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Detecting allocyclic signals in volcaniclastic fluvial successions: Facies, architecture and stacking pattern from the Cretaceous of central Patagonia, Argentina

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A B S T R A C T

The Castillo Formation and the overlying lower member of the Bajo Barreal Formation (Cretaceous) are the principal hydrocarbon-producing units of the San Jorge Basin, Patagonia, Argentina. They are mainly composed of sandstone lenses interbedded with finer-grained, tuffaceous, sheet-like strata. Both units record fluvial systems influenced by voluminous pyroclastic influx via ash-falls mainly from a western source. These fluvial systems drained from the west toward a non-marine depocenter located in the eastern part of the basin. The units were studied in the Sierra de San Bernardo, a NNW-SSE oriented fold and thrust belt located in the western sector of the basin. The objectives of this study were: (i) to assess the influence of allocyclic factors on fluvial dynamics and sedimentation, and (ii) to determine the possible link between changes in tephra reworking and configuration of channel belts. The methodology included facies and architectural analyses, as well as determination of the stacking pattern of the channel deposits. The Castillo Formation represents permanent single-channel rivers with channel-margin bars. Floodplains were commonly constructed from aqueous reworking of pyroclastic substrates (sheet-floods, debris-flows and shallow lacustrine sedimentation) and, to a lesser extent, by preservation of ash-fall deposits. The lower member of the Bajo Barreal Formation generally records braided fluvial channel belts with a more variable water discharge and, in one locality, single-channeled rivers. Constructive processes of the floodplains were similar to the underlying Castillo Formation, although other types of deposits were detected in lower proportions including hyperconcentrated flows and crevasse-splays. The different pyroclastic sediment supply between both units explains the general evolution of the fluvial systems. The stacking patterns, which are a response to base-level changes, are probably associated with the common tectonic activity recorded in the eastern part of the basin. Significant climatic changes are not detected during deposition of both units, although indicators of variability in water discharge recognized in some paleochannels of the lower member of the Bajo Barreal Formation could be linked to seasonality in the catchments.

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1. Introduction

Explosive volcanism as an allocyclic factor in fluvial environments has been widely reported in modern and ancient settings, both in near-vent locations as in distal sectors. Commonly, the studies were focused on the impact of the tephra influx on biota (e.g. reduction to elimination of plant cover, Vessell and Davies, 1981), climate (e.g. cooling by injection of sulfur aerosols, Rampino and Self, 1992), geomorphology (e.g. modification of channel patterns; Smith, 1991), volcanic hazard (e.g. flood by breakout of ignimbrite dammed valleys; Kataoka et al., 2008) and sedimentation (e.g. flow transformations; Smith and Lowe, 1991). In addition, the complex hydrological changes produced by sudden and high sediment supply have also been widely documented; including several aspects such as decrease in soil infiltration, both waxing and waning runoff, and increase of transport capacity and generation of peak flows (Montgomery et al., 1999; Major et al., 2000; Major, 2003; Major and Yamakoshi, 2005; Major and Mark, 2006). Most recent sedimentologic studies on fossil fluvial successions affected by explosive volcanism typically distinguish syn-eruptive and inter-eruptive stages (*sensu* Smith, 1991; e.g.

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Nakayama and Yoshikawa, 1997; Manassero et al., 2000; Kataoka and Nakajo, 2002; Cladera et al., 2004; Martina et al., 2006; Paredes et al., 2007; Manville et al., 2009a; Sierra et al., 2009). Differentiation between both stages is based on the recognition of characteristic lithofacies, composition of detritus and channel belt configuration. The syn-eruptive successions have a high proportion of pyroclastic components and commonly record braided and shallow confined flows, in many cases with evidence of *en masse* deposition. On the other hand, the inter-eruptive successions contain clasts of more diverse lithology and are typically represented by meandering rivers dominated by dilute flows.

Despite the well-documented discrimination of syn-eruptive and inter-eruptive conditions in fossil fluvial systems, relatively few studies have investigated the paleonvironmental significance of reworking of pyroclastic substrates (e.g. Moore, 1991; O'Halloran and Gaul, 1997; Kataoka and Nakajo, 2002; Kataoka, 2003; Umazano et al., 2008a,b; Manville et al., 2009a), which is very common in these settings and typically occurs in floodplain environments, in many cases as constructive processes. Moreover, the recent recognition of a wide variety of fluvial channel belt types in syn-eruptive successions (Cladera et al., 2004; Paredes et al., 2009) and their possible relation with other allocyclic controls have not been properly addressed. Apart from explosive volcanism, a number of external factors can also govern sedimentation in continental settings, such as climate, tectonism and base level change (Shanley and McCabe, 1998). Accordingly, the main objective of this study is to assess the effects of the pyroclastic supply and other non-volcanic allocyclic controls on fluvial dynamics and sedimentation. Additionally, potential changes in tephra reworking and configuration of channel belts will be evaluated.

The Cretaceous fluvial volcaniclastic successions of the Castillo Formation and the overlying lower member of the Bajo Barreal Formation (San Jorge Basin, central Patagonia, Argentina) offer an excellent opportunity to test the above-mentioned issues due to the good quality and laterally continuous outcrops. Both units belong to the Chubut Group (Lesta and Ferello, 1972), which is the sedimentary record of a coeval volcanic arc located to the west, whose volcanic vents were emplaced over the modern outcrops of the Patagonian Batholith (Umazano, 2009; Umazano et al., 2009).

2. Geologic framework

2.1. San Jorge Basin

The San Jorge Basin is located in central Patagonia (Argentina) and extends from the Patagonian Andes to the Atlantic Ocean between 45° S and 47° S of latitude (Fig. 1). It is the more prolific hydrocarbon producing basin in the country (Homovc and Lucero, 2002), developed initially as a Jurassic rift linked to Gondwana break-up and opening of the South Atlantic Ocean (Barcat et al., 1989; Fitzgerald et al., 1990; Fig. 2). The first NW–SE oriented depocenters were filled with volcaniclastics (Complejo Volcánico-Sedimentario, Clavijo, 1986), which constitute the economic basement of the basin. The Late Jurassic-Late Cretaceous succession can be divided into two siliciclastic megasequences or groups separated by a regional unconformity (Fig. 2; Figari et al., 1999). The lower one (Las Heras Group, Malm-Hauterivian) developed during the late rift phase and is composed of lacustrine strata, which were deposited in depocenters with NW-SE to W-E orientation.

The upper megasequence (Chubut Group, Barremian-Maastrichtian) constitutes the record of a sag basin, elongated in a W–E direction with a main depocenter located in the eastern sector (Fitzgerald et al., 1990). This megasequence was deposited in different continental environments with a pyroclastic input from the west (Sciutto, 1981; Umazano, 2009; Umazano et al., 2009) in a dominantly extensional regime. The Chubut Group outcrops in the Sierra de San Bernardo (Fig. 1), where five units can be identified. The Pozo D-129 Formation is dominated by mudstones with minor sandstones, limestones and tuffs, accumulated in stratified, occasionally anoxic, alkaline-saline lakes (Clavijo, 1986; van Nieuwenhuise and Ormiston, 1989). The organic matter-rich facies of this formation are the main hydrocarbon source-rock of the basin (Uliana et al., 1999), whereas the overlying Cretaceous units include the most important reservoirs (Jalfin et al., 2005). Laterally, the shore-zone facies of the Pozo D-129 Formation are interbedded with the fluvial coarse-grained siliciclastic deposits of the Matasiete Formation forming a unique depositional system (Sciutto, 1981; Paredes et al., 2007). The overlaying Castillo Formation (Aptian-Albian) and the lower member of the Bajo Barreal Formation (Cenomanian-Turonian) are typically composed of

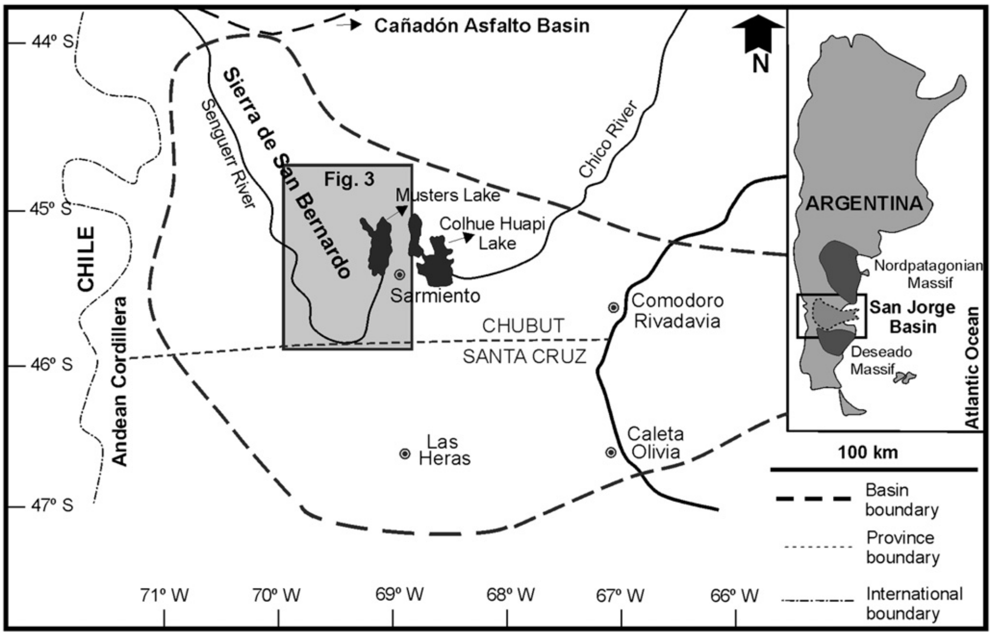

Fig. 1. Location map of the San Jorge Basin in the central Patagonia, Argentina. Location of the map in Fig. 3 is also shown.

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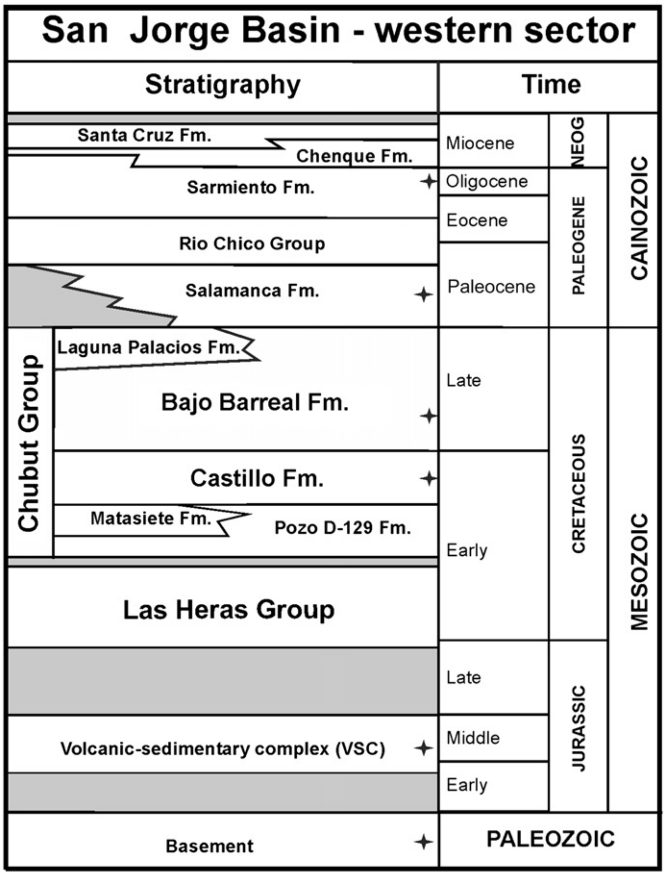

Fig. 2. Stratigraphy of the San Jorge Basin (after Umazano et al., 2008a). Gray sectors indicate hiatuses. The age of the lithostratigaphic units were established from biostratigraphical data and radiometric analyses, the latter indicated by crosses.

sandstone lenses interbedded with finer-grained, tuffaceous, sheet-like strata. Both units were deposited in fluvial to lacustrine environments under high pyroclastic influx (Bridge et al., 2000; Umazano et al., 2008a; Paredes et al., 2009). The upper member of the Bajo Barreal Formation is a fluvio-aeolian unit mainly consisting of channeled sandstones interbedded with sheet-like tuffaceous siltstones (Umazano et al., 2008a). In the western sector of the basin, the upper part of the Bajo Barreal Formation is vertically and laterally replaced by the loess–paleosol succession of the Laguna Palacios Formation (Bellosi and Sciutto, 2002).

On top of the Chubut Group, it was deposited a Maastrichtian to Middle Miocene succession integrated by marine and continental sequences (Fig. 2; Legarreta and Uliana, 1994; Bellosi, 1995).

2.2. Study area

The Sierra de San Bernardo is a fold-thrust belt comprising anticlines with eroded cores and synclines, both with N–S oriented and commonly with plunging axes (Fig. 3). Five localities were studied in the Sierra de San Bernardo: Sierra Nevada Anticline (SNA), Estancia Ocho Hermanos (EOH), Cerro Colorado de Galvéniz (CCG), Cañadón Puerta del Diablo (CPD) and Puesto Confluencia (PC) (Fig. 3). The Castillo Formation was only studied at CCG (321-m thick) and CPD (50-m thick), because in the remaining localities it is poorly exposed (Fig. 4). The lower member of the Bajo Barreal Formation was measured in all localities. It shows increasing thickness toward the south, ranging from 86 m at CPD to 395 m at PC (Fig. 4). The differentiation between the formations is mainly based on the color of the tuffaceous strata (Sciutto, 1981); the Castillo Formation is typically greenish, reddish and pinkish; while the lower member of the Bajo Barreal Formation is commonly grayish, rarely greenish or white.

3. Methodology

Sedimentary logs were measured using standard techniques; the aspects considered include lithology, grain-size, sorting, sedimentary structures, paleocurrents and fossil content. We used the terms tuffaceous sandstone and volcaniclastic conglomerate for secondary pyroclastic sediments of sand-size and gravel-size, respectively. The term tuff is reserved for primary pyroclastic sediments. In the field, paleosols were described according to Retallack (1988), whereas the description of micromorphological features follows the terminology proposed by Bullock et al. (1985).

Facies nomenclature is modified after Miall (1978), although the proposed interpretations were not always used. For description of the geometry of facies associations, as well as for their architectural analysis, we applied the criteria proposed by Bridge (1993). The apparent width of fluvial channel belt deposits with both exposed margins was measured by using a tape or GPS device and later corrected by the mean paleocurrent. Values of magnetic declination were obtained from the “Instituto Geográfico Militar” topographic charts: 4569-15 (Laguna Palacios, scale 1:100,000) and 4569-III (Sarmiento, scale 1:250,000).

