SW. The fluvial channels probably mixed their sedimentary charge, dominated by effusive volcanic lithic fragments and volcanic glass, with pyroclastic detritus that directly fall on them. Fluvial patterns were commonly meandering, although a low-sinuosity fluvial style occurred at Tres Cerros and Puesto Mesa-Cerro León localities. The floodplains of the Cerro Castaño Member were mostly constructed by sheet-floods (FA2), and in minor proportion by primary pyroclastic deposits (FA1), shallow lake sedimentation (FA3) and debris-flow deposition (FA6) (Fig. 15B). In this interval, the sheet-floods were dilute and originated as overflows from active fluvial channel-belts. The sheet-floods reworked pyroclastic-rich deposits, including ash-falls, and increased their relative water participations with a greater distance to channel margins. These stream flows commonly drained towards freshwater shallow lakes (lacking carbonate precipitation), located in distal topographic depressions. Debris-flows were probably generated by overflows from active channels that experienced bulking due to addition of loose pyroclastics (Smith and Lowe, 1991). Weakly-developed, hydromorphic palaeosols recorded within floodplain deposits suggest that time intervals with negligible sedimentation was common.

The middle part of the Cerro Castaño Member (stratigraphic interval 3) exclusively records a pedogenized floodplain environment with profuse ash-fall events (Fig. 15C). During deposition of this interval, floodplain construction mainly occurred by sedimentation from sheet-floods (FA2), which were laterally related with siliciclastic shallow lakes (FA3). Dilution of the sheet-floods towards the shallow lake shores was very usual. In minor amount, floodplain development occurred from preservation of primary pyroclastic deposits (FA1) and deposition from debris-flows (FA6).

The upper part of the Cerro Castaño Member (stratigraphic interval 4) represents a new channelized fluvial system influenced by explosive volcanism (Fig. 15D). As in the analogue stratigraphic interval 2, the fluvial channel-belts (FA5) were permanent and mostly flowed towards the E and SE; except in Huanimán and Tres Cerros localities, where the rivers flowed towards the NE and SSE, respectively. Fluvial styles were commonly meandering, with local presence of a low-sinuosity fluvial style at Tres Cerros and Puesto Mesa-Cerro León localities. The associated floodplains, which were commonly pedogenized, were built by deposition from sheet-floods (FA2), siliciclastic shallow lakes (FA3), debris-flows (FA6) and ash-fall rains (FA1) (Fig. 15D).

8. Controls on sedimentation

Classically, the allocyclic controls on fluvial basins include climate, tectonism and eustatic sea-level changes (Miall, 1996, 2000, 2014; Bridge, 2003, 2006; Catuneanu et al., 2009). When the successions are volcaniclastic-rich, the influence of volcanic influx is also relevant (Smith, 1991; Kataoka and Nakajo, 2002; Kataoka et al., 2009; Pierson and Major, 2014). In recent years, the morphology of basement rocks in some volcaniclastic fluvial successions was linked to sedimentary and geomorphic responses, while the remaining controls were interpreted as steady (e.g. Allard et al., 2014b; Umazano et al., 2014b). This section makes an assessment of the mentioned controls excluding the absolute sea-level changes and basement morphology. The first one is rejected because, according with the Cretaceous palaeogeography of Patagonia, the drainage systems have had no direct connection to the ocean (Smith et al., 1981; Gianni et al., 2015). The possible influence of basement morphology is also discarded because the analyzed sections are not in contact with volcanic Jurassic rocks which, in other sectors of the basin (e.g. in the eastern periphery), conform an irregular palaeorelief (Allard et al., 2014a; Villegas et al., accepted a,b).

8.1. Pyroclastic sediment supply

The ubiquitous participation of volcaniclastic detritus, both as primary ash-fall deposits and mixed in tuffaceous sandstones, suggests an important influence of coetaneous explosive volcanism. The temporal change of fluvial style from unconfined conditions in the Puesto La Paloma Member (stratigraphic interval 1) to channeled systems in the Cerro Castaño Member, particularly the stratigraphic interval 2, would be a response to a diminution of the pyroclastic sediment supply. A greater pyroclastic influx during deposition of Puesto La Paloma Member would be responsible for the common generation of type 2 dilute flows recorded as sheet-floods (Smith and Lowe, 1991). Considering that the underlying Bardas Coloradas Member includes common channel-belt bodies with very scarce participation of pyroclastic detritus (Allard et al., 2010c; Villegas et al., 2014; Brea et al., 2016), the presence of sheet-flood deposits with high sediment concentration in the Puesto La Paloma Member suggests an increase of the transport rate or channel adaptation to aggrading conditions, as response to increased pyroclastic input (Manville et al., 2009; Pierson and Major, 2014). The presence of stacked palaeosols upward the Puesto La Paloma Member additionally suggests a decrease in the relative sedimentary rate. In this context, we tentatively consider to the Puesto La Paloma Member as a syn-eruptive stratigraphic interval (Smith, 1991).

A reduced pyroclastic influx during deposition of the Cerro Castaño Member favored the channelization of the fluvial systems. Within this scheme the stratigraphic interval 3, which is fully composed of pyroclastic-rich floodplain facies, including the highest relative participation of ash-fall deposits, is compatible with a time span with major sediment supply. According to Smith (1991), the sections with meandering fluvial style can be interpreted as the record of inter-eruptive periods. The low-sinuosity fluvial system from the Tres Cerros and Puesto Mesa-Cerro León localities does not fit in the Smith's model. The low sinuosity and absence of point bars of the rivers from the mentioned localities may be more consistent with a syn-eruptive period; perhaps suggesting a localized high pyroclastic sediment supply, as interpreted for other Cretaceous analogue successions from Patagonia

(Umazano et al., 2012b). Despite this, the fluvial patterns at Tres Cerros locality were more probably controlled by intrabasinal tectonic activity (see the following section 8.2).

