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Mechanisms of aggradation in fluvial systems influenced by explosive volcanism: An example from the Upper Cretaceous Bajo Barreal Formation, San Jorge Basin, Argentina

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Abstract

The Late Cretaceous succession of the San Jorge Basin (Patagonia, Argentina) records different continental settings that interacted with explosive volcanism derived from a volcanic arc located in the western part of Patagonia. This paper discusses the contrasting aggradational mechanisms in fluvial systems strongly influenced by explosive volcanism which took place during sedimentation of the Bajo Barreal Formation. During deposition of the lower member of the unit, common ash-fall events and scarce sandy debris-flows occurred, indicating syn-eruptive conditions. However, the record of primary pyroclastic deposits is scarce because they were reworked by river flows. The sandy fluvial channels were braided and show evidence of important variations in water discharge. The overbank flows (sheet-floods) represent the main aggradational mechanism of the floodplain. In places, subordinate crevasse-splays and shallow lakes also contributed to the floodplain aggradation. In contrast, deposition of the upper member occurred in a fluvial–aeolian setting without input of primary volcaniclastic detritus, indicating inter-eruptive conditions. The fluvial channels were also braided and flowed across low-relief floodplains that mainly aggraded by deposition of silt-sized sediments of aeolian origin (loess) and, secondarily by sheet-floods.

The Bajo Barreal Formation differs from the classic model of syn-eruptive and inter-eruptive depositional conditions in the presence of a braided fluvial pattern during inter-eruptive periods, at least at one locality. This braided fluvial pattern is attributed to the high input of fine-grained pyroclastic material that composes the loessic sediments.

Keywords: Alluvial aggradation; Explosive volcanism; Cretaceous; San Jorge Basin; Argentina

1. Introduction

Explosive volcanism can introduce large volumes of sediments into different types of marine and continental settings. In alluvial environments, the influx of pyroclastic flows, surges or ash-fall events strongly influences the landscape and sedimentation in a number of ways. An abundant volcaniclastic input can modify topography and drainage patterns (Smith, 1991), and can eliminate sediment-stabilizing vegetation (Vessell and Davies, 1981). Primary volcaniclastic deposits are commonly redistributed immediately after eruptions by processes such as debris-flows, hyperconcentrated-flows and fluvial flows (e.g. Kataoka and Nakajo, 2002). In some cases, reworked volcaniclastic deposits are better represented in the rock record than primary volcaniclastic deposits (O'Halloran and Gaul, 1997). Furthermore, the voluminous but discontinuous input of tephra induces changes in equilibrium profiles of rivers and generates cycles of

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sedimentation and incision that correspond with syn-eruptive and inter-eruptive periods, respectively (Smith, 1987, 1991). In contrast with non-volcanic alluvial settings, where aggradation and basin fill are primarily related to basin subsidence and/or sediment input from adjacent uplifts (Miall, 1996), most aggradation occurs during the short-lived syn-eruptive periods in fluvial volcaniclastic environments (Smith, 1991).

The influence of explosive volcanism on alluvial sedimentation in near-vent locations has been widely reported (e.g. Smith, 1991; O'Halloran and Gaul, 1997; Kataoka and Nakajo, 2002; Martina et al., 2006) and facies models have been proposed (e.g. Cas and Wright, 1987; Smith, 1991). However, studies on the effects of abundant input of tephra on distal sites are scarce (e.g. Moore, 1991; Shane, 1991; Nakayama and Yoshikawa, 1997). In both settings, detailed investigations of the processes of alluvial aggradation in fluvial systems with frequent ash-fall events are few (e.g. Nakayama and Yoshikawa, 1997) and they therefore remain poorly understood.

Accumulation of the Middle Jurassic to early Miocene succession in central Patagonia, Argentina, was strongly influenced by widespread volcaniclastic input. The Bajo Barreal Formation from the Cretaceous Chubut Group (Lesta et al., 1980) of the San Jorge Basin, central Patagonia, represents a record of fluvial channels and thicker floodplain deposits, which are mainly composed of reworked tuffs (Bridge et al., 2000; Tunik et al., 2004; Umazano et al., 2005, 2006a). Although the formation is almost entirely composed of volcaniclastic detritus, the precise location of the source volcanic vents is unknown. The high quality of outcrops of the Bajo Barreal Formation at selected localities offers the opportunity to examine the aggradational mechanisms in fluvial systems strongly influenced by ash-fall events. The characterization and interpretation of fluvial reworking processes and their lateral (spatial) and vertical (temporal) variability is emphasized here.

2. Geological setting and study area

The San Jorge Basin is located in central Patagonia (between 44–47° S and 66–71° W) covering the southern sector of Chubut province and the northern sector of Santa Cruz province, Argentina (Fig. 1). It is the first and most prolific oil basin of the country. The basin boundaries are (Fig. 1): the Nordpatagonian Massif and Cañadón Asfalto Basin to the north, the Deseado Massif to the south, the Andes to the west and the continental margin of the Atlantic Ocean to the east (Sylwan, 2001).

The San Jorge Basin is an extensional intracontinental trough developed on Palaeozoic continental crust, and linked to the break-up of Gondwana and opening of the South Atlantic Ocean during Jurassic times (Barcat et al., 1989; Fitzgerald et al., 1990). The basin was filled with pyroclastic and epiclastic sediments from the Jurassic to the Miocene (Fig. 2). The Middle Jurassic–Early Cretaceous deposits compose the first sediments associated with active faulting and extension commonly ascribed to a synrift stage (e.g. Fitzgerald et al., 1990; Figari et al., 1999; Bellosi et al., 2002). Middle Jurassic, NW–SE trending half-grabens were partially filled with dominantly continental volcanic sediments assigned to the Bahía Laura and Lonco Trapial groups (Lesta and Ferello, 1972). During the Early Cretaceous, lacustrine sediments of the Las Heras Group were deposited in grabens and half-grabens, with depocenters distributed between blocks composed of the Lonco Trapial Group (Bellosi et al., 2002).

A new phase of sedimentation that started in the Early Cretaceous is represented by the Chubut Group (Lesta and Ferello,

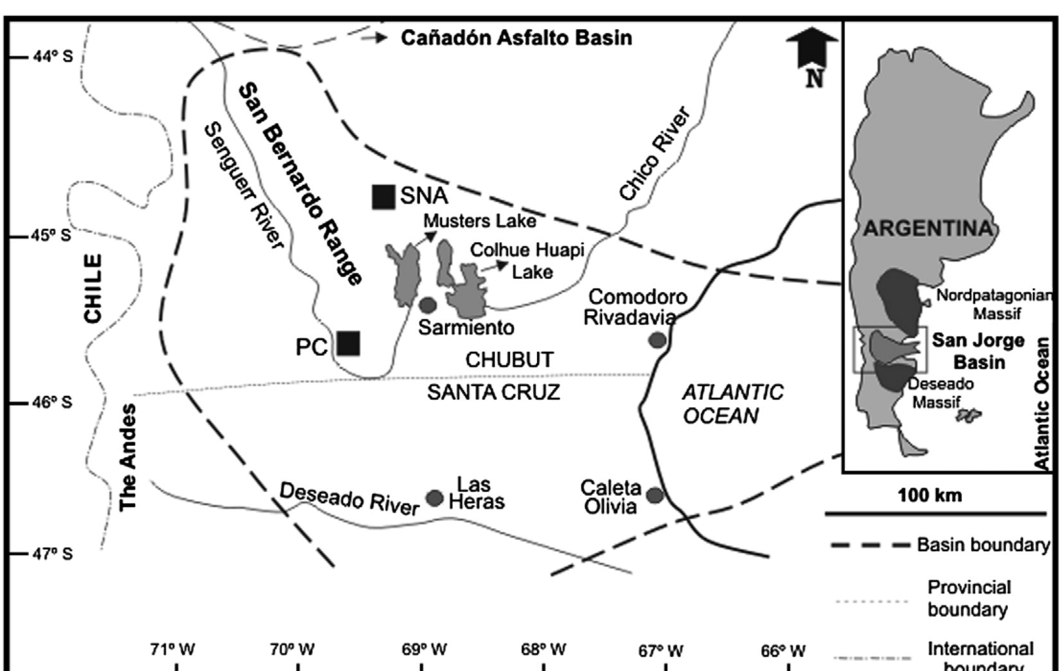

Fig. 1. Location map for the San Jorge Basin, Argentina, showing the studied localities: Puesto Confluencia (PC) and Sierra Nevada Anticline (SNA).