4. Facies associations

Seventeen sedimentary facies were distinguished on the basis of lithology, texture, sedimentary structures and fossil content. A summary of the description and interpretation of recognized sedimentary facies is offered in Table 1. These sedimentary facies can be grouped into seven facies associations (FA). They include: pedogenically modified ash-fall deposits (FA1), fluvial channel belt deposits (FA2), crevasse-splay deposits (FA3), tuffaceous sheet-flood deposits (FA4), sandy debris-flow deposits (FA5), hyper-concentrated flow deposits (FA6) and shallow lake deposits (FA7) (Table 2). The stratigraphic position of each facies association at every locality is shown in Figs. 5–9. The proportion of the facies associations discriminated by locality and stratigraphic unit is shown in Table 3.

4.1. Facies association 1: pedogenically modified ash-fall deposits

4.1.1. Description

FA1 is composed of well-sorted, fine to medium-grained, vitric, rarely laminated, commonly massive tuffs (facies Tm) that pass upward into tuffaceous paleosols (facies P) (Fig. 10). Individual beds have non erosive bases, are 0.10–0.70 m thick and display a lateral extent of up to 2.5 km. Beds are commonly stacked forming sheet-like bodies up to 4.2 m thick with diffuse parallel stratification and mantle bedding (*sensu* Cas and Wright, 1987). Excluding location EOH, FA1 occurs in all localities, both in the Castillo and Bajo Barreal formations, although always in low proportion (up to 7%, Table 3). Facies Tm contains accretionary lapilli in the Castillo Formation and in the basal part of the Bajo Barreal Formation at SNA. The accretionary lapilli are composed of a coarse core surrounded by multiple rims of finer-grained material (R-type accretionary lapilli *sensu* Schumacher and Schmincke, 1991). These aggregates frequently show prolate shapes with the long axis parallel to the bedding planes.

Facies P includes paleosols with both differentiation (sub-facies P1) and absence of horizons (sub-facies P2). Sub-facies P1 occurs only in the lower part of SNA, where it is composed of two stacked and burrowed horizons with different color, rhizolith density and microscopic pedofeatures. The upper horizon is a 0.15–0.20 m thick,

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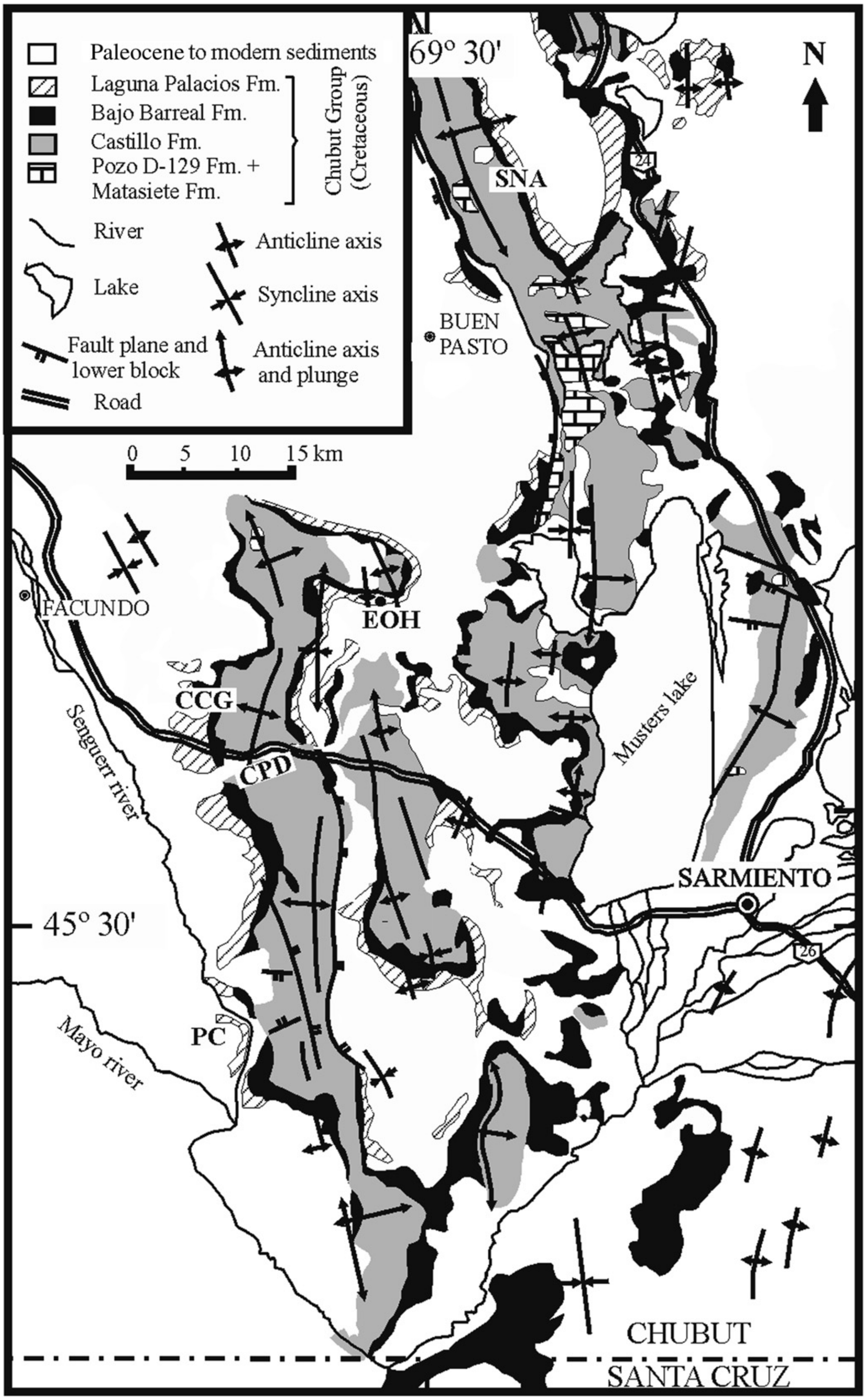

Fig. 3. Geological map of the Sierra de San Bernardo showing the studied localities: Sierra Nevada Anticline (SNA), Estancia Ocho Hermanos (EOH), Cerro Colorado de Galvéniz (CCG), Cañadón Puerta del Diablo (CPD) and Puesto Confluencia (PC).

yellowish-gray (5Y 8/1), fine-grained tuff with angular blocky peds. Under the microscope, the coarse fraction (40%) is mostly composed of volcanic glass (pumice and shards) altered to zeolite; minor components include plagioclase, monocrystalline quartz, volcanic lithic fragments and pyroxenes. The fine fraction (60%) is yellowish-brown non-recrystallized clay. The observed micromorphological features are mosaic-speckled b-fabric, millimeter-thick root traces, voids with quasi-coatings of clay and Fe–Mn aggregate nodules. The

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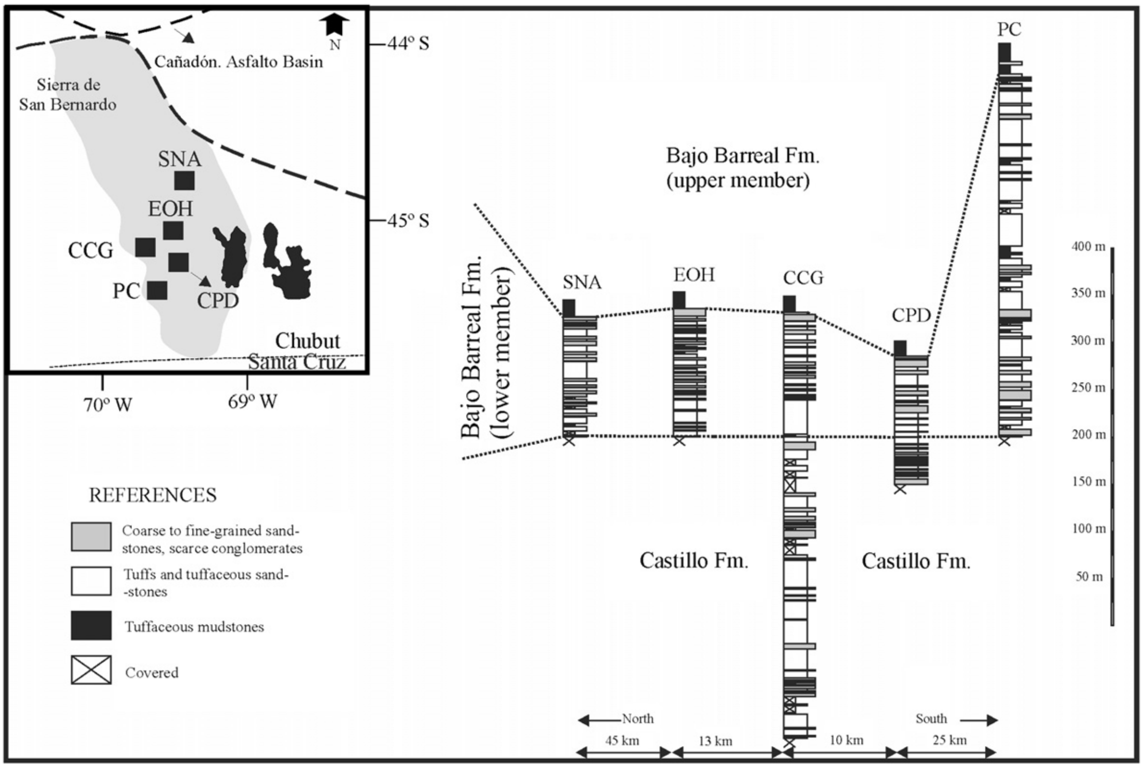

Fig. 4. Synthetic sedimentary logs of the Castillo Formation and the lower member of the Bajo Barreal Formation.

lower horizon is a 0.40–0.45 m thick, massive, light greenish-gray (5G 8/1), fine-grained tuff. In comparison with the upper horizon, it has a similar coarse-fine ratio, less recrystallized groundmass and scarce nodules. Sub-facies P2 is composed of 0.40–0.50 m thick, burrowed, apedal, yellowish-gray (5Y 8/1), fine-grained tuff. Composition of the coarse (30%) and fine (70%) fractions is similar to those described for sub-facies P1. The sole observed micromorphological features are millimeter-sized rhizotubules and Fe-Mn nodules.

4.1.2. Interpretation

Tuff beds with mantle bedding, lacking evidence for erosion at the base and absence of cross-bedding are generally interpreted as product of atmospheric suspension settling of volcanic ash (e.g. Walker, 1973; Cas and Wright, 1987; Houghton et al., 2000). Each massive or laminated bed (facies Tm) records one event of tephra fall and those with internal lamination suggest a temporal variability in the eruption intensity. Levels with accretionary lapilli indicate phreatomagmatic volcanism or ash aggregation in the troposphere (Gilbert et al., 1991; Gilbert and Lane, 1994; James et al., 2003). Common prolate shape of the accretionary lapilli is attributed to post-depositional compaction.

Presence of paleosols (facies P) overlying ash-fall deposits (facies Tm) suggests discontinuous sub-aerial sedimentation and weathering of the pyroclastic deposits, which served as parent material. Paleosols with stronger development (sub-facies P1) could represent longer periods of landscape stability and/or wetter conditions than those represented by the less developed paleosol levels.

4.2. Facies association 2: fluvial channel belt deposits

4.2.1. Description

FA2 commonly consists of isolated sandstone-conglomerate bodies with different geometries (sheet and ribbon), which show irregular or concave-upward, erosive basal surfaces (Fig. 11A). Thicknesses of individual FA2 deposits range from 0.50 m to 12.50 m, with thicker bodies occurring in the Bajo Barreal Formation and southwards in the study area (see details in Section 5). Corrected channel belt width ranges between 9.90 m and 599 m, and exhibits an increase in the mean value toward the southern extreme of the studied transect. Bodies commonly show a fining-upward trend, beginning with trough cross-bedded conglomerates (facies Ct) or breccias with horizontal stratification and rare imbrication (facies Bh), passing upward into trough cross-bedded sandstones (facies St) or massive sandstones with common scour and fill structures (facies Sm). Alternatively, the basal part of some bodies may be composed of these sandstone facies with few intercalated conglomerate lenses (facies Ct). Scarce FA2 bodies have yielded transported Araucariacea log remains (Pujana et al., 2007), dinosaur bones (e.g. Martínez et al., 2004) and partial oil impregnation. The deposits of FA2 occur in all localities of both formations, commonly interbedded with sheet-flood deposits (FA4), to which follow in order of decreasing abundance (Table 3). Some bodies of this facies association from the Bajo Barreal Formation exhibit synsedimentary deformation in sandstone levels with plane-parallel lamination and parting lineation (facies Sh) or low-angle cross-bedded (facies Sl), as well as laminated tuffaceous mudstones (facies Mh). The uppermost occurrence of this FA at the EOH section includes a basal level of fine-grained tuff with abundant burrows and root traces (sub-facies P2). All sandstone facies are composed in decreasing order of abundance by volcanic lithic fragments, plagioclase, K-feldspar and monocrystalline quartz. Paleocurrent data suggest a paleodrainage toward the E–SE in all localities, with minor variation of the paleoflow between both studied units.

4.2.2. Interpretation

FA2 deposits are interpreted as fluvial channel belts considering their geometry, erosive bases and fining-upward trend (e.g. Allen,

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Table 1
Description and interpretation of the sedimentary facies.