8.2. Tectonism

The contrasting thickness of analyzed sections, particularly the higher values of the stratigraphic interval 4 at Puesto Mesa-Cerro León zone (Fig. 14; upper part of the Cerro Castaño Member), suggests a greater rate of creation of accommodation space that may be related with a compartmentalized basin controlled by differential activity of faults (Figari et al., 2015). Other evidence of tectonic activity at regional scale such us progressive unconformities and/or changing palaeocurrent data were not observed. However, NW-SE tectonic lineaments close to Sierra de la Manea in the northern part of the study area (Figari and Courtade, 1993; Proserpio, 1987; Figari, 2005), which probably represent faulting (Figari et al., 2015), would have controlled the palaeodrainage at Huanimán and Tres Cerros localities (see Fig. 3). In addition, the low-sinuosity fluvial pattern recorded at the Tres Cerros locality could have been controlled by fault activity as the palaeocurrent directions are nearly parallel to the lineaments. The inference of syn-sedimentary tectonic activity is supported by the presence of stratigraphically adjacent fluvial channel-belt deposits with near orthogonal to opposite palaeocurrents and without signs of nodal avulsion (e.g. Bridge, 2006; Paredes et al., 2007; Umazano et al., 2012b). This phenomenon can be appreciated, for example, between the second and third channel-belt deposits counting from the log base in Huanimán locality (Fig. 8A).

8.3. Climate

The record of fluvio-aeolian interaction and shallow lakes with micritic limestones in the Puesto La Paloma Member (stratigraphic interval 1) indicates relatively arid climatic conditions (cf. Langford and Chan, 1989; Parrish, 1998). Carbonate precipitation in alkaline lakes is strongly related with a semi-arid climate (Tanner, 2010). It is important to mention that more westwards (Estancia Aguada La Piedra), there are also lacustrine limestone facies in the Puesto La Paloma Member in a similar stratigraphic position (Brea et al., 2016). This situation is consistent with a low degree of chemical weathering (CIA) of pedogenized deposits, and mean annual precipitation values (MAP) ranging from 200 to 700 mm/yr, obtained from geochemical proxies (Krause et al., 2014). In addition, the stacked palaeosols with coexistence of hydromorphic and calcification features in the upper section of this unit from the Tres Cerros and La Juanita localities suggests seasonal climate (Krause et al., 2014).

During deposition of the Cerro Castaño Member (stratigraphic intervals 2 to 4) the climate would have been wetter. This is inferred from: i) the dominant record of permanent discharge in all fluvial channels (Miall, 1996), ii) the absence of facies with contrasting climatic significance from floodplain deposits (Langford and Chan, 1989; Parrish, 1998), iii) the absence of carbonate lake deposits and greater participation of lacustrine facies (Miall, 1996) and iv) palaeosols lacking calcic features (e.g., Wright et al., 2000; Retallack, 2001). The evidence of scarce flow rate in some channel deposits would represent seasonality in the catchments (Parrish, 1998; Blum and Tornqvist, 2000; Cecil, 2003). In summary, there is a temporal trend towards more humid climatic conditions in the analyzed sections.

9. Conclusions

The sedimentological study of Puesto La Paloma and Cerro Castaño members (Cretaceous of Somuncurá-Cañadón Asfalto Basin, Patagonia, Argentina) employing facies and architectural analysis, as well as determining stratigraphic intervals according with the participation of different facies associations (alluvial stratigraphy), allowed reaching the following main conclusions.

The sedimentary setting and stratigraphic framework of both members were influenced by ash fallouts, temporal climate change and intrabasinal tectonic activity.

The Puesto La Paloma Member (stratigraphic interval 1) records ephemeral and unconfined fluvial sedimentation (sheet-floods) linked to high pyroclastic influx. The presence of poorly developed palaeosols in fluvial facies, which in some cases bear calcic and hydromorphic pedofeatures, indicates discontinuous sedimentation. At local scale, and commonly in reduced amount, the sedimentary palaeoenvironment included shallow lakes with alkaline waters, which may represent ponding in distal positions of the flood events, as well as transverse aeolian dunes and dry interdune zones. These facies association and palaeosols are compatible with relatively arid climatic conditions.

The Cerro Castaño Member represents a fluvial system that received variable supply of volcanic ash and developed under wetter climatic conditions. It was divided, from base to top, into stratigraphic intervals 2, 3 and 4. During lapses of decreasing primary pyroclastic influx (stratigraphic intervals 2 and 4), permanent fluvial channel-belts developed on vegetated floodplains. River patterns were commonly meandering and, locally, of low-sinuosity. General palaeodrainage was towards E-SE, but in some localities was probably controlled by active tectonic activity. Overbank flows as sheet-floods was the main mechanism for constructing floodplains. Lake sedimentation, debris flows and ash falls have had a subordinated participation. With increased pyroclastic influx (stratigraphic interval 3), the fluvial system became unconfined and ephemeral. This disorganized fluvial system, in which ash-falls were preserved, included sheet-floods, lakes and debris-flows.

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