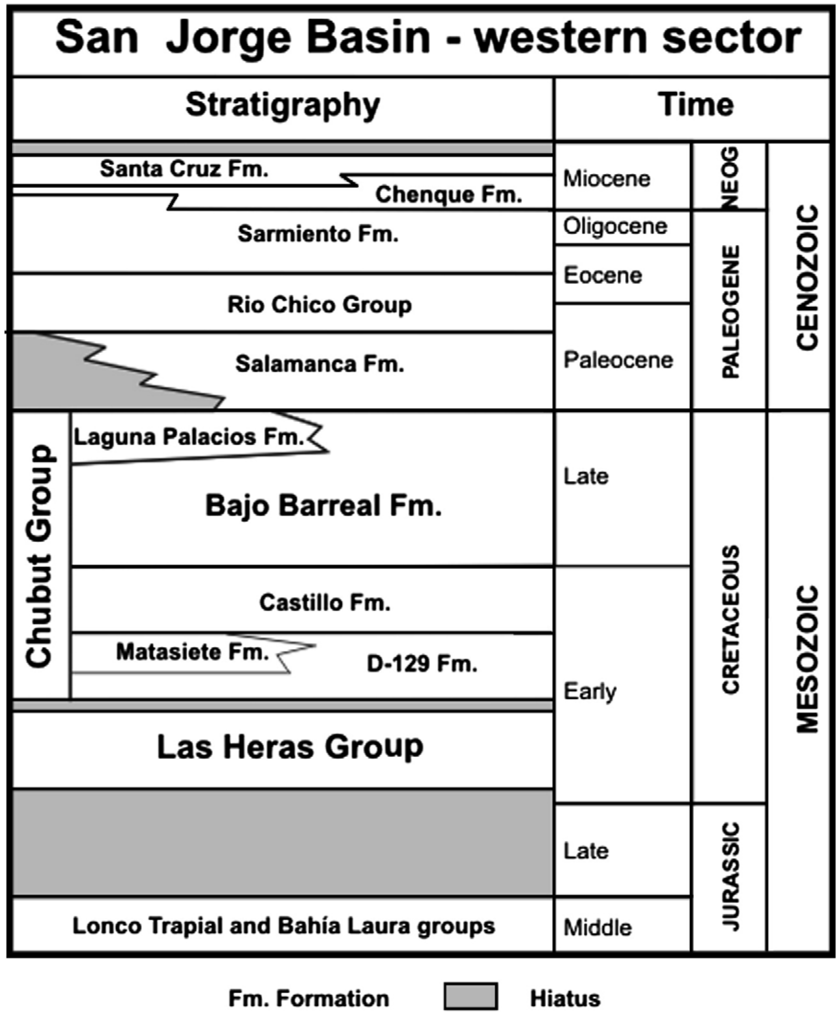

Fig. 2. Stratigraphy of the western sector of the San Jorge Basin (modified from Legarreta and Uliana, 1994; Bellosi and Jalfin, 1996; Bellosi et al., 2002).

1972), which is interpreted as the deposits of the sag stage (Fitzgerald et al., 1990) or a new rifting event (Figari et al., 1999). The Chubut Group mainly overlies the Jurassic Lonco Trapial Group and constitutes the asymmetrical filling of a basin elongate in a W–E direction (Jalfin et al., 2002). The sedimentary succession of the Chubut Group is composed of continental sediments with abundant primary volcaniclastic material (Sciutto, 1981) derived from westerly sources (Tunik et al., 2004). The Chubut Group outcrops are restricted to the western sector of the basin, where five units are recognized, in ascending order: the D-129, Matasiete, Castillo, Bajo Barreal and Laguna Palacios formations (Fig. 2). The D-129 Formation includes organic-rich lacustrine and marginal-lacustrine sediments, which are the main source rocks in the basin (Uliana et al., 1999; Barreda et al., 2003), whereas the overlying formations act as hydrocarbon reservoirs (Jalfin et al., 2005). Towards the margin of the basin, the lacustrine facies are replaced by fluvial deposits of the Matasiete Formation (Sciutto, 1981; Paredes et al., 2003, 2007). The overlying Castillo and Bajo Barreal formations were deposited in fluvial to lacustrine environments, accompanied by frequent ash-fall events (Bridge et al., 2000). Two informal members can be distinguished in the Bajo Barreal Formation (Sciutto, 1981). The lower member is mainly composed of laterally continuous tuff beds interbedded with lenses of fluvial sandstones that increase in abundance toward the top of the member. The upper member is dominated by siltstones and subordinate thinner sandstone lenses. The sandstone bodies of the Bajo Barreal Formation constitute the main hydrocarbon reservoirs of the basin (Rodríguez and Littke, 2001; Homovc and Lucero, 2002). The upper unit of the Chubut Group is the Laguna Palacios Formation, a tuffaceous loess–palaeosol succession, which records the final continental sedimentation in the San Jorge Basin (Bellosi and Sciutto, 2002). Two episodes of Atlantic marine transgressions occurred in Maastrichtian and Miocene times which resulted in alternation of marine (Salamanca and Chenque formations) and continental (Río Chico Group and Sarmiento and Santa Cruz formations) sedimentation in the basin (Legarreta and Uliana, 1994; Bellosi, 1995).

The Chubut Group mainly crops out in the San Bernardo Range, which originated by compression linked to Andean tectonism (Peroni et al., 1995). The San Bernardo Range is a fold belt with an NNW–SSE orientation, a length of approximately 600 km and a width of less than 100 km in most places. This study was conducted in two localities of the San Bernardo

Range, called Puesto Confluencia and Sierra Nevada Anticline, both in the Chubut province and located approximately 68 km apart (Figs. 1 and 3). Puesto Confluencia (45° 43’ 33” S; 69° 41’ 11” W) is located on the eastern margin of the Senguerr River, at the southwestern end of the San Bernardo Range. At this locality, the Bajo Barreal Formation is 450 m thick and dips 5° to SW, composing the western limb of a faulted anticline with an axial trace oriented approximately N–S (Sciutto, 1999; Umazano et al., 2005). The second section of the Bajo Barreal Formation is 176 m thick and was measured in the eastern limb of the Sierra Nevada Anticline (44° 50’ 50” S; 69° 25’ 21” W), where the strata dip 10° to NE. This anticline is an asymmetrical structure with an NW–SE axial trace and northward plunge (Sciutto and Martínez, 1996). In both localities, the studied sections overlie poorly exposed pyroclastic rocks assigned to the Castillo Formation (although the contact is covered) and are covered by aeolian and fluvial sediments of the Laguna Palacios Formation (Fig. 3). At Puesto Confluencia, the Laguna Palacios–Bajo Barreal contact is covered. Fluvial conglomerates and sandstones of the Río Chico Group overlie the partially eroded uppermost section of the Laguna Palacios Formation.

3. Methods and terminology

The measurement of the sedimentary logs was made using standard sedimentologic techniques. Rock names for mixtures of pyroclastic and epiclastic fragments are based in the proportion of the pyroclastic fraction and the average grain-size (Fisher and Schmincke, 1984). Shapes of sediment bodies were classified according to width, length and thickness (Bridge, 1993). Some selected sandstone bodies were studied using the architectural element analysis technique (Miall, 1985). Soil thin-section descriptions are after Bullock et al. (1985).