Facies	Subfacies	Lithology and texture	Sedimentary structures	Fossil content	Interpretation
Tm	–	Well-sorted, medium to fine-grained, vitric tuff	Massive, rarely with plane-parallel lamination, concretions. Levels with accretionary lapilli	–	Sub-aerial ash-fall event
TSs	–	Poorly sorted, vitric tuffaceous sandstone	Diffuse parallel stratification, reverse grading of pumice fragments, concretions	–	Hyperconcentrated flow
TSc	–	Poorly sorted, medium to fine-grained, vitric tuffaceous sandstone	Cross-bedding with possible tangential foresets	–	Sub-aqueous migration of tuffaceous bedforms
Bh	–	Poorly sorted, clast-supported, intraformational, fine-grained breccia	Diffuse horizontal-stratification, rare imbrication	–	Fluvial channel lag
VCm	–	Poorly sorted, matrix-supported, fine-grained tuffaceous conglomerate	Massive, rare normal grading	–	Sub-aerial debris-flow
Ct	–	Moderately well-sorted, clast-supported, fine-grained conglomerate	Trough cross-bedding	Araucariaceae logs	Migration of 3-D, gravely dunes in fluvial channels and bars
Sm	–	Moderately well-sorted, medium to fine-grained sandstone	Massive, scours at base	–	Dilute water flow with high concentration of sediments
TSm	–	Moderately well-sorted, medium to fine-grained, vitric tuffaceous sandstone	Massive, scours at base, concretions	Logs and vertebrate remains	Reworking of pyroclastic substrates by dilute flows with low water-sediment ratio
Sh	–	Moderately well-sorted, coarse to fine-grained sandstone	Plane-parallel lamination, load casts, parting lineation	Dinosaur bones	Water stream in conditions of upper-stage plane bed. Later physic disruption of the sediments
TSh	–	Moderately well-sorted, medium to fine-grained, vitric tuffaceous sandstone	Plane-parallel lamination	Unidentified burrows	Reworking of pyroclastic substrates by stream flows with development of upper-stage plane beds
St	–	Moderately well-sorted, coarse to fine-grained sandstone	Trough cross-bedding	Araucariacea logs and dinosaur bones	Sub-aqueous migration of 3-D sandstone dunes
TSt	–	Well-sorted, fine-grained, vitric tuffaceous sandstone	Trough cross-bedding	–	Reworking of pyroclastic substrates by water flows with development of dunes with sinuous crests
Sp	–	Moderately well-sorted, medium-grained sandstone	Planar cross-bedding	–	Sub-aqueous migration of 2-D sandstone dunes
Sl	–	Moderately well-sorted, medium to fine-grained sandstone	Low-angle cross-bedding, parting lineation	–	Sub-aqueous migration of low-amplitude bedforms or upper-stage plane bedforms over a dipping surface
Mh	–	Tuffaceous mudstone	Plane-parallel lamination, rarely massive	*Palaeophycus*, *Taenidium*, *Planolites*? and other unidentified burrows, fresh-water palynomorphs	Settling of suspended sediments in standing water
Mr	–	Tuffaceous mudstone	Asymmetrical ripples, occasional climbing ripples, desiccation cracks, rain drop imprints	*Palaeophycus*, *Taenidium*, *Planolites*? and other unidintified burrows	Weak unidirectional Water flows with reduced participation of settling from suspension, occasional emergence
P	P1	Fine-grained tuff with two pedogenic horizons	Massive, rare lamination or stratification	Root traces and burrows	Pedogenesis on ash-fall deposits (better developed soils)
	P2	Fine-grained tuff or tuffaceous sandstone, both without differentiation of horizons	Massive, rare lamination or stratification	Root traces, burrows (*Taenidium barretti*, *Skolithos*), insect pupal chambers (*Rebuffoichnus sciuttoi*)	Incipient pedogenesis on volcaniclastic deposits (poorly developed soils)

1964; Walker and Cant, 1984; Miall, 1996; Bridge, 1993, 2003, 2006; Gibling, 2006). A detailed characterization of these deposits is realized made below through its architectural analysis (see Section 5). Dominance of facies Ct, Bh, St, Sh and Sl indicates prevalence of tractive deposition from dilute flows. However, the presence of interbedded laminated mudstones (facies Mh) in some sandstone bodies of the Bajo Barreal Formation formed by settling from suspension suggests a pause in the bed load transport. In particular, facies Ct and St were formed by migration of gravely and sandy three-dimensional dunes, respectively. Breccias with horizontal stratification (facies Bh) are interpreted as lag deposits. Horizontal laminated sandstones with parting lineation (facies Sh) record migration of upper-stage plane beds. Sandstones with low-angle cross-bedding (facies Sl) would represent migration of washed-out dunes or upper-stage plane beds deposited on dipping surfaces. Massive sandstones (facies Sm) originated from flows with high sediment concentrations, which cannot generate bed-forms (type 2 dilute flow *sensu* Smith and Lowe, 1991).

Most of the bodies are interpreted as permanent fluvial channel belts due to the absence of evidence for sub-aerial exposure (e.g. sub-aerial bioturbation, pedogenesis and/or mud-cracks) in the lower part of the bodies (Bridge et al., 2000; Bridge, 2003, 2006). Nevertheless, the presence of beds generated during upper stage plane bed conditions (facies Sh and Sl) associated with layers originated from settling from suspension (facies Mh) in the Bajo Barreal Formation suggest important discharge fluctuations during deposition of this

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Table 2
Sedimentological features and interpreted depositional environment for each facies association.

Facies association	Facies	Lower bounding surface	Geometry	Interpretation
FA1	Tm and P	Non-erosive	Sheet (mantle bedding and good lateral continuity)	Pedogenically modified ash-fall deposit
FA2	Ct, Bh, St and Sm. Rare participation of Sh, Sl, Mh and P	Erosive, irregular or concave-upward	Sheet, channel or ribbon	Fluvial channel belt deposit
FA3	Sm, St and Mh	Plane and ocassionaly erosive	Lobe to sheet	Crevasse-splay deposit
FA4	TSm and TSh (dominant), minor participation of TSt and P. Rare occurrence of Sm, Sh, St, Sp and Sl	Plane and locally erosive	Sheet	Tuffaceous sheet-flood deposit
FA5	VCm and TSt, occasionally P	Undulated and locally erosive	Sheet or plane-convex	Sandy debris-flow deposit
FA6	TSs and TSc	Undulated and locally erosive	Sheet although with important lateral variation in thickness	Hyperconcentrated flow deposit
FA7	Mh and Mr	Plane and non erosive, in some cases concave-upward	Sheet or channel	Shallow lake deposit

facies association (Tunbridge, 1981; Dreyer, 1993; Long, 2006). Conclusive evidence for intermittent sedimentation was only detected in EOH, where one channel belt deposit exhibited root traces (sub-facies P2) in its lower part.

Although a physical connection with crevasse-splay deposits (FA3) was not observed; those bodies of the FA2 that are contiguous and at a similar stratigraphic position that FA3 deposits could represent crevasse channels.

4.3. Facies association 3: crevasse-splay deposits

4.3.1. Description

FA3 includes lobe to sheet-shaped sandstone bodies with occasional erosive bases (Fig. 11B). They are mostly composed of trough cross-bedded or massive sandstones (facies St and Sm, respectively). In some cases, the sandstones are covered by massive, rarely laminated tuffaceous mudstones (facies Mh). The

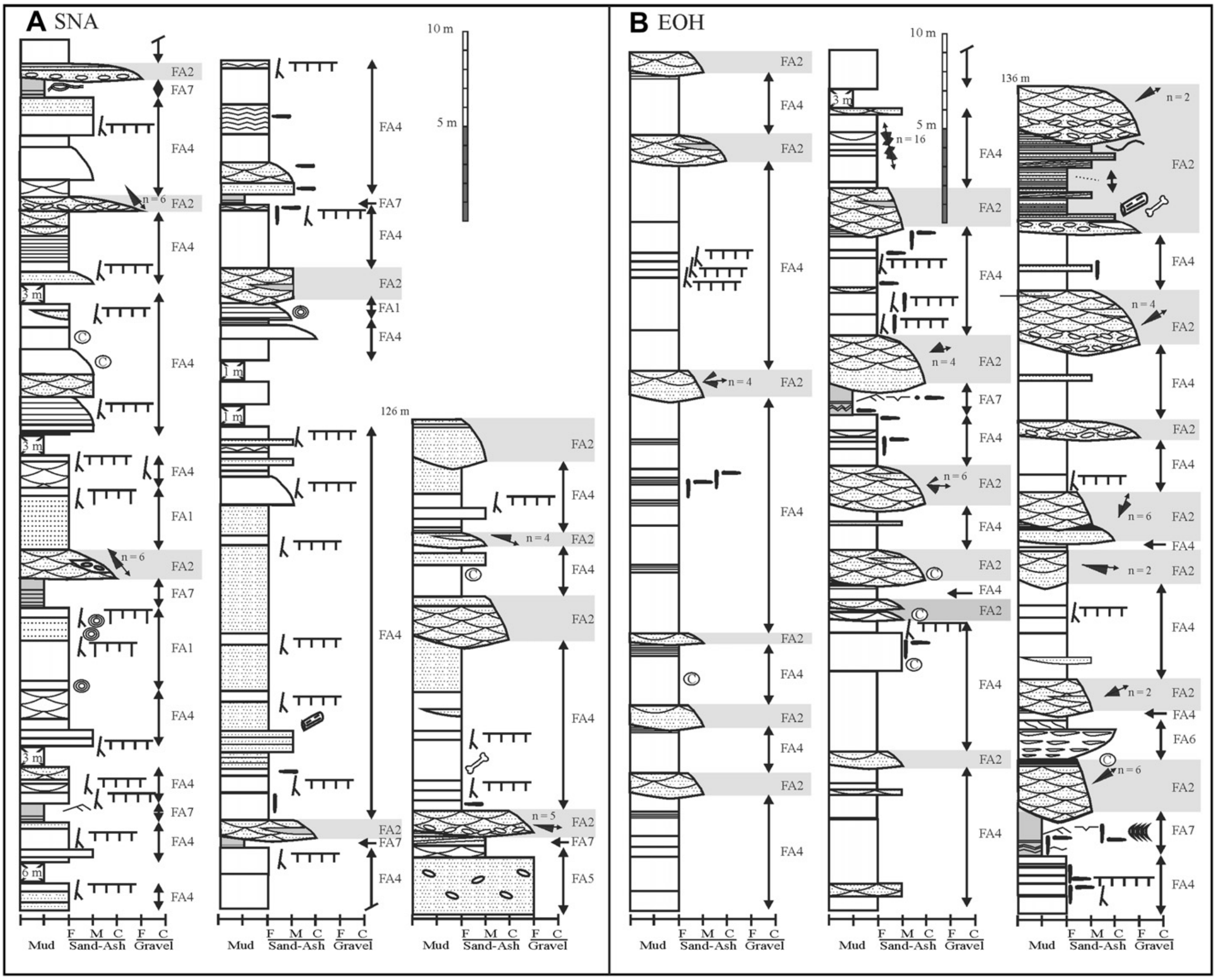

Fig. 5. Detailed sedimentary logs of localities SNA (A) and EOH (B). Data are arranged in ascending stratigraphic order from left to right. See references in Fig. 9.

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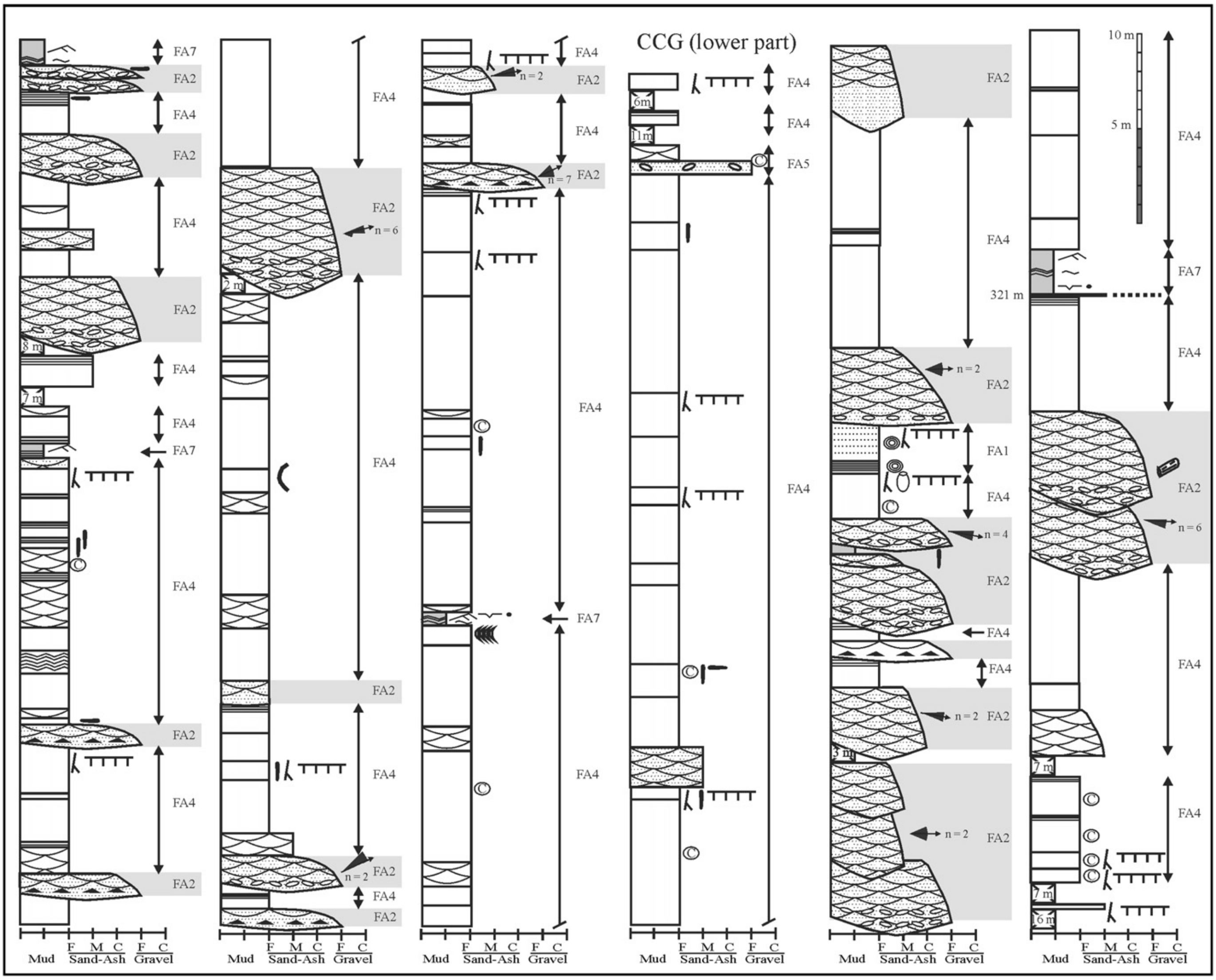

Fig. 6. Detailed sedimentary log of the basal part of locality CCG. Data are arranged in ascending stratigraphic order from left to right. The contact between Castillo and Bajo Barreal formations is indicated by a dotted line. See references in Fig. 9.

occurrence of subtle fining-upward sequences is common. Sandstone composition is similar to that described for the preceding facies association. FA3 deposits are surrounded by highly bioturbated sheet-flood deposits (FA4) and they have a maximum thickness of 1.50 m and a lateral extent exceeding 10 m (Fig. 11B). Internally, sandstone bodies exhibit discontinuous surfaces parallel to the convex-upward top, which have scour and fill structures and gravel-sized intraclasts. Lobe geometry is typically detected in sections oriented cuasi-perpendicular to paleoflow directions, whereas sheet geometry was observed in sections oblique to parallel to the paleoflow direction of the associated channel belt deposits. FA3 was only recorded in PC, where it represents less than 1% of the section (Table 3).

4.3.2. Interpretation

Geometry of the FA3 (flat bottom and convex-upward top) suggests an origin as crevasse-splays (Miall, 1996). The smaller grain-size and thickness relative to associated fluvial channel belt deposits supports such a genesis (Galloway and Hobday, 1996). The fining-upward trend can be attributed to a gradual reduction in water discharge with a transition from conditions of tractive transport (facies Sm and St) to settling (facies Mh). Presence of erosive surfaces within sandstone bodies reflects multiple episodes of deposition and suggests discontinuous growth of the splay (Stear, 1983). These surfaces could indicate an increase of the distance to the active fluvial channel belt (Bridge, 2006).

4.4. Facies association 4: tuffaceous sheet-flood deposits

4.4.1. Description

FA4 is mainly composed of massive or parallel-laminated, vitric, tuffaceous sandstones (facies TSm and TSh, respectively), forming sheet-like packages with a lateral continuity of several hundreds of meters and up to 34 m thick (Fig. 11C). Individual beds are decimeters to meters thick and show erosive lateral superposition (amalgamation). Occurrence of sub-angular, tuffaceous, gravel-sized intraclasts is common. In many cases there are thin intercalations of vitric tuffaceous sandstones with trough cross-bedding (facies TSt) or paleosols without differentiation of horizons (subfacies P2). Thin sandstone levels with horizontal lamination (facies Sh), trough cross-bedding (facies St), planar cross-bedding (facies Sp), low-angle cross-bedding (facies Sl) or massive aspect (facies

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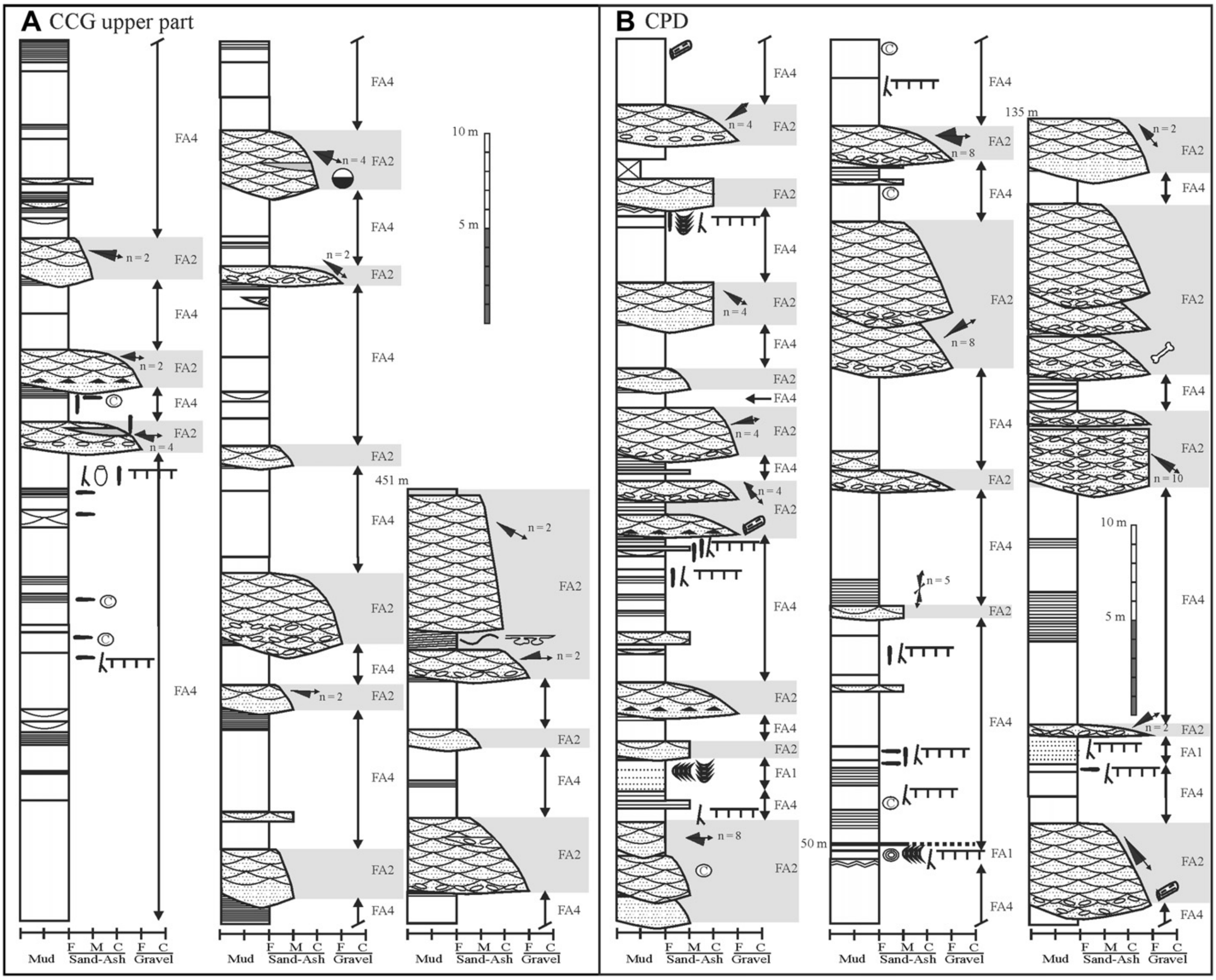

Fig. 7. Detailed sedimentary logs of localities CCG (upper part, A) and CPD (B). Data are arranged in ascending stratigraphic sense from left to right. The contact between Castillo and Bajo Barreal formations is indicated by a dotted line. See references in Fig. 9.

Sm) were also recorded. Transition from facies TSm to facies TSh was commonly observed, in few cases exhibiting fining-upward trend. Facies association 4 overlies primary pyroclastic substrates (FA1) and displays lateral transitions to fluvial channel belt deposits (FA2) and shallow lacustrine deposits (FA7). FA4 dominates the Castillo and Bajo Barreal formations in all localities (Table 3), commonly sandwiching FA2 deposits. Scarce available paleocurrent data indicate two average paleoflow directions: toward the NE and toward the SW (see Figs. 5–9).

4.4.2. Interpretation

Considering the sheet-like geometry and dominance of massive and laminated vitric tuffaceous sandstones in FA4 deposits, we envisage a genesis as sheet-floods that remobilized pyroclastic deposits (Cas and Wright, 1987; d'Atri et al., 1999; Martina et al., 2006; Fisher et al., 2007; Hampton and Horton, 2007; Nichols and Fisher, 2007). During these events, large volumes of sediment were transported in turbulent suspension, generating massive (facies TSm and Sm) or laminated beds (facies TSh and Sh) when flow velocity wanes. Transition from facies TSm to facies TSh indicates an increase in the water-sediment ratio (dilution *sensu* Fisher, 1983) and the coeval development of upper-stage plane beds during a single event. Facies that record the development of different types of sub-aqueous dunes (facies TSt, St, Sp and Sl) represent relatively more distal sectors of the sheet-floods. Intervals of negligible deposition are indicated by the presence of poorly developed paleosols (sub-facies P2). Sheet-like geometry of these deposits suggests unconfined flows, which have been described for different alluvial settings: (i) ephemeral streams (e.g. Stear, 1983); (ii) alluvial fans (e.g. Parkash et al., 1983); (iii) distal braided and poorly defined fluvial systems (e.g. Tunbridge, 1981); and (iv) floodplains (e.g. Bridge et al., 2000). The latter possibility is considered more probable according to the vertically and laterally related facies associations.

4.5. Facies association 5: sandy debris-flow deposits

4.5.1. Description

FA5 is mainly composed of poorly sorted, matrix-supported, massive or normally graded volcaniclastic conglomerates (facies VCm) with scarce and thin intercalations of vitric tuffaceous sandstones showing trough cross-bedding (facies TSt) (Fig. 11D). Geometry is sheet-like or plano-convex with undulating and locally erosive bases. Maximum thickness is 3.60 m and lateral extent can

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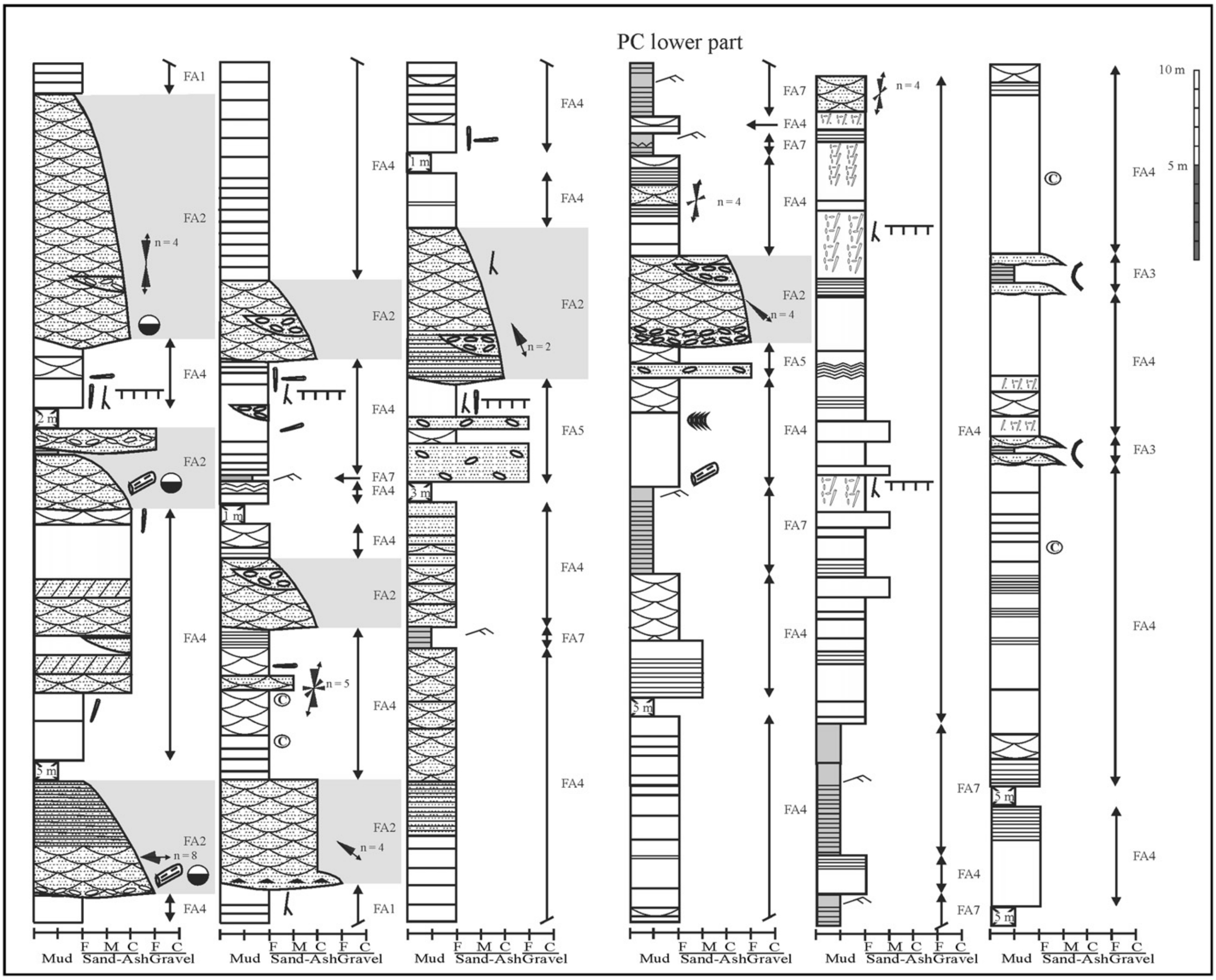

Fig. 8. Detailed sedimentary log of the basal part of locality PC. Data are arranged in ascending stratigraphic order from left to right. See references in Fig. 9.

reaches hundreds of meters. Amalgamation and stacking of beds assigned to VCm facies is very common. Composition of the clasts of the facies include: (i) sub-rounded volcanic lithic fragments of andesitic composition, and (ii) sub-rounded to sub-angular tuffaceous intraclasts with undeformed internal lamination. Clast size ranges from coarse sand to pebble with a mode in the granule interval. Matrix is medium to fine-grained vitric tuff. In some cases, the top of the bodies shows rhizoliths and burrows (sub-facies P2). This FA occurs in the Castillo (CCG section) and Bajo Barreal (SNA and PC sections) formations as thin intercalations within thicker sheet-flood deposits (Table 3).

4.5.2. Interpretation

Features of the facies VCm and its association with paleosols (sub-facies P2) suggest deposition from sub-aerial debris-flows (Shultz, 1984; Smith and Lowe, 1991; Best, 1992; Nakayama and Yoshikawa, 1997). Tuffaceous intraclasts and locally erosive bases suggest debris-flows that partially eroded the underlying deposits. Common occurrence of ungraded and matrix-supported beds point to pseudoplastic debris-flows and the scarce beds with normal grading could suggest more dilute debris-flows. Under this rationale, each *en masse* sedimentation unit (bed assigned to facies VCm) was reworked by aqueous dilute streams to form dunes with sinuous crests (facies TSt; Smith, 1987). These streams could belong to a late episode of a single debris-flow event or represent an independent flow (Nemec and Steel, 1984). The upper part of some deposits was modified by pedogenic processes and burrowed by organisms (sub-facies P2).