4. Facies analysis

The description and interpretation of the different sedimentary facies and facies associations (Fa) are summarized in Tables 1 and 2, respectively. In both measured logs, the lower member is composed of channel sandstones (Fa2) interbedded with floodplain deposits composed of primary and reworked volcaniclastic strata, tuffaceous sandstones and tuffaceous siltstones (Fig. 4). Floodplain development of this member included pyroclastic ash-

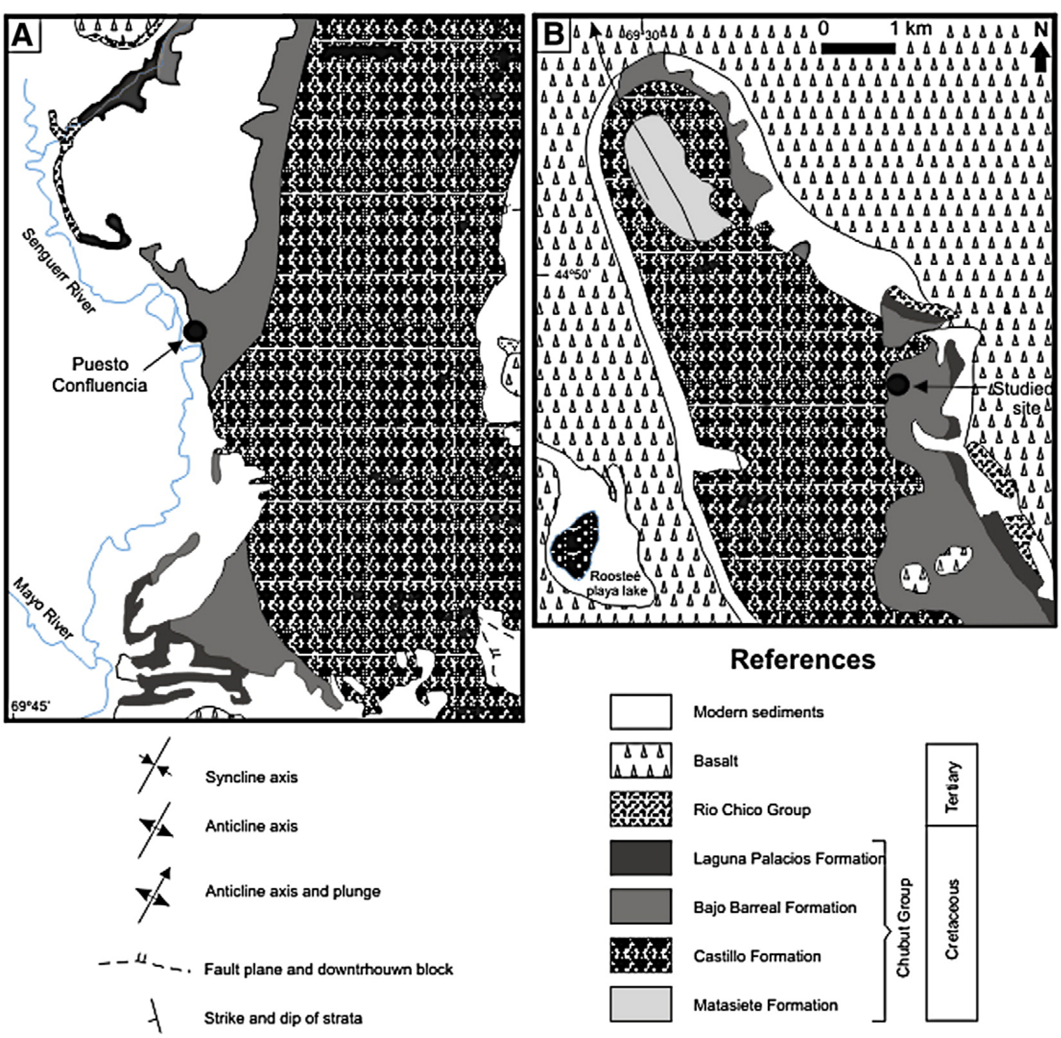

Fig. 3. Geological maps of the studied localities. (A) Puesto Confluencia area (after Sciutto, 1999). (B) Sierra Nevada Anticline (modified from Sciutto and Martínez, 1996).

Table 1
Description and interpretation of facies

Facies	Lithology and texture	Sedimentary structures	Fossil content	Interpretation
T1	Well-sorted, fine-grained, vitric tuff	Diffuse parallel stratification. Levels with R-type accretionary-lapilli	–	Single ash-fall event
T2	Well-sorted, fine-grained, vitric tuff	Massive. Levels with R-type accretionary-lapilli	–	Multiple ash-fall events
T3	Moderately well-sorted, medium- to fine-grained tuff, intraclasts	Massive, rare normal grading, frequent scours at base	Localized important bioturbation (*Taenidium barretti*, *Skolithos* and undetermined burrows) Root traces. Dinosaur bones	Stream-flow during high discharge conditions
T4	Moderately well-sorted, medium- to fine-grained tuff, intraclasts	Deformed to undisturbed horizontal lamination	Rare levels with burrows and/or root traces	Upper stage plane-bed flow conditions
T5	Moderately well-sorted, medium- to fine-grained tuff, intraclasts	Trough cross-bedding	Rare levels with burrows and/or root traces	Migration of 3D dunes
P	Tuff, tuffaceous sandstone, tuffaceous siltstone	Massive, macro and microscopic pedofeatures	Burrows and root traces. In places, highly bioturbated	Pedogenic processes on volcaniclastic deposits
G1	Moderately well-sorted, clast or matrix-supported, fine-grained conglomerate	Trough cross-bedding	Abundant gymnosperm logs in places	Migration of 3D dunes
S1	Moderately well-sorted, coarse- to fine-grained sandstone and tuffaceous sandstone	Trough cross-bedding	Abundant gymnosperm logs and root traces at certain levels	Migration of 3D dunes
S2	Moderately well-sorted, coarse- to fine-grained sandstone and tuffaceous sandstone	Horizontal lamination, in places deformed	–	Upper stage plane-bed flow
S3	Moderately well-sorted, medium- to fine-grained sandstone and tuffaceous sandstone	Massive, common scours at base	–	Stream-flow during high discharge conditions
S4	Moderately well-sorted, medium-grained tuffaceous sandstone	Planar cross-bedding	–	Migration of 2D dunes
S5	Moderately well-sorted, medium-grained tuffaceous sandstone	Asymmetrical ripples	–	Migration of ripples
S6	Moderately well-sorted, medium-grained tuffaceous sandstone	Low-angle cross-bedding	–	Migration of washed-out or humpback dunes
S7	Poorly-sorted, fine-grained tuff with scarce gravel-sized clasts	Massive	–	Sub-aerial debris-flow
F1	Tuffaceous siltstone	Massive or with horizontal lamination	–	Settling from suspension
F2	Tuffaceous siltstone	Wave ripple structures	–	Settling from suspension Influence of the waves
F3	Tuffaceous siltstone	Structureless or with diffuse parallel stratification	–	Fine-grained aeolian deposition of pyroclastic detritus

fall events (Fa1), crevasse-splays (Fa3), sheet-floods (Fa4), sandy debris-flows (Fa5) and shallow lacustrine sedimentation (Fa6). In contrast, the upper member is composed of tuffaceous siltstones of aeolian origin (Fa7) interbedded with channel sandstones (Fa2) and sheet-flood deposits (Fa4). Explosive volcanism coeval with the sedimentation of Bajo Barreal Formation is intermediate to acid in composition, as suggested by geochemical analysis of tuffaceous floodplain deposits.