4.6. Facies association 6: hyperconcentrated flow deposits

4.6.1. Description

FA6 is represented by a single deposit recorded in section EOH (2% of the measured thickness, Table 3). It consists of 0.20–1.70 m thick, poorly sorted tuffaceous sandstones with diffuse planar stratification (facies TSs), which pass-upwards via transitional contact to 0.05–0.15 m thick, cross-bedded tuffaceous sandstones (facies TSc) (Fig. 11E). FA6 deposit is dominated by facies TSs ($\approx$80%) and shows sheet-like geometry, although with important lateral variations in thickness (0.25 m to 1.80 m in 300 m). In detail, facies TSs comprises reversely graded, lapilli-sized, prolate, sub-rounded to sub-angular, low-sphericity pumice fragments floating in a matrix of medium to fine-grained vitric tuff. Long axes of the pumice fragments are parallel to bedding planes. Spherical

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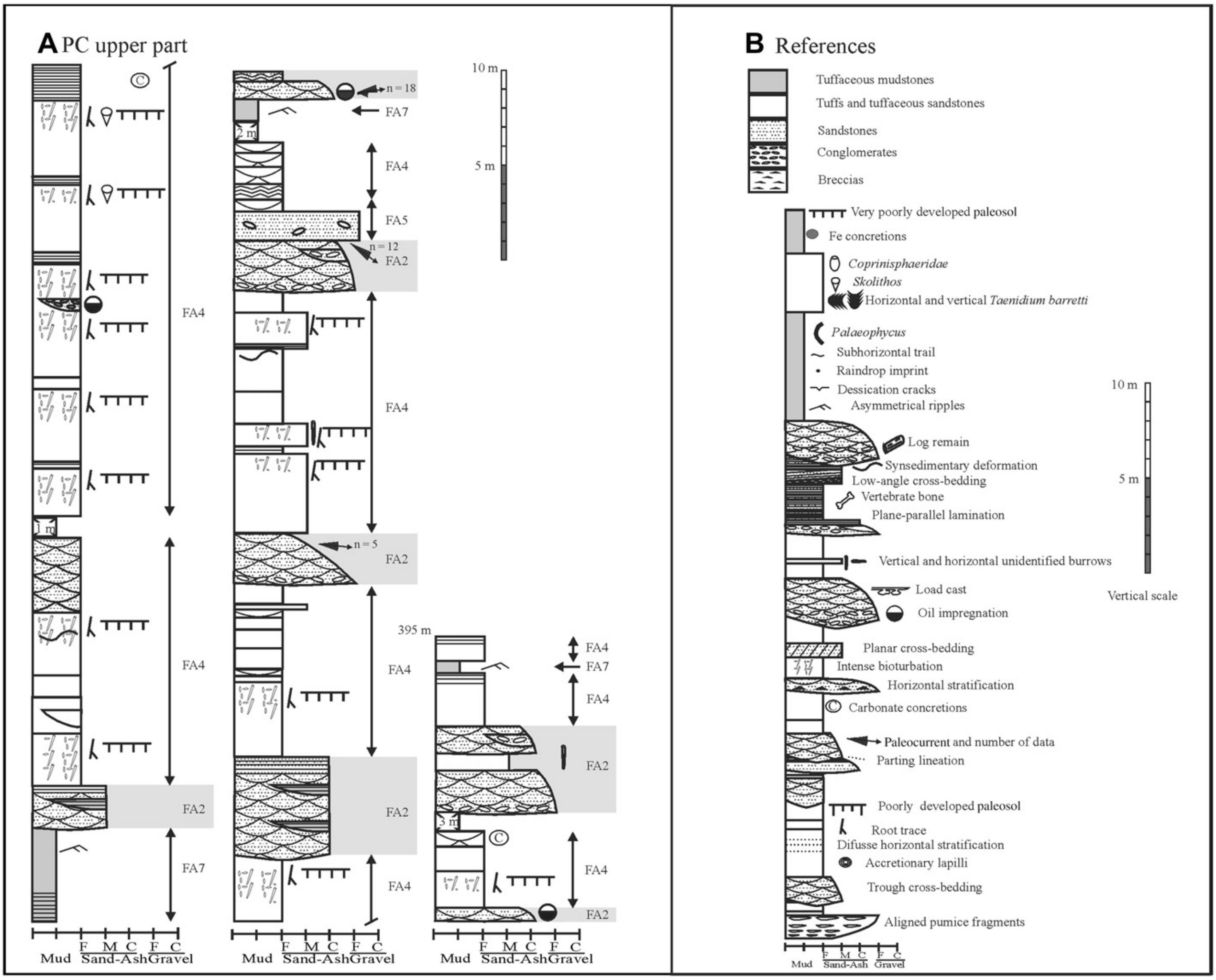

Fig. 9. Detailed sedimentary log of locality PC (upper part, A) and references (B). Data are arranged in ascending stratigraphic order from left to right.

carbonate concretions up to 2 mm in diameter commonly occur. Facies TSc is a poorly sorted, medium to fine-grained, vitric tuffaceous sandstones with possible tangential foresets dipping at 30°. FA6 overlies a fluvial channel-belt deposit (FA2) and is covered by a sheet-flood deposit (FA4).

4.6.2. Interpretation

The vertical facies succession with predominance of diffusely stratified, reversely graded pumice-rich layers in the basal part (facies TSs) and cross-bedded tuffaceous sandstones in the upper sector (facies Tsc) suggest that FA6 could represent a hyper-concentrated flow, which underwent dilution during deposition (Scott, 1988; Smith and Lowe, 1991), or water-saturated pumice fragments that sequentially settled from a floating pumice raft and latterly reworked (Manville et al., 2002). The first possibility is more probable because facies TSs shows diffuse stratification, the pumice fragments are not vertically imbricated and the matrix content remains invariable. In particular, facies TSs would have

Table 3
Proportion of the facies associations discriminated by localities and stratigraphic units.

Facies associations (%)	Castillo Formation					Bajo Barreal Formation (lower member)				
	SNA	EOH	CCG	CPD	PC	SNA	EOH	CCG	CPD	PC
FA1	–	–	1	5	–	7	0	0	1	1
FA2	–	–	16	36	–	8	25	23	24	17
FA3	–	–	0	0	–	0	0	0	0	1
FA4	–	–	61	57	–	66	68	75	75	65
FA5	–	–	1	0	–	3	0	0	0	2
FA6	–	–	0	0	–	0	2	0	0	0
FA7	–	–	1	0	–	4	3	2	0	6
Covered	–	–	20	2	–	12	2	0	0	8
Total	–	–	100	100	–	100	100	100	100	100

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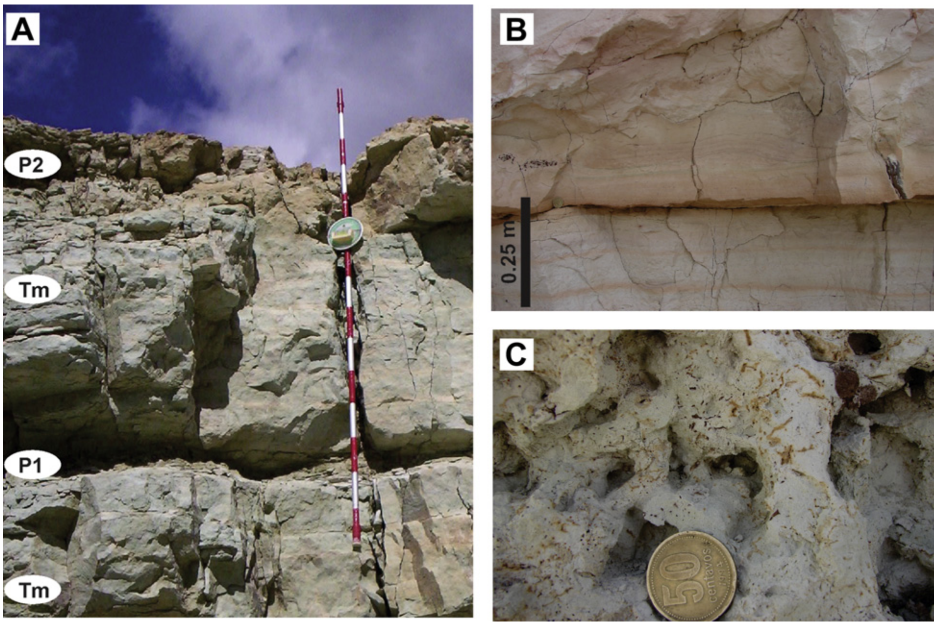

Fig. 10. Primary pyroclastic deposits (FA1). (A) Pedogenically modified ash-fall deposit composed of massive tuffs (facies Tm) with intercalations of paleosols with and without differentiation of horizons (subfacies P1 and P2, respectively); Jacob's staff is 1.50 m long. (B) Detail of ash-fall deposit constituted by tuffs with plane-parallel lamination in the base that pass upwards to massive tuffs; coin is 25 mm in diameter. (C) Detail of a paleosol without differentiation of horizons, note the abundant presence of root tubules; coin is 25 mm in diameter.

been essentially deposited grain-by-grain through the action of several mechanisms of sediment support including turbulence, dispersive forces and buoyancy. The latter mechanism in combination with the low density of pumice fragments originated reversely graded beds. The facies TSc records migration of dunes after flow transformation (dilution) either due to addition of fluid or deposition of sediment. This dilution is probably also associated with flow waning.

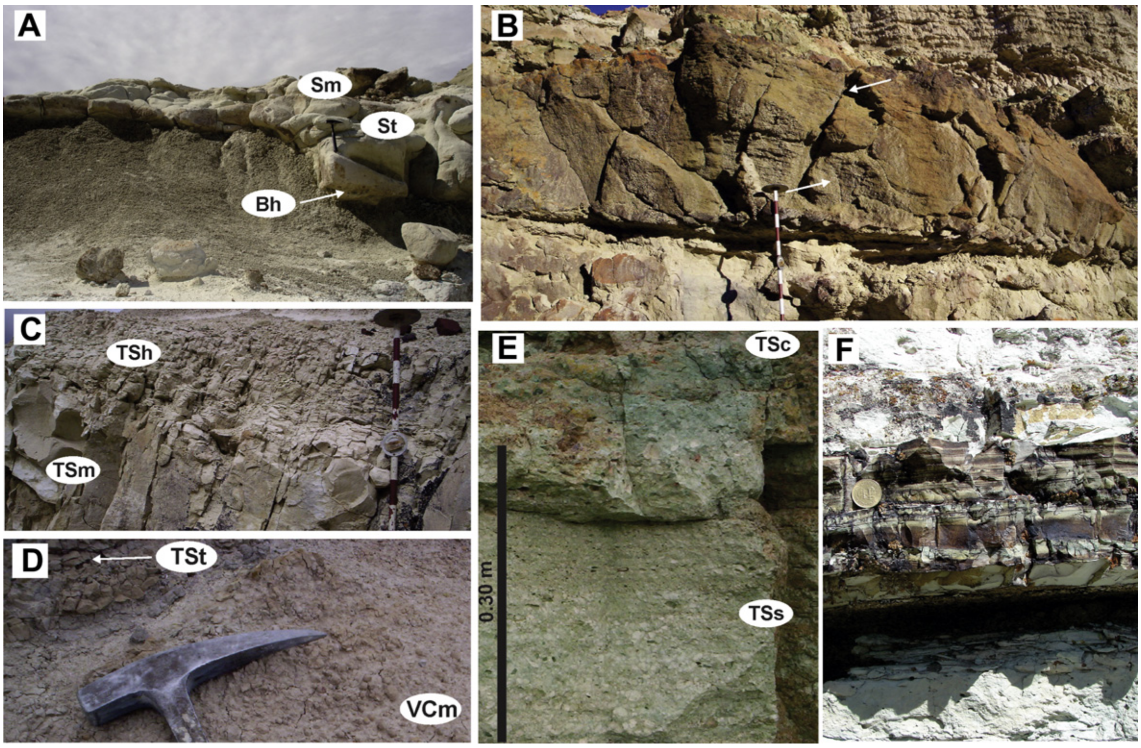

Fig. 11. Field photographs of fluvial facies associations. (A) Fluvial channel belt (FA2) constituted of discontinuous and diffusely stratified breccias (facies Bh) at the base which pass-upward to trough cross-bedded or massive sandstones (facies St and Sm, respectively); hammer is 0.33 m long. (B) Crevasse-splay (FA3) composed of massive sandstones (facies Sm); note the lobe-shaped geometry and internal erosive surfaces parallel to the top (arrows); each division of Jacob's staff is 0.10 m thick. (C) Massive to plane-parallel laminated tuffaceous sandstones (facies TSm and TSl) representing a sheet-flood event (FA4); each division of Jacob's staff is 0.10 m long. (D) Massive and matrix-supported conglomerate (facies TCm) underlying a trough cross-bedded tuffaceous sandstone (facies TSt) recording a reworked debris-flow (FA5); head of the hammer is 0.18 m long. (E) Cross-bedded tuffaceous sandstones (facies TSc) overlying stratified tuffaceous sandstones (facies TSs), both represent a hyperconcentrated flow that experienced dilution (F) Massive and plane-parallel laminated mudstones (facies Mh) deposited in a shallow lake (FA7); coin is 25 mm in diameter.

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4.7. Facies association 7: shallow lake deposits

4.7.1. Description

FA7 includes tuffaceous mudstones with parallel-lamination, rarely massive due to bioturbation (facies Mh) or with asymmetric climbing ripples (facies Mr) (Fig. 11F). In both facies is common the presence of deformed laminae and burrows (including *Palaeophycus*, *Taenidium* and possibly *Planolites*). FA7 deposits are arranged in sheet-like or plano-convex bodies with a lateral extent ranging from tens to hundreds of meters; and thickness ranging from decimeters to meters. Deposits have non-erosive bottoms and tops eroded by fluvial channel belt (FA3) or sheet-flood (FA5) deposits. Very subtle coarsening-upward cycles defined by a transition from basal massive or laminated tuffaceous claystones (facies Mh) to rippled tuffaceous siltstones at the top (facies Mr) are commonly recognized. Some cycles show desiccation cracks and rain drop imprints in the upper part. FA7 was recorded in the Castillo (CCG) and Bajo Barreal (SNA, EOH, CCG and PC) formations, with a greater participation in the southernmost locality (Table 3).

4.7.2. Interpretation

Mudstones with plane-parallel lamination or ripples arranged in packages with non-erosive bases suggest sub-aqueous deposition in a relatively shallow lacustrine environment (e.g. Talbot and Allen, 1996; Nakayama and Yoshikawa, 1997). Facies Mh was generated by settling from a suspension (Collinson and Thompson, 1982). Facies Mr is compatible with a lower-stage tractive unidirectional flow and migration of asymmetrical ripples (Jopling and Walker, 1968; Collinson and Thompson, 1982; Allen, 1984); occasional climbing ripples indicate a sporadic increase in vertical aggradation rate during ripple migration. Absence of evaporites and crystal casts denotes fresh to salty lakes (Hardie et al., 1978). The mentioned cycles display a shallowing-upward trend as suggested by the coarsening-upward trend and the presence of plane-parallel lamination in the lower part and ripples, desiccation cracks and rain drop imprints in the top. These cycles may be interpreted as progradation of littoral facies over basinal facies, probably linked to decreasing of the lake area and movement of the shoreline toward the center of the basin (e.g. van Houten, 1964; Melchor, 2007).

5. Architecture and dimensions of the fluvial channel belt deposits (FA2)

Two major river styles were distinguished using the arrangement of the large-scale inclined stratasets of the FA2 deposits: (i) braided fluvial system, and (ii) single-channel (meandering?) fluvial system (Sections 5.1 and 5.2, respectively). The vertical and lateral variations in thickness of the FA2 deposits are also discussed here (Section 5.3).

5.1. Braided fluvial system

5.1.1. Description

A braided fluvial system characterizes the Bajo Barreal Formation at localities CCG, CPD and PC. The bodies that represent this fluvial style are composed of large-scale inclined stratasets that, in sections near orthogonal to the average paleocurrent direction, are convex-upward or concave-upward. In the first case, the large-scale inclined stratasets dip between 15° and 24° in opposed directions to adjacent channel floors located on either side (Fig. 12). Commonly, the direction of maximum dip of these large-scale inclined stratasets is near orthogonal respect to the adjacent channel margin. In some cases, these large-scale inclined stratasets are partially truncated by a concave-upward erosive surface (Fig. 12). Large-scale inclined stratasets have a thickness of decimeters to meters and a width of tens to hundreds of meters. Internally, they display a fining-upward trend and the most common vertical facies arrangement is Bh or Ct at the base followed by facies St or Sm; with facies Sh, Sl and Mh as minor contributors.

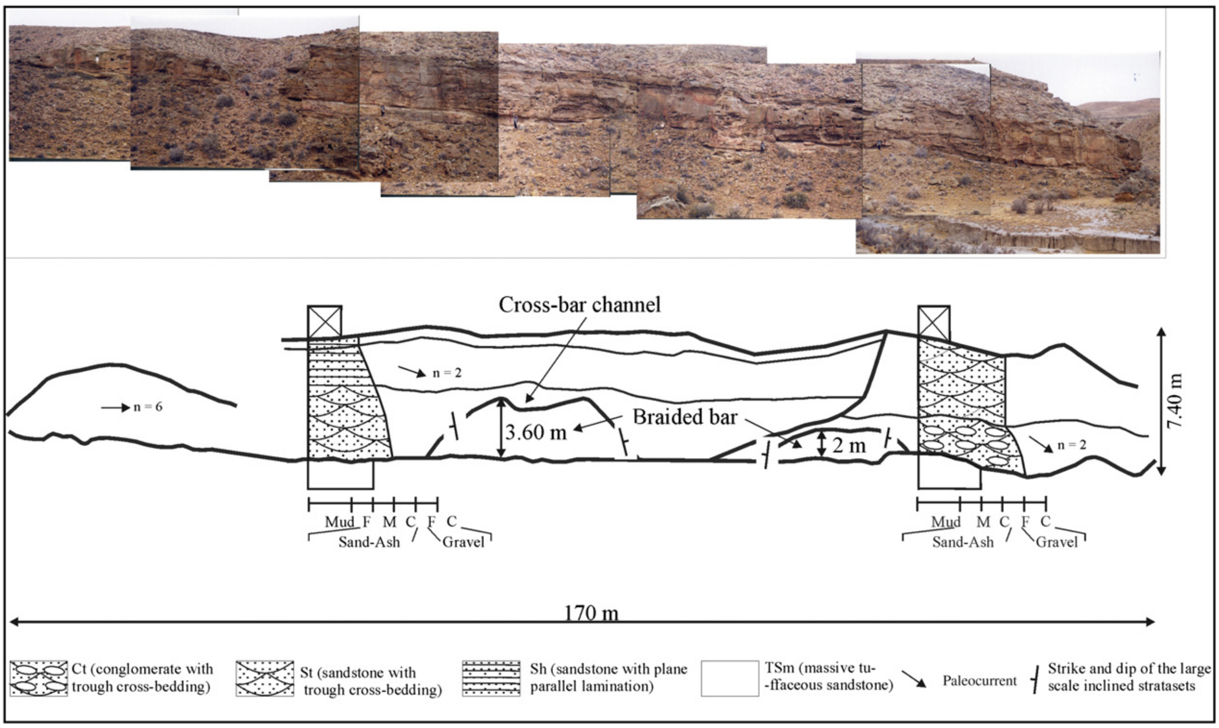

Fig. 12. Arrangement of large-scale inclined stratasets (coarser lines) in two amalgamated fluvial channel belts with braided bars (braided system). The thinner lines indicate the contact between different facies within a same large-scale inclined strataset. The pictured body belongs to the Bajo Barreal Formation at PC (interval from 1.50 m to 7.50 m). Vertical scale is exaggerated approximately ×2. Outcrop orientation is N 90°.

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5.1.2. Interpretation

Large-scale inclined stratasets are deposits formed by the migration of channel bars and channel fills; each large-scale inclined stratum would represent individual flood events (Bridge, 1993, 2003, 2006). The presence of large-scale inclined stratasets with convex-upward tops and coeval channel floors on both sides suggests a braided pattern (Khan et al., 1997; Bridge et al., 2000; Lunt et al., 2004). Low dispersion of the paleocurrent data and absence of levee deposits are consistent with this configuration (Bridge, 1985). Concave-upward erosive surfaces in the upper part of some braided bars are interpreted as cross-bar channels (Fig. 12).

5.2. Single-channeled (meandering?) fluvial system

5.2.1. Description

A single-channel fluvial system is typical of the Castillo Formation in both studied localities, and also characterizes the Bajo Barreal Formation at the EOH section. The bodies of this fluvial style are composed of large-scale inclined stratasets, which show two distinctive features in near orthogonal sections: (i) the stratasets dip up to 13° in approximately the same direction; and (ii) a suite of stratasets defines a laterally stacked pattern (Fig. 13). The large-scale inclined stratasets are gently inclined; the last ones can reach a sub-horizontal attitude. Internally, large-scale inclined stratasets fine-upwards and generally exhibit a vertical transition from facies Bh or Ct to facies St or Sm. In the Bajo Barreal Formation, some large-scale inclined stratasets are overlain by a centimeter-thick mudstone drape (facies Mh, Fig. 14). The uppermost body of the Bajo Barreal Formation has abundant sheet-like sandstone beds with horizontal lamination (facies Sh) or low angle cross-bedding (facies Sl), which are eroded by large-scale inclined stratasets composed of trough cross-bedded conglomerates and sandstones (facies Ct and St, Fig. 15).

5.2.2. Interpretation

Typical lateral stacking of the large-scale inclined stratasets (Fig. 13 and Fig. 14) indicates single-channel rivers (Bridge, 1993, 2003, 2006) with lateral migration of a channel-margin (point?) bar and the adjacent thalweg (e.g. Bridge et al., 2000; Georgieff and Gonzalez Bonorino, 2002), probably within a single fluvial channel belt. These fluvial channel-belt deposits are tentatively considered to be meandering because of the presence of a single channel with bars attached to the margin of the channel. Presence of mudstone drapes on the top of some large-scale inclined stratasets in the Bajo Barreal Formation suggests variable water discharge during deposition of this unit.

Those deposits dominated by facies Sh or Sl (Fig. 15) are interpreted as the product of quick and poorly confined floods in conditions of upper-stage flow (Tunbridge, 1981, 1984; Stear, 1983; Miall, 1996; Long, 2006). Vertical transition to facies Ct or St suggests waning flow during the terminal stages of the floods.

5.3. Thickness of fluvial channel belts

The thickness of fluvial channel-belt deposits discriminated by locality and stratigraphic unit is summarized in Fig. 16. The Castillo Formation shows the highest average thickness values at locality CCG (2.73 ± 1.41 m; $n = 19$; Fig. 16); thickness of individual fluvial channel-belt deposits ranges from 0.90 m to 8.60 m. In locality CPD, the average thickness is 1.68 ± 0.81 m ($n = 11$; Fig. 16); data ranges between 0.90 m and 3.55 m. Mean thickness calculated using all data of the unit is 2.20 ± 2.18 m ($n = 30$).

The lower member of the Bajo Barreal Formation exhibits, from north to south, thicker fluvial channel-belt deposits (Fig. 16). Average thickness of these deposits in this unit is 2.5 ± 1.14 m ($n = 67$), only 0.3 m thicker than in the Castillo Formation. However, average thickness quadruples from 1.20 ± 0.61 m ($n = 9$)

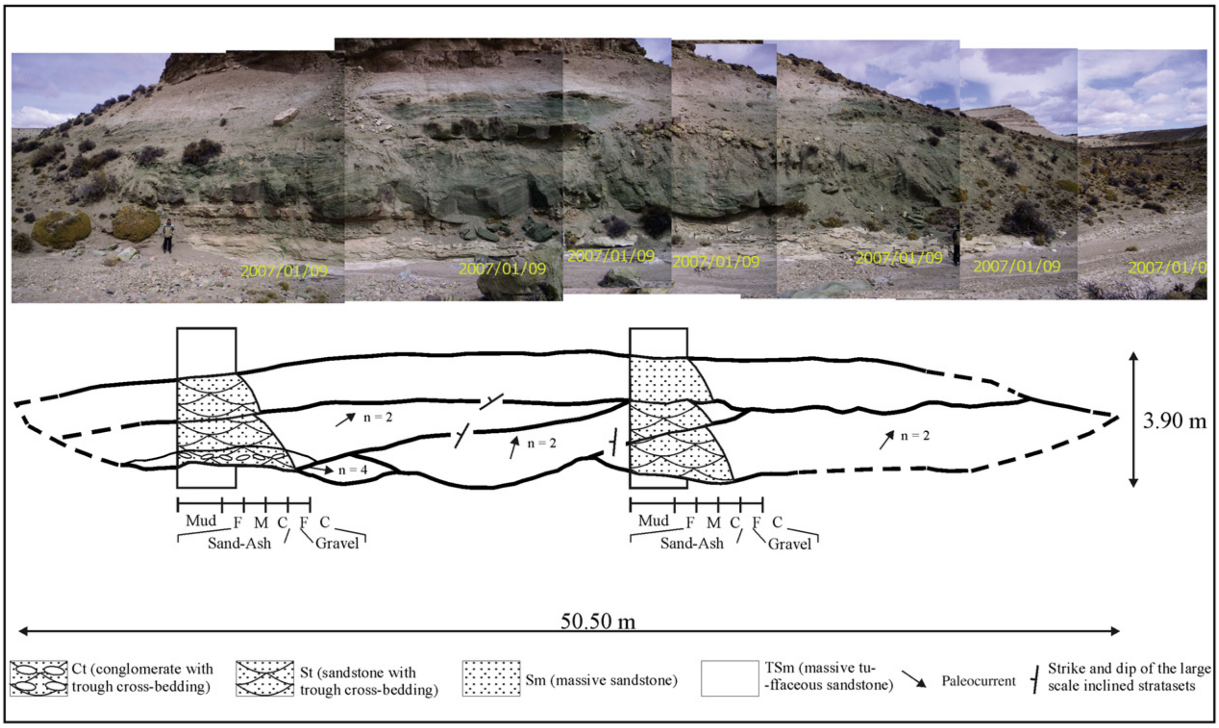

Fig. 13. Organization of large-scale inclined stratasets (coarser lines) in a fluvial channel belt with attached-margin bars (meandering system), the river migrated from right to left. The thinner lines indicate the contact between different facies within a same large-scale inclined strataset. The pictured body belongs to the Castillo Formation at CPD (interval from 24.80 m to 27.10 m). Outcrop orientation is N 108°.

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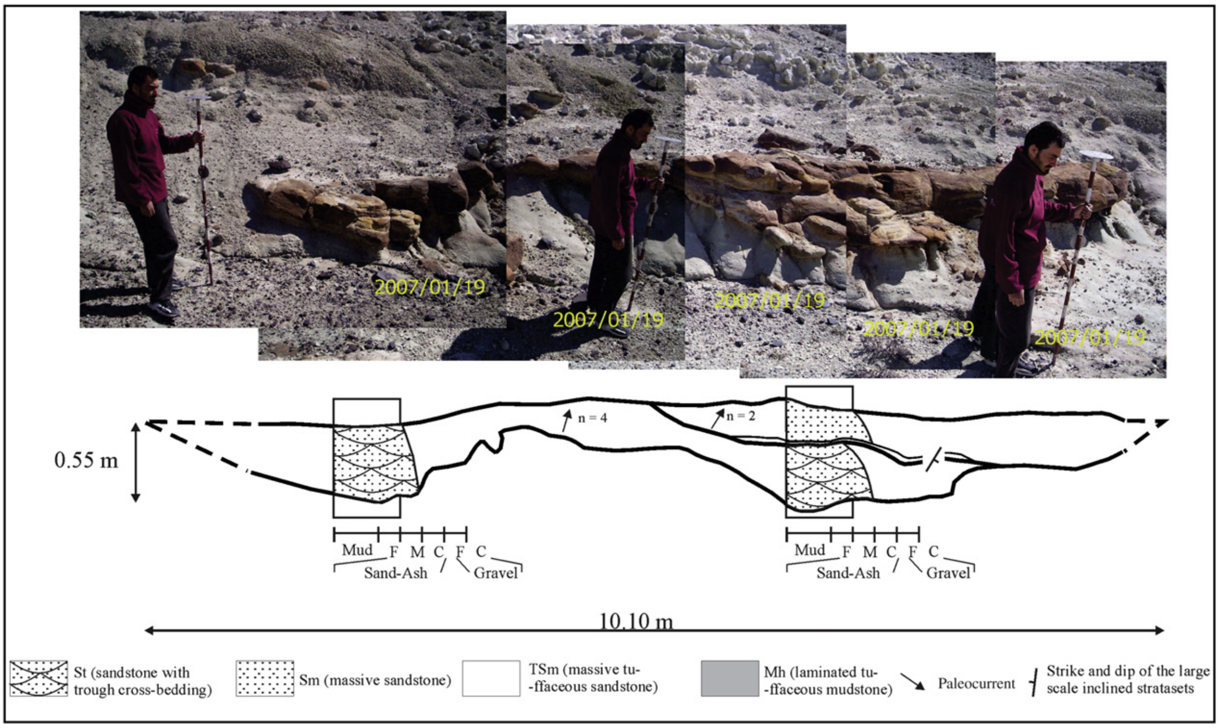

Fig. 14. Disposition of large-scale inclined stratasets (coarser lines) in a fluvial channel belt with mud-draped, attached-margin bars (meandering system), the river migrated from left to right. The thinner lines indicate the contact between different facies within a same large-scale inclined stratasets. The pictured body belongs to the Bajo Barreal Formation at EOH (interval from 53 m to 53.50 m). Outcrop orientation is N 170°.

in the section SNA to 4.39 ± 2.58 m at PC ($n = 15$; Fig. 16). Thickness of individual fluvial channel belt deposits ranges from 0.50 m to 12.50 m; the largest values are commonly recorded in southernmost locality (PC).