Table 2
Sedimentological characteristics and interpreted environment of deposition of facies associations

Facies association	Facies	Lower bounding surface	Geometry	Interpretation
Fa1	T1, T2 and P	Non-erosional	Sheet (mantle bedding and good lateral continuity)	Pedogenically modified pyroclastic-fall deposits
Fa2	G1 and S1. S2, S3 and F1 are in places	Erosional and concave upward	Sheet to plane convex	Fluvial channel deposits
Fa3	S1, S3 and F1	Smooth and flat erosional	Lobe to sheet	Crevasse-splay lobe
Fa4	T3, S3 and P are dominant. Minor amounts of T4, T5, S1 and S2 Rare occurrence of S4, S5 and S6	Planar and slightly erosional	Sheet	Sheet-flood deposits interbedded with palaeosols
Fa5	S7, S1 and P	Undulatory and locally erosional	Sheet or plano-convex	Sub-aerial debris-flow deposits and palaeosols
Fa6	F1 and F2	Non-erosional and planar or concave upward	Sheet to channel	Shallow lacustrine deposits
Fa7	F3 and P	Non-erosional	Sheet (mantle bedding)	Loess–palaeosol deposits

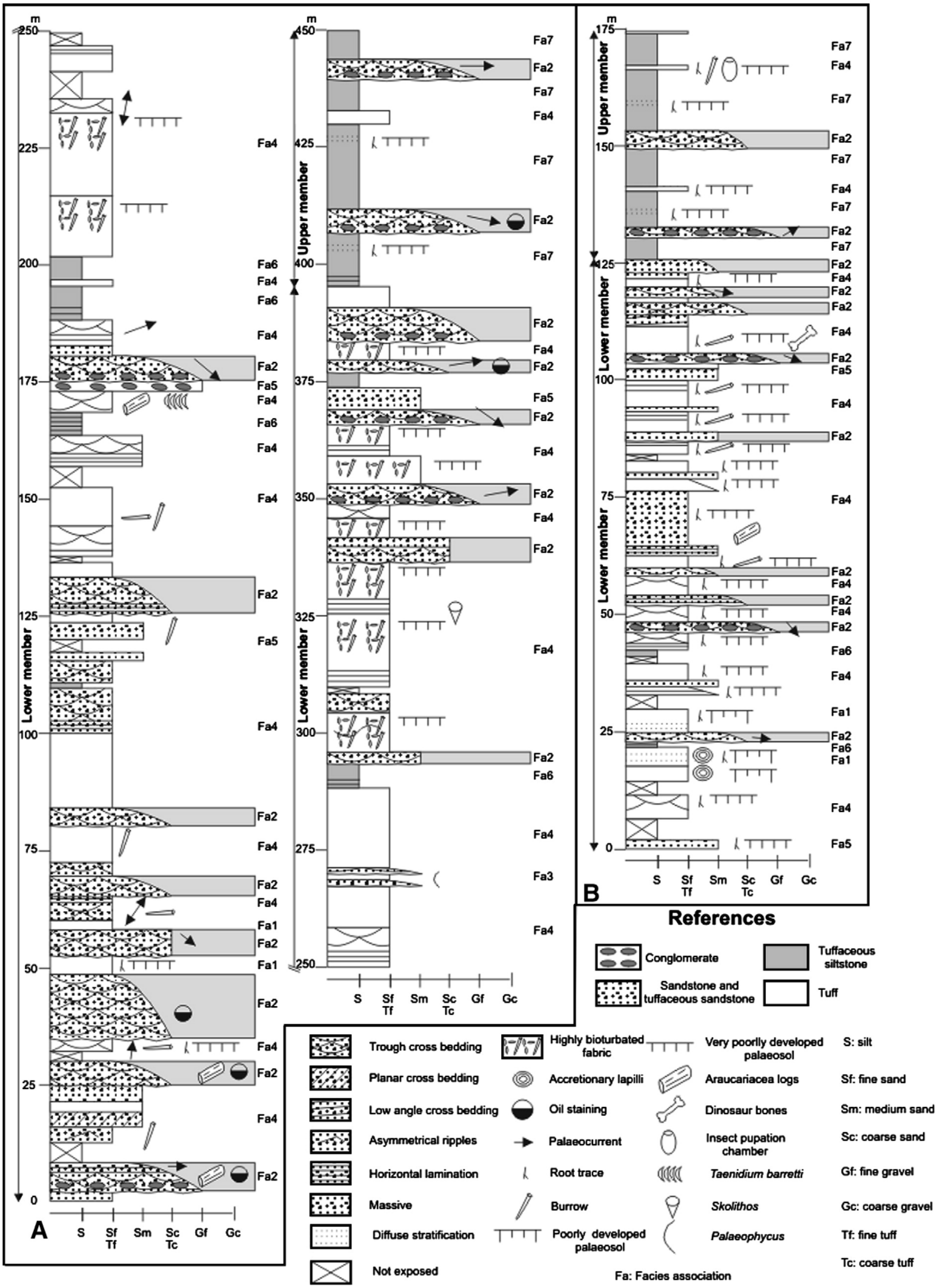

Fig. 4. Measured sedimentary logs of the Bajo Barreal Formation. (A) Puesto Confluencia. (B) Sierra Nevada Anticline.

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

4.1.1. Description

Facies association 1 (Fa1) includes well-sorted, fine-grained, vitric tuff beds with diffuse parallel stratification (facies T1) or massive structure (facies T2). This Fa is restricted to the basal part of the lower member at both localities. The upper part of some beds shows millimetre-wide root traces and subvertical burrows 5–15 mm in diameter (facies P, Fig. 5A). Individual beds are laterally continuous over kilometres and range from 0.45 m to 0.70 m thick. Commonly, they are vertically stacked conformable sheet-like bodies up to 8 m thick and maintain a relatively uniform thickness (mantle bedding sensu Cas and Wright, 1987). The vitric fragments are commonly altered to clay, quartz and/or zeolites (analcime and clinoptilolite). At Sierra Nevada Anticline, R-type accretionary lapilli, consisting of a coarse-grained core surrounded by multiple rims (Schumacher and Schmincke, 1991) are common in places (Fig. 5B). In some cases, these particles are prolate with the long axis parallel to the stratification plane. The features of facies P vary between localities. In the northern locality (SNA), facies P is typically represented by two horizons with different color, root trace content and microscopic pedofeatures. The upper yellowish gray (5Y 8/1) horizon is 0.15–0.20 m thick and shows angular blocky peds. The coarse fraction (40%) is composed of highly altered glass shards and scarce weathered plagioclase, quartz, volcanic lithic fragments and pyroxenes. The fine fraction is yellowish-brown non-recrystallized clay. In thin sections, common pedofeatures are mosaic-speckled b-fabric, root traces, void quasi-coatings and Fe–Mn aggregate nodules. The lower light greenish gray (5G 8/1) horizon is 0.40–0.45 m thick and lacks peds. It has a similar coarse–fine ratio, coarse-fraction composition, less recrystallized ground-mass and scarce nodules. At Puesto Confluencia, facies P occurs as an apedal, yellowish gray (5Y 8/1), 0.40–0.50 m thick horizon. This horizon shows a coarse fraction (30%) similar in composition to that described for the facies P in Sierra Nevada Anticline, including root traces and Fe–Mn nodules.

4.1.2. Interpretation

Well-sorted tuffs showing mantle bedding and absence of cross-stratification are typical characteristics of pyroclastic-fall deposits (e.g. Walker, 1973; Cas and Wright, 1987; Houghton et al., 2000). Whereas massive beds could represent single ash-fall events, those with diffuse parallel stratification would record multiple ash falls. R-type accretionary lapilli commonly originate from phreatomagmatic eruptions associated with magma-meteoric water interaction (Gilbert and Lane, 1994). The prolate shape of accretionary lapilli is attributed to compaction. The presence of accretionary lapilli is generally regarded as indicative of a location proximal to the vent (Moore and Peck, 1962). In particular, this type of accretionary lapilli indicates that the sedimentation occurred within a few kilometres of the volcanic source (Schumacher and Schmincke, 1991). After deposition, the pyroclastic-fall deposits were slightly to moderately modified by pedogenesis (Bullock et al., 1985; Retallack, 1988) as suggested by the presence of facies P. The degree of development of palaeosols was greater at Sierra Nevada Anticline, where they display similarities to Andisols (Soil Survey Staff, 1999). At Puesto Confluencia, the degree of development of palaeosols was less, and they can be compared with Entisols (Soil Survey Staff, 1999).