6. Depositional model

The schematic diagram of Fig. 17 summarizes the alluvial stratigraphy of both studied units, illustrating the relationships

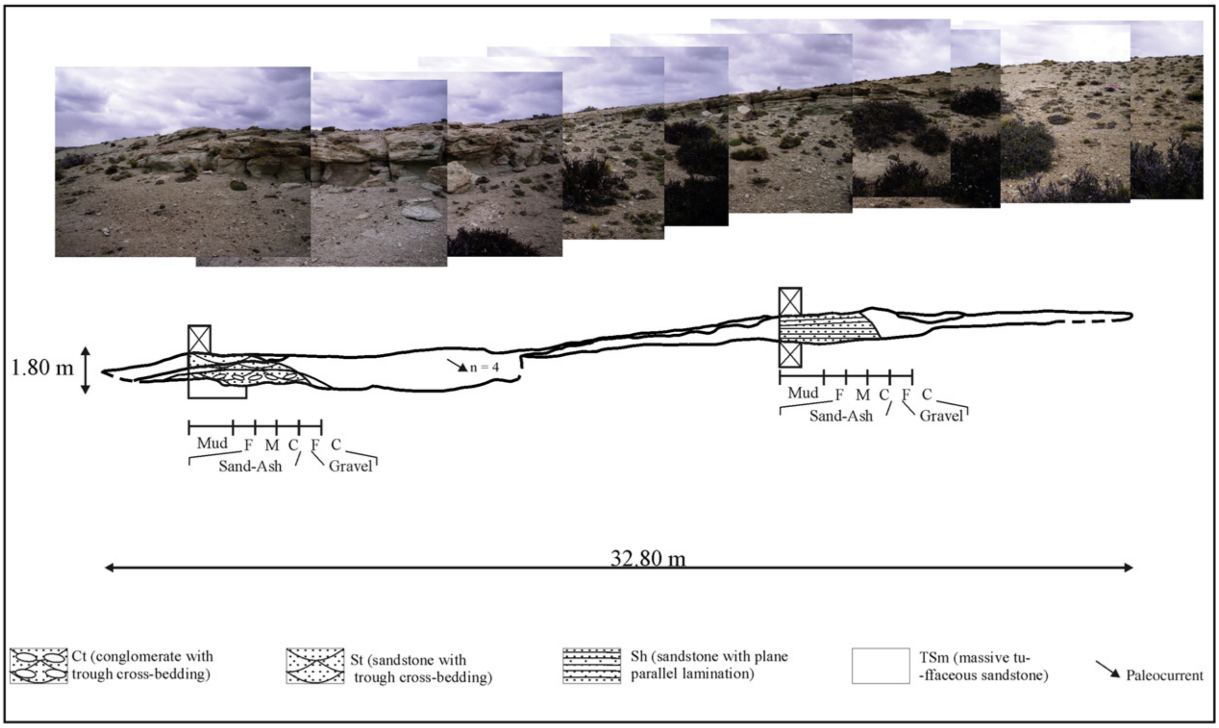

Fig. 15. Arrangement of large-scale inclined stratasets (coarser lines) in two amalgamated fluvial channel belts: one (right) dominated by sheet-like laminated sandstones, and other (left) with attached-margin bars (meandering system). The thinner lines indicate the contact between different facies within a same large-scale inclined strataset. The pictured body belongs to the Bajo Barreal Formation at EOH (interval 181 m to 183 m). Outcrop orientation is N 15°.

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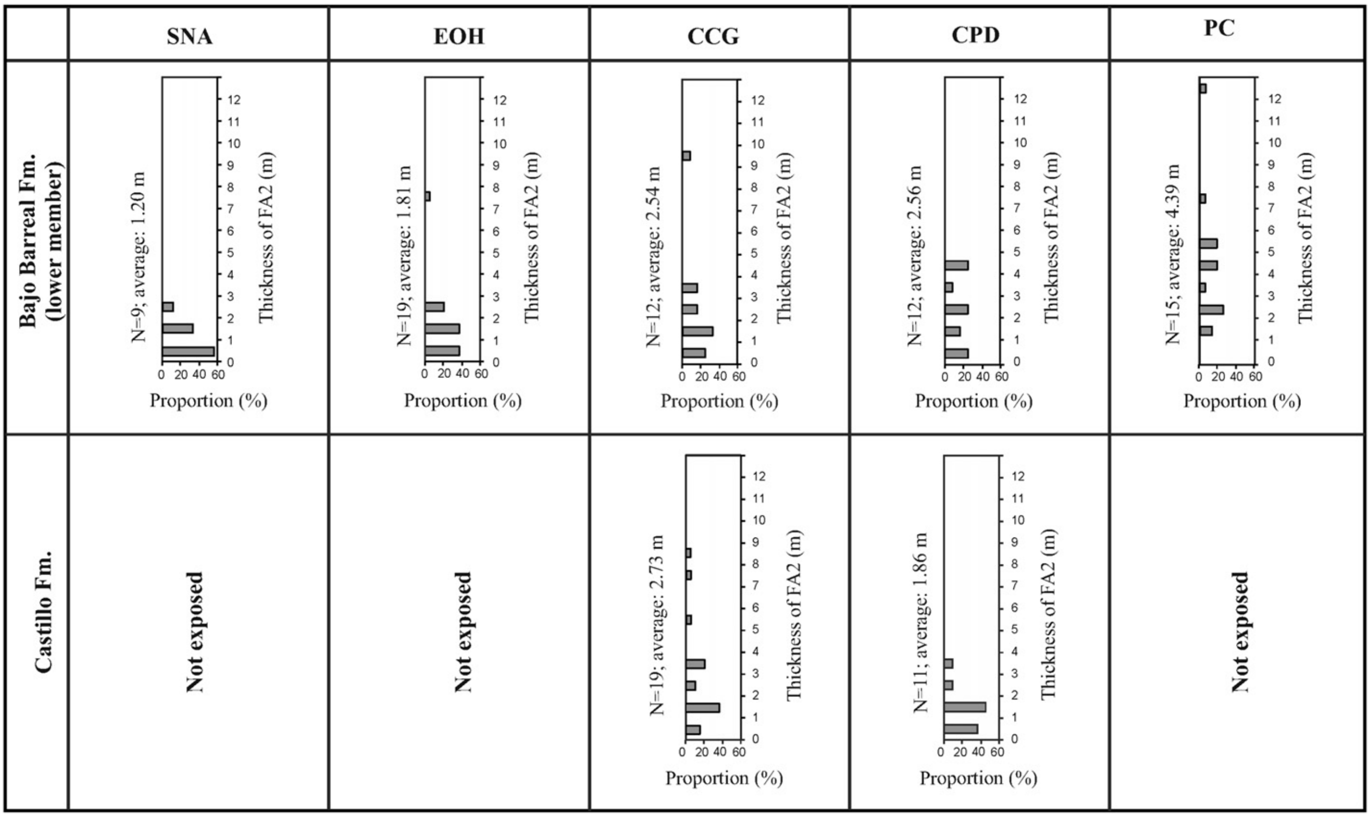

Fig. 16. Histograms of thickness for fluvial channel belt deposits from the Castillo and Bajo Barreal formations discriminated by locality.

between the more representative facies associations. The Castillo Formation was deposited in a fluvial setting with intermittent ash-falls from a western source (cf. Paredes et al., 2009, 2011; Fig. 18A). Ash-fall deposits (FA1) uniformly mantled the topography (cf. Wright et al., 1980; Houghton et al., 2000) and were partially to fully reworked by fluvial channeled flows and unconfined flood events. Fluvial channel belts (FA2) redistributed the primary pyroclastic material and also transported older sand-sized detritus from a volcaniclastic source area located to the east of the Patagonian Batholith, in the western margin of the San Jorge Basin

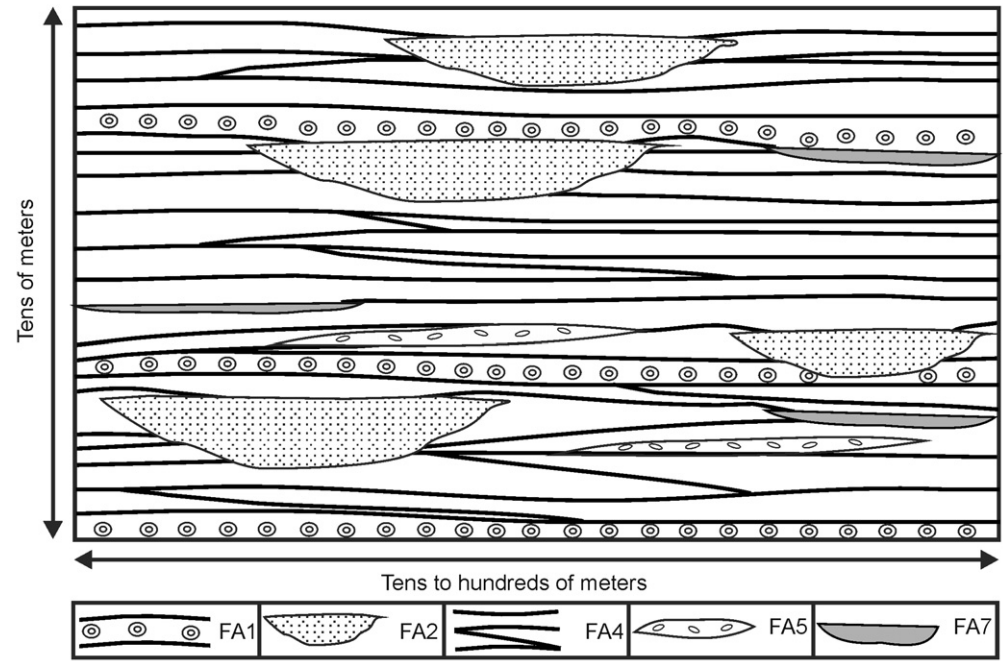

Fig. 17. Schematic representation of vertical and lateral relationships between pedogenically modified ash-falls (FA1), fluvial channel belts (FA2), tuffaceous sheet-floods (FA4), sandy debris-flows (FA5) and shallow lakes (FA7). It was constructed from observations of very well exposures of the Castillo Formation at CPD and the lower member of the Bajo Barreal Formation at CPD and PC.

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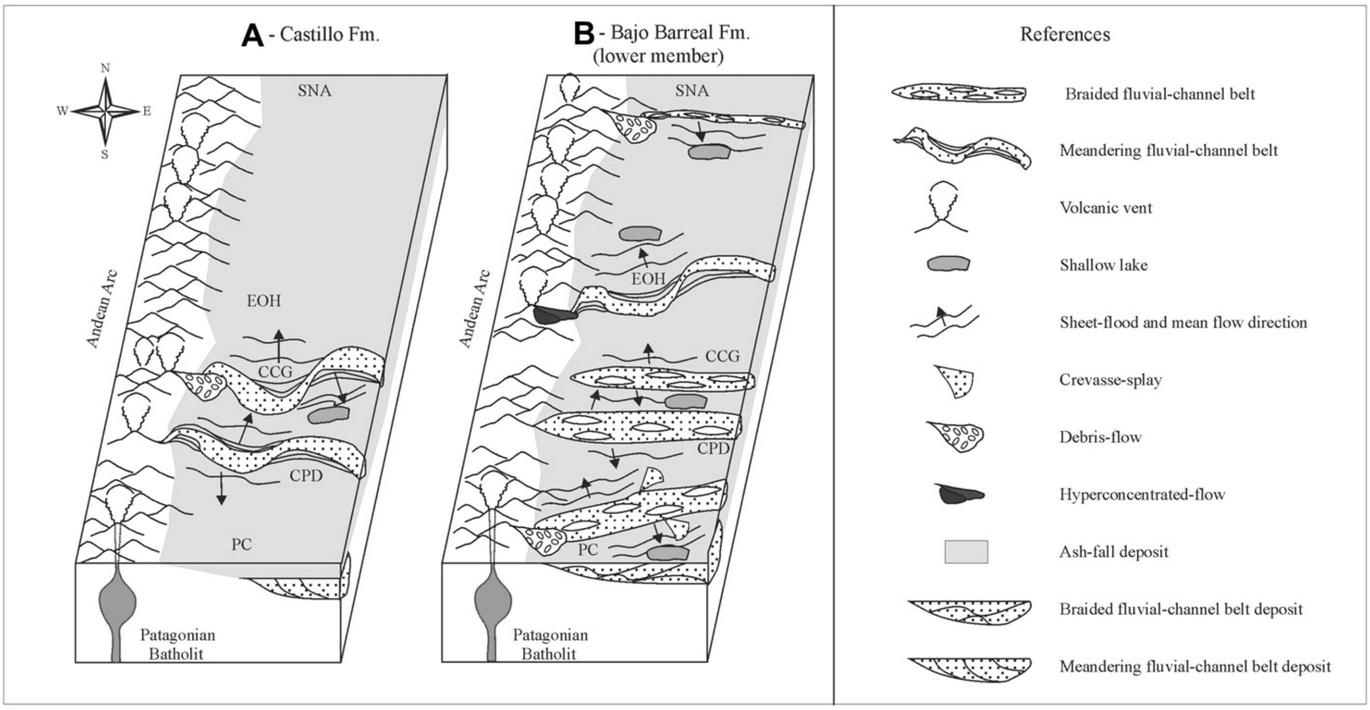

Fig. 18. Paleoenvironmental reconstruction of the Castillo (A) and Bajo Barreal (B) formations in the western sector of the San Jorge Basin.

(Umazano, 2009; Umazano et al., 2009). Fluvial channel belts flowed eastward and were composed of permanent, single channels with point(?) bars attached to their margins. These channel belts (FA2) were relatively thicker at CCG than at CPD to the south.

Construction of the adjacent floodplain (see Fig. 18A) mainly occurred from overbank flows as sheet-floods (FA4) and in minor proportion by preservation of primary pyroclastic deposits (FA1), debris-flows (FA5) and shallow lacustrine sedimentation (FA7). FA5 and FA7 only participate as aggradational floodplain mechanisms at CCG. Frequent overbank flows removed primary or reworked pyroclastic sediments, providing fine-grained material to the distal topographic depressions where shallow lakes were located (cf. Rust, 1978). Paleocurrent indicators suggest that the sheet-floods flowed at nearly right angles to the E–SE mean paleocurrent recorded in the associated fluvial channel belts. On the other hand, aggradation of channel belts during high sediment load episodes also could have dammed tributaries and generated shallow lakes (Manville, 2001; Manville et al., 2005, 2009b). Debris-flows (FA5) recorded in this unit could be related to collapse of the volcanic edifices (cf. Voight and Elsworth, 1997; Ur et al., 2000; Vallance, 2000) or remobilization of proximal pyroclastic deposits triggered by torrential rains or snow melting (cf. Smith and Lowe, 1991; Hodgson and Manville, 1999; Manville et al., 2000; van Westen and Daag, 2005). In modern environments, such flows can travel more than 100 km from the source (e.g. Mothes et al., 1998), which is consistent with the estimated distance for the vent edifices (cf. Umazano, 2009). Nevertheless, a provenance from closer sources cannot be entirely discarded. During short periods of negligible sedimentation rate, floodplain deposits were weakly pedogenized with development of apedal soils without differentiation of horizons.

The lower member of the Bajo Barreal Formation was also deposited in a fluvial setting with discontinuous influx of ash-falls from the west (cf. Umazano et al., 2008a, 2009; Fig. 18B). Fluvial reworking of the primary pyroclastic deposits (FA1) by channeled and unconfined flows was very common. Although the depositional environment is similar to that interpreted for the underlying Castillo Formation, there was a substantial change in the pattern of the fluvial channel belts, subtle differences in floodplain constructive processes, and a greater variability in water discharge. Except for EOH, all sections contain deposits of permanent and braided fluvial channel belts (FA2) with an eastward drainage direction. In EOH, fluvial channel belts were single-channeled with channel-margin bars. There, episodic water flows allowed soil development on channel floors. Several fluvial channel belts from all localities, both braided and single channel types, record high-energy flow deposits indicating important fluctuations in water discharge (Tunbridge, 1981; Dreyer, 1993; Long, 2006). From north to south, fluvial channel belt deposits are progressively thicker (cf. Sciutto, 1981).

The observed contrast in the fluvial channel styles between Castillo and Bajo Barreal formations is not correlated with a change in the constructive mechanisms of the floodplains. The dominant and ubiquitous aggradational process was the remobilization of ash-fall deposits (FA1) by sheet-floods (FA4) produced by channel overflows (Fig. 18B). Sedimentation in shallow lakes (FA7) also contributed to floodplain development at most localities (SNA, EOH, CCG and PC). Locally, minor floodplain development occurred from deposition of hyperconcentrated flows (FA6 in EOH), crevasse-splays (FA3 in PC) and debris-flows (FA5 in SNA and PC). Crevasse-splay and sheet-flood deposits could represent proximal and distal parts of the same overflow event (e.g. McKee et al., 1967; Fisher et al., 2007; Nichols and Fisher, 2007). As a rule, intervals with negligible sedimentation rate are indicated by massive soils lacking development of horizons (sub-facies P2). Only the basal part of the succession at SNA locality exhibits a greater pedogenic development, with paleosols showing two horizons with a pedal structure (sub-facies P1). This suggests a relatively low sedimentation rate for this part of the succession, probably reflecting a greater distance from active channels (e.g. Kraus, 1986, 1997).

7. Stacking pattern

The vertical stacking pattern of fluvial channel belt deposits for each locality is used to distinguish system tracts (*sensu* Legarreta et al., 1993; Fig. 19). Unconventional systems tracts such as "forestepping"

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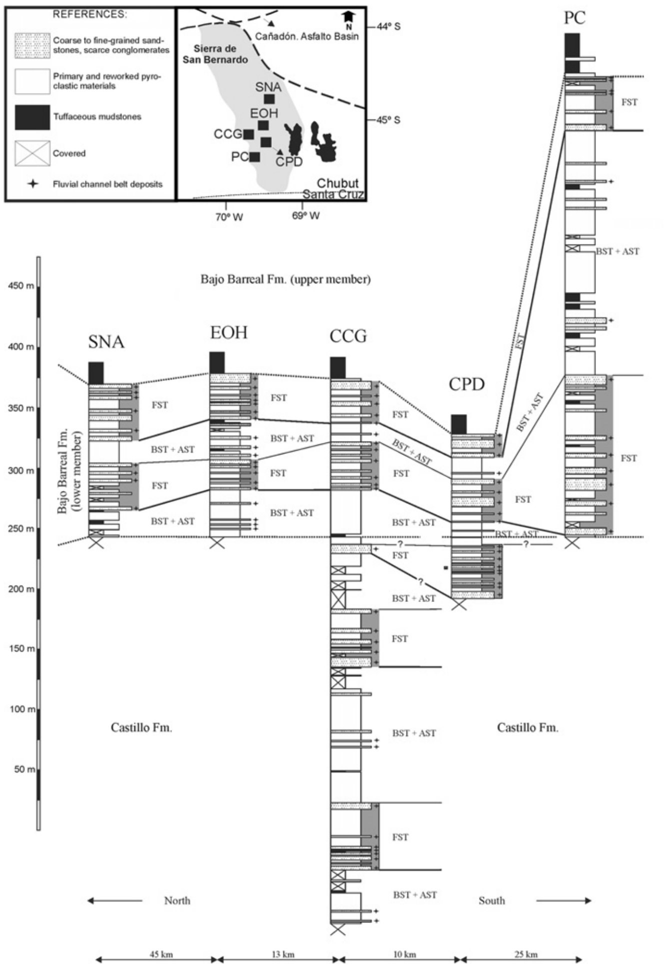

Fig. 19. Synthetic stratigraphic sections of the Castillo Formation and the lower member of the Bajo Barreal Formation showing their stacking patterns using sequence stratigraphy terms (FST: forestepping system tract, BST: backstepping system tract, AST: aggradational system tract).

(FST), "backstepping" (BST) and "aggradational" (AST), mainly defined by the ratio of channel sandstones to floodplain fine-grained deposits and channel sandstone thickness, have been used for regional correlation of fully fluvial strata (e.g. Olsen et al., 1995; Leckie et al., 2004). This is a useful method in successions without discontinuity surfaces or unconformities (Catuneanu et al., 2009), as it can be observed in seismic lines (Fitzgerald et al., 1990) and outcrops (Umazano, 2009). In this context, the FSTs are characterized by a major density of channel belt deposits which, in relation to the remaining system tracks, are commonly thicker and coarser-grained. The discrimination between BSTs and ASTs was not possible because the maximum flood surfaces cannot be recognized.

The Castillo Formation has an average percentage of channeled facies of 26% (16% in CCG and 36% in CPD; Table 3). Nevertheless, a concentration of channeled facies (up to 50% approximately) is detected in three recognized FST, in which the thicker and coarser-grained fluvial channel belt deposits also occur (Fig. 19); two in the CCG section (basal and middle part) and one in the uppermost interval of the CPD section. The FST recognized in CPD section may be equivalent to a thicker fluvial channel belt deposit of the upper part of CCG section. These FST are separated by deposits with minor proportion of channeled facies (less than 10%), which are assigned to BST and AST (Fig. 19).

The lower member of the Bajo Barreal Formation does not exhibit a substantial change in the proportion of fluvial channel-belt deposits compared with the Castillo Formation (average percentage of channeled facies is 19%). In particular, the lowest proportion of channeled deposits is detected at the SNA section (8%); whereas higher and relatively uniform values are observed in the remaining localities (ranging from 17% to 25%; Table 3). In all localities, two FST were distinguished in the lower member of the Bajo Barreal Formation (Fig. 19). These FST contain up to 50% of channeled facies and the thicker and coarser-grained fluvial channel belt deposits. The intervening BST+AST deposits typically have minor participation (less than 10%) or absence of channeled facies.

8. Controls on fluvial sedimentation

The major allocyclic controls in continental basins and particularly on fluvial sedimentation include climate, tectonism, eustatic sea-level changes and volcanism (e.g. Smith, 1991; Miall, 1996, 2000; Bridge, 2006; Catuneanu et al., 2009). The vertical and lateral uniformity of the macro and micro-features of most paleosols (in the Castillo Formation and the lower member of the Bajo Barreal Formation) suggests that the topography, climate and vegetation cover were similar during their deposition (cf. Kraus, 1987; Kraus and Aslan, 1999). This is supported by the absence of floodplain facies with contrasting climatic significance such as aeolian or evaporite deposits (cf. Glennie, 1987; Langford and Chan, 1989; Smoot and Lowenstein, 1991; Parrish, 1998), and a palynomorph assemblage recovered from the subsurface of the eastern sector of the basin, which suggests temperate to warm humid climate (Archangelsky et al., 1994). At Cerro Ballena (46° 41′ 01″ S; 69° 12′ 19″ W), located to the southeast of the study area and close to the main basin depocenter, paleosols with different degrees of development have been defined in the Bajo Barreal Formation; this differentiation was only based in macroscopic pedofeatures (Legarreta et al., 1993). The different degree of paleosol development in this case may record climatic signals or episodes of landscape stability associated to the common syn-sedimentary tectonic activity registered in this part of the basin (Georgieff and Di Benedetto, 2006). In other hand, the evidence for a discontinuous water discharge in the fluvial channel belt deposits of the lower member of the Bajo Barreal Formation would represent seasonality in the catchments (e.g. Parrish, 1998; Blum and Tornqvist, 2000; Cecil, 2003).

Evidences indicating intrabasinal tectonism during deposition of both units in the analyzed localities, such as thickness changes in the fluvial channel belt deposits related to folds and faults (e.g. Bridge, 2006), or adjacent fluvial channel belt deposits with near orthogonal paleocurrents and without signs of nodal avulsion (e.g. Paredes et al., 2007) were not found. Moreover, the uniform composition and similar provenance of the channel sandstones in both units (Umazano et al., 2009; Umazano and Visconti, 2009) suggests an absence of significant tectonic uplift in the source area (cf. Bridge, 2006). However, syn-sedimentary faulting has been reported toward the east and southeast of the study area, closer to the main basin depocenter, from outcrops and subsurface data (Hechem, 1998; Georgieff and Di Benedetto, 2006; Georgieff et al., 2009). The possible influence of this tectonic activity on depositional systems is discussed in the next paragraph, in which base-level changes are considered.

In order to evaluate the influence of eustatic sea-level changes, it is important to clarify that two paleogeographic schemes were proposed for Cretaceous time in the San Jorge Basin. Fitzgerald et al. (1990) defined two Cretaceous depositional sequences; the lower is equivalent to the D-129/Matasiete depositional system and the upper includes the Castillo and Bajo Barreal formations. According to these authors, the upper depositional sequence represents fluvial systems with the Atlantic Ocean as absolute base-level. Conversely, Hechem (1998) inferred a centripetal drainage system

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without oceanic connection, with a basin center located in the eastern sector of the basin for the lower member of the Bajo Barreal Formation. Considering the Hechem's model, which is based on greater amount of information, the stacking pattern of the channel-belt deposits recognized in the studied units would have been linked to relative base-level changes. In particular, the four (?) forestepping system tracts (FST) represent conditions of low deposition rates and restricted floodplain width (i.e. limited accommodation space) as a response to base-level fall, whereas the backstepping and aggradational system tracts (BST and AST, respectively) record relatively higher deposition rates on a broad alluvial plain (i.e. high accommodation space) in response to base-level rise (Legarreta et al., 1993; Shanley and McCabe, 1994). In this context, the extensional syn-sedimentary faulting detected in the eastern sector of the basin (Hechem, 1994, 1998; Georgieff and Di Benedetto, 2006; Georgieff et al., 2009) suggests that tectonic activity would have caused relative base-level fluctuations and concomitantly the high density of the channeled facies with local variations. Particularly, the trend to southward increase in the thickness of the fluvial channel belt deposits in the lower member of the Bajo Barreal Formation could be related to proximity to base-level, which typically increases the sensitivity of the fluvial system (e.g. Blum and Price, 1998; van Heijst and Postma, 2001). This interpretation is supported by the presence of stronger-developed paleosols in the marginal areas with lower sedimentation rate, (cf. Wright and Marriott, 1993; Kraus and Aslan, 1999) such as in section SNA. Although syntectonic evidences in the study area were not detected, the local variations in thicknesses and vertical density (stacking) of channeled facies may be explained by a different accommodation space due to local tectonic activity.

The Castillo Formation and the lower member of the Bajo Barreal Formation are pyroclastic-rich successions that record the interplay between fluvial systems and ash-falls derived from a coeval volcanic arc located approximately 120 km away (Umazano, 2009; Umazano et al., 2009). Considering the conceptual background for ancient fluvial systems affected by explosive volcanism (Smith, 1991), both units could represent syn-eruptive periods. This interpretation suggests that the fluvial channel belts recorded in the Castillo Formation could be related to low magnitude individual eruptions, which would have produced scarce amount of pyroclastic material that did not exceed the geomorphic threshold for aggradation and precluded the development of braided rivers. In this context, the general change from meandering systems in the Castillo Formation to braided systems in the lower member of the Bajo Barreal Formation could represent an increase in the sediment flux due to enhanced volcanic activity in the arc. In the case of the lower member of the Bajo Barreal Formation at EOH, a locally reduced pyroclastic influx could be responsible for the single channel configuration, although the influence of other autocyclic factors cannot be discarded (e.g. relative stability of the channel margins; Schumm, 1985).

9. Conclusions

The Castillo Formation and the lower member of the Bajo Barreal Formation (Cretaceous of Patagonia, Argentina) record sedimentation in fluvial systems that drained from the west. These fluvial systems were affected by frequent ash-falls, and common remobilization of friable pyroclastic material by water and gravity processes, and by changes in the relative base-level, which caused typical stacking patterns according with the concepts of continental sequence stratigraphy. The origin of base-level changes could have been related to tectonic activity. The studied units were deposited without evidence of intrabasinal climatic changes, although some channeled deposits of the lower member of the Bajo Barreal Formation show indications of important water discharge variation probably linked to seasonal climate in the catchments.

The Castillo Formation represents permanent and single-channel rivers with channel-margin bars, which mainly transported volcaniclastic sand-dominated bed-loads. Floodplains commonly developed from aqueous reworking of pyroclastic substrates by sheet-floods, debris-flows and through shallow lacustrine sedimentation. Preservation of primary pyroclastic deposits is rare. According with Smith (1991), the unit could be considered as a fully syn-eruptive interval, where fluvial channel belts were not significantly affected by low-intensity volcanic eruptions, which prevented the modification of the channel pattern.

The overlying lower member of the Bajo Barreal Formation mostly records braided fluvial channel belts with more variable water discharge and, in one locality, single-channel rivers. Both river types mainly transported sand-sized volcaniclastic sediment as bed-load and flowed eastward. Constructive processes of the adjacent floodplains are similar to those of the Castillo Formation, although deposits of hyperconcentated flows and crevasse-splays are found locally. The braided channels and overbank facies are considered syn-eruptive deposits (cf. Smith, 1991).

The detected environmental changes are mostly consistent with the widely used facies model for fluvial volcaniclastic successions. The temporal evolution from meandering to braided systems recorded in the studied units could represent an increase in sediment flux due to a trend toward more intense volcanic activity in the arc.

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