4.2. Facies association 2: fluvial channel deposits

4.2.1. Description

Facies association 2 (Fa2) consists of sandstone-conglomerate bodies with sheet to plano-convex geometry in cross-section and concave-upward basal and internal erosion surfaces (Fig. 6A).

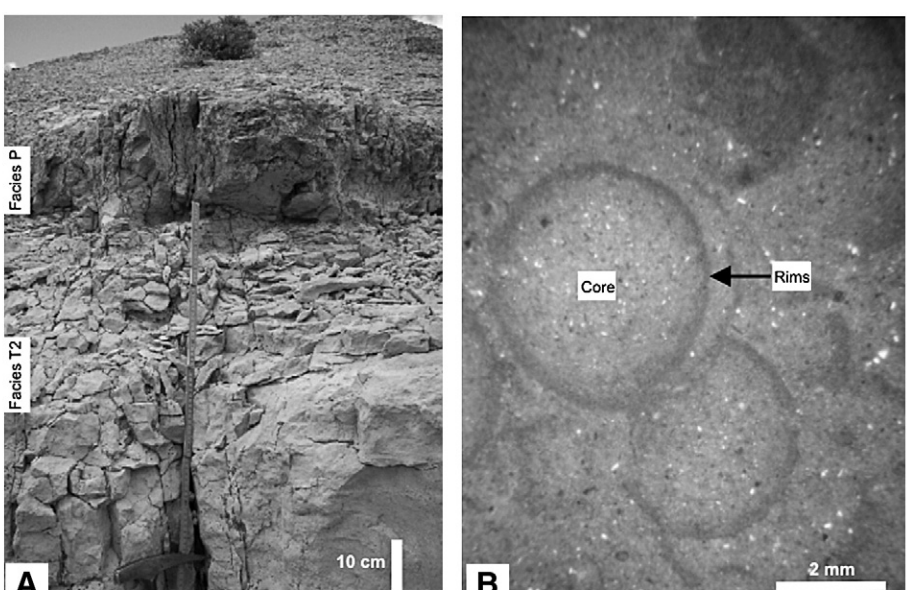

Fig. 5. Primary pyroclastic deposit. (A) 2 m thick, ash-fall deposit composed of massive, fine-grained, vitric tuff (T2) and a poorly developed palaeosol (P). (B) Thin section of facies T2 with R-type accretionary lapilli.

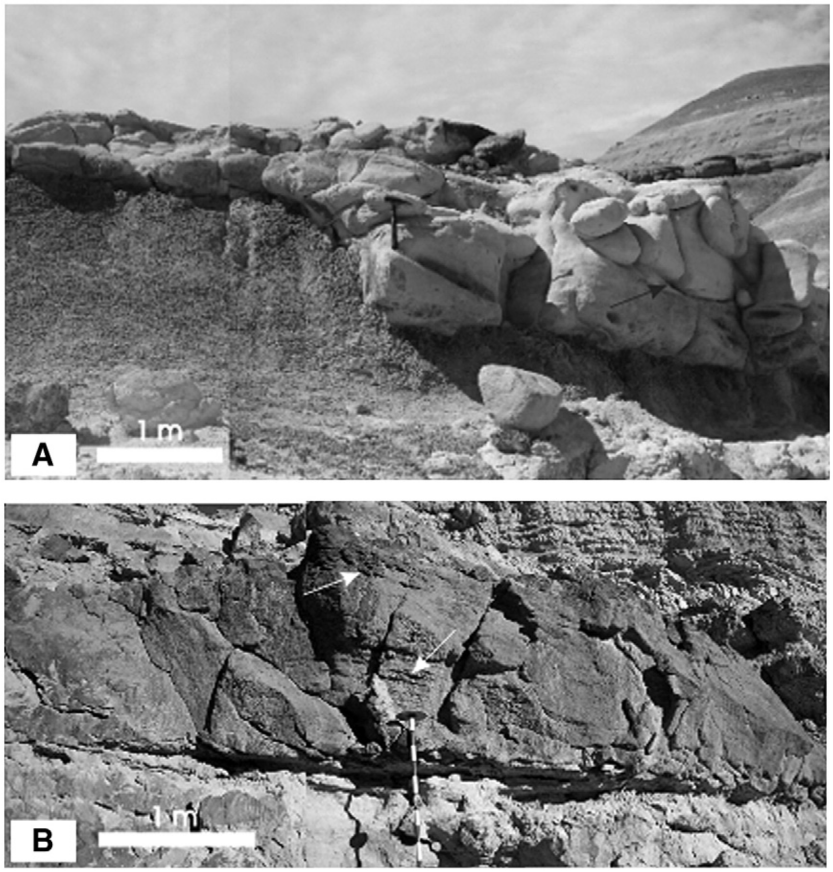

Fig. 6. Photomosaics of sandstone bodies. (A) Fluvial channel deposit (Fa2) composed of massive, medium- to fine-grained sandstones. Note the irregular and concave-upward base and the plane top. The arrow points to an internal erosion surface. (B) Crevasse-splay deposit (Fa3) composed of massive, medium- to-fine-grained sandstones. Note the planar base and the convex-upward top. The arrows indicate internal surfaces parallel to the top surface.

Although this Facies association has similar abundance in both members, greater thickness and density of channel deposits in vertical section are detected in the lower member at Puesto Confluencia (see Section 5). The bodies commonly fining upwards and are composed of matrix- to clast-supported, fine-grained conglomerates with trough cross-bedding (facies G1), grading upward to coarse- to fine-grained sandstones with trough cross-bedding (facies S1). Scarce decimetre-thick beds composed of horizontally laminated, coarse- to fine-grained sandstones (facies S2) or massive tuffaceous siltstones (facies F1) occur within these bodies. In places, similar bodies composed of medium- to fine-grained structureless sandstones (facies S3) were observed at Sierra Nevada Anticline. Partial oil staining and abundant Araucariaceae log remains (Pujana et al., in press), which are up to 0.5 m in diameter and 2 m long, are common at Puesto Confluencia. The sandstones are mostly feldespathic litharenites and litharenites (Folk et al., 1970), dominated by volcanic lithic fragments, glass shards and plagioclase. Several samples display scarce root structures filled with silica and clinoptilolite and/or analcime cement. Palaeocurrent data from trough cross-bedded sandstones and conglomerates indicate a unidirectional palaeoflow toward E-SE at both localities. Mean directions of palaeoflow are N 95° (n=20, range: N 59° to N 123°) at Sierra Nevada Anticline and N 89° (n=76, range: N 70° to N 150°) at Puesto Confluencia. At the northern locality most of the palaeocurrent data (80%) are in the range N 80° to N 120°, whereas at the southern locality most of the palaeocurrent data (80%) range from N 80° to N 130°.

In views nearly perpendicular to the mean palaeocurrent direction, plano-convex bodies of Fa2 reach a lateral extent of <200 m and 32 m at Puesto Confluencia and Sierra Nevada Anticline, respectively. The thickness of these plano-convex bodies ranges from 0.30 m to 2 m at Sierra Nevada Anticline (mean=1.1 m, n=22) and from 0.65 m to 10.4 m at Puesto Confluencia (mean=3.3 m, n=21). The channel-form deposits are made up of sets of large-scale inclined strata (Bridge, 1993) that range from decimetres to metres thick and tens to hundreds of metres wide. At Puesto Confluencia, several views normal to mean palaeocurrent show large-scale inclined strata sets with convex-upward tops that dip in opposite directions toward adjacent channels on both sides (Fig. 7). In places, these large-scale inclined strata sets with convex-upward tops are truncated by a concave-upward surface. At Sierra Nevada Anticline, the reduced lateral continuity of the Fa2 deposits and the lack of section transverse to mean palaeocurrent direction does not allow for a detailed architectural description.

4.2.2. Interpretation

The deposits of Fa2 are interpreted as fluvial channel bars and fills because of the presence of moderately well-sorted,

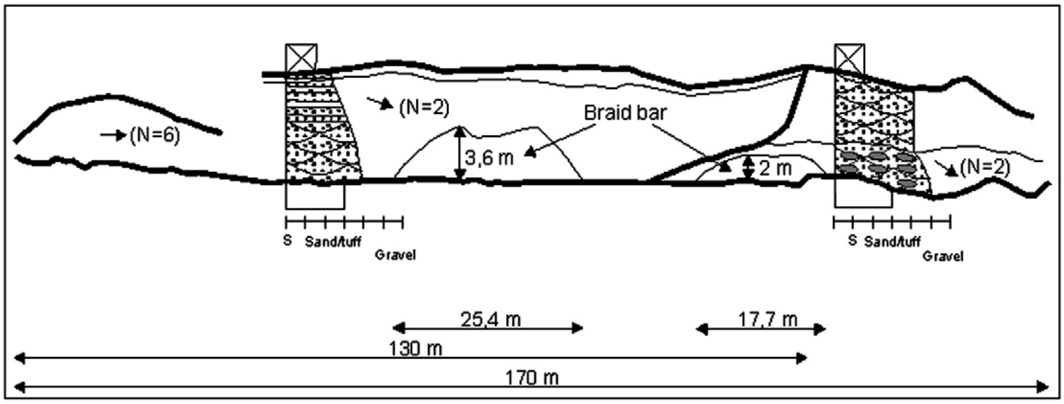

Fig. 7. Architecture and sedimentary logs of a sandstone body corresponding to a fluvial channel deposit (Fa2). The vertical scale is exaggerated. Orientation of outcrop: N15° E. Average palaeocurrent: N 89°E ($n=10$).

fining-upward successions, erosional bases and plano-convex geometry of the sandstone-conglomerate bodies (e.g. Allen, 1964; Walker and Cant, 1984; Miall, 1996; Bridge, 2003). The trough cross-bedded conglomerates and sandstones (facies G1 and S1) were deposited by migration of three-dimensional dunes. The horizontal laminated sandstones (facies S2) were formed on upper-stage plane beds (Miall, 1996). Massive silt beds (facies F1) originated by settling from suspension and imply a break in bedload transport formed during periods of little or no discharge. Facies S3 (massive sandstones) represents sediments transported during high discharge conditions in which the sediments cannot be redistributed into bed-forms (Smith and Lowe, 1991). The lack of root structures, desiccation cracks and sub-aerial bioturbation in the filling of the main channel deposits suggest that the flows were perennial (Bridge et al., 2000). Nevertheless, the presence of beds with horizontal lamination forming an important proportion of the channel-fill succession suggests that the streams suffered substantial variations in water discharge (Tunbridge, 1984).

The large-scale inclined strata sets represent the deposits of migrating channel bars and channel fills; each large-scale inclined stratum would represent individual flood events (Bridge, 1993, 2003). At Puesto Confluencia, the common occurrence of a braid bar (large-scale inclined strata set with convex-upward top) with coeval channels in either side in views normal to palaeoflow (Fig. 7) suggests a braided pattern (Bridge et al., 2000; Lunt et al., 2004). The low dispersal of palaeocurrent data and absence of levee facies are consistent with a braided pattern. The concave-upward erosion surfaces in the upper part of some bar deposits are interpreted as cross-bar channels. At Sierra Nevada Anticline, the palaeocurrent data also display a low dispersal, which suggest a similar braided pattern, although adequate sections for architectural analysis were not found.

4.3. Facies association 3: crevasse-splay deposits

4.3.1. Description

Facies association 3 (Fa3) includes lobe to sheet-shaped sandstone bodies, mostly composed of trough cross-bedded (facies S1) or massive (facies S3) medium- to fine-grained sandstones with a very subtle fining-upward trend (Fig. 6B). This Facies association is only recognized in the lower member of the succession at Puesto Confluencia. Locally, the sandbodies are capped by massive tuffaceous silts (facies F1) bearing *Palaeophycus* burrows. These sandstone bodies are surrounded by bioturbated sheet-flood deposits (Fa4) and show a maximum thickness of 1.5 m and a lateral extent of tens of metres. Laterally, minor isolated channelized sandbodies occur, although physical connection with Fa2 deposits was not observed directly. The lobe geometry of Fa3 deposits is typically observed in sections near-perpendicular to the palaeocurrent direction measured in fluvial channel deposits, whereas a sheet-like geometry was recorded in sections oblique-to-parallel to the palaeotransport direction. The bases of the sandbodies are flat and erosional with scarce gravel-sized intraclasts. One sandbody shows internal discontinuous surfaces that are parallel to the convex-upward morphology of the top (Fig. 6B), and displays low-relief scours filled with sandstone and gravel-sized intraclasts.

4.3.2. Interpretation

The sandbodies with planar base and convex-upward top are interpreted as crevasse-splay deposits. A smaller grain-size and thickness than those of channel deposits are typical features of crevasse-splay deposits. The occurrence of intraclasts and scoured surfaces in one sandstone body reflects multiple episodes of erosion and sedimentation. Massive tuffaceous siltstones (F1) that locally cover the sandstone bodies imply settling from suspension, probably during waning-flow conditions. Minor channelized sandbodies could represent crevasse channels. The scarcity of crevasse-splay deposits suggests that channel stability was relatively low (Galloway, 1981) and/or that the channels were too short-lived to build up extensive channel-margin deposits (Dreyer, 1993). In equivalent stratigraphic sections cropping out in different parts of the San Bernardo Range, sandstone bodies with similar geometry and thickness have been interpreted as originating from hyperconcentrated and unconfined flows (Hechem, 1994, 1998). However, the presence of cross-bedding and scours are not consistent with the characteristics of hyperconcentrated flows (Smith, 1986, 1988).

4.4. Facies association 4: sheet-flood deposits

4.4.1. Description

Facies association 4 (Fa4) is the dominant Facies association in the lower member at both localities, although it is also rarely present in the upper member. It comprises laterally continuous sheet-like beds mainly composed of massive reworked tuffs (facies T3) and tuffaceous sandstones (facies S3), both with scattered, rounded intraclasts. In some places, facies T3 exhibits an overall normal grading, although scarce pumice intraclasts are concentrated in the upper part of the beds. Beds show planar and slightly erosional bases with frequent low-relief scour and fill structures and aligned intraclasts. The tops are planar to undulatory. Individual beds are amalgamated laterally and some form sheet-like bodies that extend for several hundred metres. Bed thickness ranges from decimetres to metres, but some beds are vertically stacked forming successions up to 25 m thick. Several deposits of Fa4 are capped by fine-grained tuffs bearing scarce thin root traces and vertical to horizontal burrows including *Taenidium barretti* and *Skolithos* isp. (facies P). At Puesto Confluencia, numerous occurrences of facies P from the lower member display a highly bioturbated fabric composed of a diffuse mass of tunnels with few identifiable trace fossils, similar to that described for the overlying Laguna Palacios Formation (Genise and Bellosi, 2004; Bedatou et al., 2005). At Sierra Nevada Anticline, facies P has more root traces and fossil insect pupation chambers occur rarely in the upper member (Sciutto and Martínez, 1996; Genise et al., 2007; Fig. 4). Subordinate facies include reworked tuffs and tuffaceous sandstones showing deformed to undisturbed horizontal lamination (facies T4, S2) or trough cross-bedding (facies T5, S1). Additional facies were rarely recorded in a single locality, such as medium-grained tuffaceous sandstones with planar cross-bedding (facies S4) or asymmetrical ripples (facies S5, both at Puesto Confluencia, Fig. 4), and medium-grained tuffaceous sandstones with low-angle cross-bedding (facies S6, at Sierra Nevada Anticline, Fig. 4). In places, deposits of Fa4 form 1–5 m thick fining-upward cycles that grade upward from S3 or T3 to S2 or T4 (Fig. 8A). Scarce palaeocurrent data measured from trough cross-bedding in tuffaceous sandstones and tuffs indicate two dominant directions of palaeoflow: toward NE and SW.

4.4.2. Interpretation

Scattered, rounded intraclasts within tuff beds suggest that Fa4 is composed of reworked pyroclastic ash-fall deposits (e.g. d'Atri et al., 1999). Moreover, the occurrence of sedimentary structures and a mixture of epiclastic and pyroclastic sediments are indicative of volcaniclastic deposits reworked by water or wind. In particular, massive (T3 and S3) and horizontal laminated (T4 and S2) facies originated during sheet-flood events (Cas and Wright, 1987). During these events, large

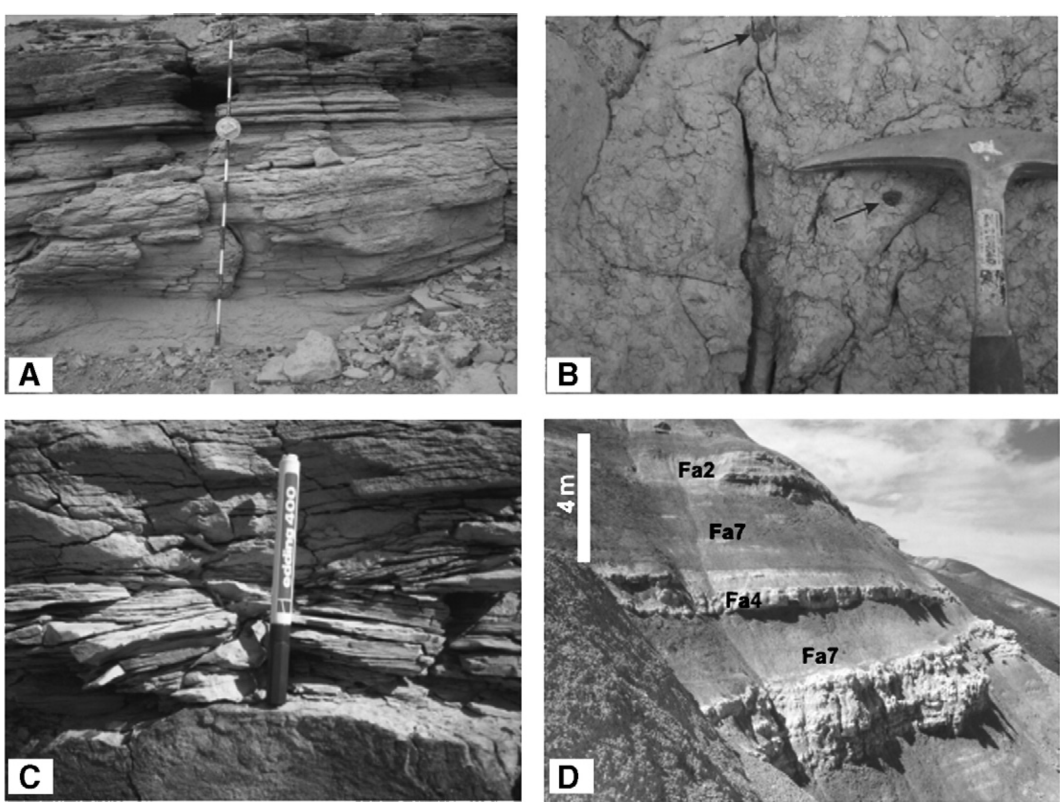

Fig. 8. Examples of some non-primary pyroclastic facies associations. (A) Sheet-flood deposit (Fa4) composed of massive, medium-grained tuffaceous sandstones that grade upward to horizontal laminated, fine-grained tuffaceous sandstones forming a 1.3 m thick sequence. Jacob's staff is 1.5 m long. (B) Sub-aerial sandy debris-flow deposit (Fa5) with scarce gravel-sized clasts (see arrows) dispersed in a tuffaceous sandstone matrix. Hammer is 12 cm long. (C) Tuffaceous siltstone with wave ripple structures deposited in a shallow lake (Fa6). Pencil is 13 cm long. (D) Loess deposits (Fa7) interbedded with pedogenically modified sheet-flood (Fa4) and fluvial channel (Fa2) deposits.

volumes of sediment were carried out in suspension. When flow velocity wanes, rapid rates of sedimentation occur leading, in places, to the deposition of massive or horizontal laminated deposits (Cas and Wright, 1987). The sheet-like geometry of the beds suggests unconfined flows (Martina et al., 2006), like those recorded in ephemeral streams (Stear, 1983), terminal fans (Parkash et al., 1983) or poorly developed distal braided fluvial systems (Tunbridge, 1981). It is interpreted that deposition from sheet-flood events occurred on alluvial plains and was laterally related to shallow lacustrine settings (Fa6) and fluvial channels (Fa2). Scour and fill structures, aligned intraclasts in the bases of amalgamated sheet-flood deposits, and palaeosols indicate discontinuous sedimentation. Although sheet-floods mostly flowed as upper-stage plane-bed flows, 3D, 2D and washed-out or humpback dunes also occurred rarely. Low-angle cross-bedding (facies S6) could represent plane beds deposited on initially dipping surfaces. In both localities, facies P records a very weak pedogenic modification of sheet-flood deposits during pauses in sedimentation, producing soils comparable to Entisols (Soil Survey Staff, 1999). In places, the original sedimentary structure was totally destroyed by biological activity.

4.5. Facies association 5: sandy debris-flow deposits

4.5.1. Description

Facies association 5 (Fa5) is characterized by structureless gravelly and tuffaceous bodies with sheet or plano-convex geometry, some of which show localized trough cross-bedding and root traces and burrows (facies S7, S1 and P). This rare Facies association is generally interbedded with sheet-flood deposits (Fa4) and is restricted to the lower member. Individual beds are 0.4–1.5 m thick and extend laterally for several hundred metres. In places, they are vertically stacked and laterally amalgamated reaching a thickness of 3.6 m. The basal surfaces of these deposits are undulatory and locally erosional. Deposits of Fa5 are mainly composed of scarce gravel-sized clasts floating in a matrix of medium- to fine-grained, vitric tuff (facies S7, Fig. 8B). The gravel-sized clasts include sub-rounded volcanic lithic fragments of andesitic composition and minor amounts of sub-rounded to sub-angular, tuffaceous intraclasts similar to those found in sheet-flood deposits (Fa4). Grain-size of the clasts ranges between coarse-sand and pebble, and is commonly granule-sized. The deposits are poorly-sorted, massive, non-graded and commonly show scarce root traces and burrows (facies P) on their tops. In places, trough cross-bedded sandstones (facies S1) occur as ribbons within the stacked debris-flow deposits.

4.5.2. Interpretation

The characteristics of Fa5 are suggestive of deposition from sandy sub-aerial debris-flows. Poor sorting, massive and non-graded beds indicate *en masse* freezing of the sediment (Shultz, 1984; Smith and Lowe, 1991; Best, 1992). Dominance of non-erosional bases and a matrix-supported fabric also suggest deposition from debris-flows (Nakayama and Yoshikawa, 1997). Sub-rounded to sub-angular, tuffaceous intraclasts indicate that the debris-flows partially originated from erosion of underlying sheet-flood (Fa4) and pyroclastic-fall (Fa1) deposits. After deposition, the upper parts of deposits were slightly modified by pedogenic processes and burrowing organisms. Cross-bedded sandstones that occur within stacked debris-flow represent reworking of these deposits by normal stream-flow (Smith, 1987), either as a tail of the debris-flow or as a separate flow.

4.6. Facies association 6: shallow lacustrine deposits

4.6.1. Description

Facies association 6 (Fa6) comprises sheet-like to channel-like tuffaceous siltstone bodies up to 10 m thick, which have lateral extent ranging from tens to hundreds of metres. Although the bodies of Fa6 were recorded in the lower member of both localities, the thicker intervals occur at Puesto Confluencia. Individual deposits of Fa6 have non-erosional bases and tops scoured by fluvial channels (Fa2) or capped by sheet-flood (Fa4) deposits. The dominant facies is massive or horizontal laminated tuffaceous siltstones (facies F1), with minor tuffaceous siltstones showing deformed wave ripple structures (facies F2; Fig. 8C).

4.6.2. Interpretation

The siltstone bodies with non-erosional bases of the Fa6 represent sedimentation in a shallow lacustrine environment. The massive or horizontal laminated tuffaceous siltstones (facies F1) settled out from suspension in standing water (Nakayama and Yoshikawa, 1997). The tuffaceous siltstones with wave ripple structures (facies F2) are attributed to oscillatory flows (e.g. de Raaf et al., 1977). Deformation of the wave ripple structures is attributed to compaction.

4.7. Facies association 7: loess deposits

4.7.1. Description

Facies association 7 (Fa7) is composed of tuffaceous siltstones that form sheet-like bodies up to 20 m thick. The Fa7 deposits dominate the upper member of both sections and are locally interbedded with sheet-flood (Fa4) and fluvial channel deposits (Fa2). Individual beds that constitute these bodies are laterally traceable for several kilometres and have non-erosional bases. The tuffaceous siltstone beds are structureless or have uncommon discontinuous diffuse stratification (facies F3, Fig. 8D) and in places show root traces (facies P). The dominant grains are clay-altered or zeolite-replaced glass shards and subordinate amount of plagioclase, quartz, potassium feldspars and volcanic lithic fragments.

4.7.2. Interpretation

The dominant processes of deposition of facies F3 is aeolian transport of fine-grained pyroclastic material and sub-aerial deposition in down-wind distal areas of the source pyroclastic deposits. In particular, facies F3 is considered a loess deposit on the basis of the uniform silt-grade grain-size, massive to diffusely stratified siltstone beds and basal contacts that lack evidence for erosion (Pye, 1987; Johnson, 1989). Root traces indicate pedogenic modification (facies P) and allow this Fa to be interpreted as loess–palaeosol succession.

5. Distribution of facies associations

The proportions (in percent thickness) of the different facies associations for each analyzed locality are shown in Table 3. The dominant facies associations vary between the lower and upper members in both measured logs (Fig. 4; c.f. Sciutto, 1981). The lower member is composed of weakly pedogenically modified floodplain deposits (Fa1, Fa3, Fa4, Fa5 and Fa6) intercalated with fluvial channel deposits (Fa2). In both localities, floodplain deposits are dominated by sheet-floods (Fa4) with subordinate pyroclastic ash falls (Fa1), sandy debris-flows (Fa5) and settling in shallow lakes (Fa6). Fa1 is restricted to the basal part of the lower member. Although the overall ratio of channel–floodplain facies is similar at both localities ($C/F \approx 0.18$), channel deposits are concentrated in the basal and upper third of the lower member (Homovc and Lucero, 2002; Umazano et al., 2006a) locally reaching C/F values of 0.30. The main differences in the lower member between the Puesto Confluencia and Sierra Nevada Anticline localities are: a) presence of scarce crevasse-splay deposits (Fa3) and greater thickness of fluvial channel (Fa2) and shallow lacustrine deposits (Fa6) in the former; b) occurrence of more proximal primary pyroclastic facies (Fa1) and greater soil development in the latter.

The upper member is composed of floodplain deposits dominated by palaeosol–loess successions (Fa7) and subordinate sheet-flood deposits (Fa4) intercalated with fluvial channel deposits (Fa2). The overall channel–floodplain ratio is similar in both localities ($C/F \approx 0.16$), but this member lacks concentrations of channel deposits (Umazano et al., 2006a). The only remarkable difference between Puesto Confluencia and Sierra Nevada Anticline localities is the presence of thicker fluvial channel deposits in the southern locality.

6. Depositional setting of the Bajo Barreal Formation

The contrasting facies composition and vertical distribution of the lower and upper members of the Bajo Barreal Formation suggest that they were deposited in different fluvial systems. A similar distinction is made in the western part of the basin (Sciutto, 1981, 1999; Sciutto and Martínez, 1996; Rodríguez, 1992), suggesting that these differences can be correlated basinwide.

Table 3
Amount (as percent thickness of the measured sections) of the different facies associations in each analyzed locality

Facies association	Percent thickness			
	lower member		upper member	
	SNA	PC	SNA	PC
Fa1 — Pyroclastic ash-fall deposits	6.9	1.3	0	0
Fa2 — Fluvial channel deposits	11	21.71	3.4	2
Fa3 — Crevasse-splay deposits	0	0.9	0	0
Fa4 — Sheet-flood deposits	49.40	53.36	1.7	2
Fa5 — Sandy debris-flow deposits	2.9	4.7	0	0
Fa6 — Shallow lacustrine deposits	1.7	4.9	0	0
Fa7 — Loess deposits	0	0	23	9.13

SNA: Sierra Nevada Anticline, PC: Puesto Confluencia.

In both localities, the lower member of the Bajo Barreal Formation was deposited in a fluvial setting with common ash-fall events (Fig. 9A) derived from a volcanic arc located in the western part of Patagonia (Tunik et al., 2004, Umazano et al., 2006b). Primary pyroclastic deposits (Fa1) covered the topography uniformly (c.f. Wright et al., 1980; Houghton et al., 2000) and represent typical syn-eruptive periods (Smith, 1991). These primary pyroclastic deposits were partially to totally reworked by fluvial channels and sheet-floods. The deposits formed by these fluvial flows represent sedimentation during a relatively short period following cessation of volcanic activity (Smith, 1991). Fluvial channels (Fa2) flowed toward E-SE, in agreement with the general palaeodrainage inferred for the entire basin during deposition of the Bajo Barreal Formation (Hechem, 1994, 1998). Some fluvial channel fills record episodic and high-energy flows indicating major variations in discharge. The fluvial channels were braided, at least at Puesto Confluencia as suggested by the presence of mid-channel bars. In the case of Sierra Nevada Anticline, no diagnostic feature for identification of the channel pattern was found, although the low palaeocurrent dispersal suggests a braided pattern. Non-pyroclastic volcanic lithic fragments in samples of fluvial channels indicate an input of volcanic material derived from weathering of an older volcanic source-rock, which is different from the contemporaneous pyroclastic volcanism. Considering the palaeotransport direction, modal sandstone and geochemical data that suggest a provenance from undissected-transitional arc (c.f. Tunik et al., 2004; Umazano et al., 2006b), it is considered that the Jurassic–Cretaceous volcanic successions cropping out in the western part of the Chubut province are the most likely source.

The vertical accretion of floodplains occurred by deposition from crevasse-splays (Fa3), sheet-floods (Fa4), sub-aerial debris-flows (Fa5) and settling from suspension in shallow lakes (Fa6). The more frequent overbank flows were sheet-floods that remobilized primary and/or reworked pyroclastic sediments. Unconfined flows commonly flowed toward the NE and SW and could have supplied fine sediment to shallow lakes located in distal floodplain topographic depressions. Less commonly, the crevasse-splays contributed to floodplain development. Debris-flows could be related to the collapse of volcanic vents or the remobilization of primary pyroclastic deposits triggered by heavy rainfall or snow melting. In modern settings, the resulting flows can be loaded with abundant volcanic materials and travel more than 100 km from the source area (e.g. Mothes et al., 1998). During periods of low deposition rate, floodplain deposits were pedogenically modified.

The upper member of the Bajo Barreal Formation records sedimentation in a mixed fluvial–aeolian setting (Fig. 9B). The fluvial channels (Fa2) display a braided pattern at Puesto Confluencia, as in the lower member, and flowed toward the E-SE across a wide, low-relief floodplain. The floodplains received a large input of fine-grained pyroclastic material transported by wind from a distant source area, which suffered weak soil development. The sheet-floods (Fa4), although less

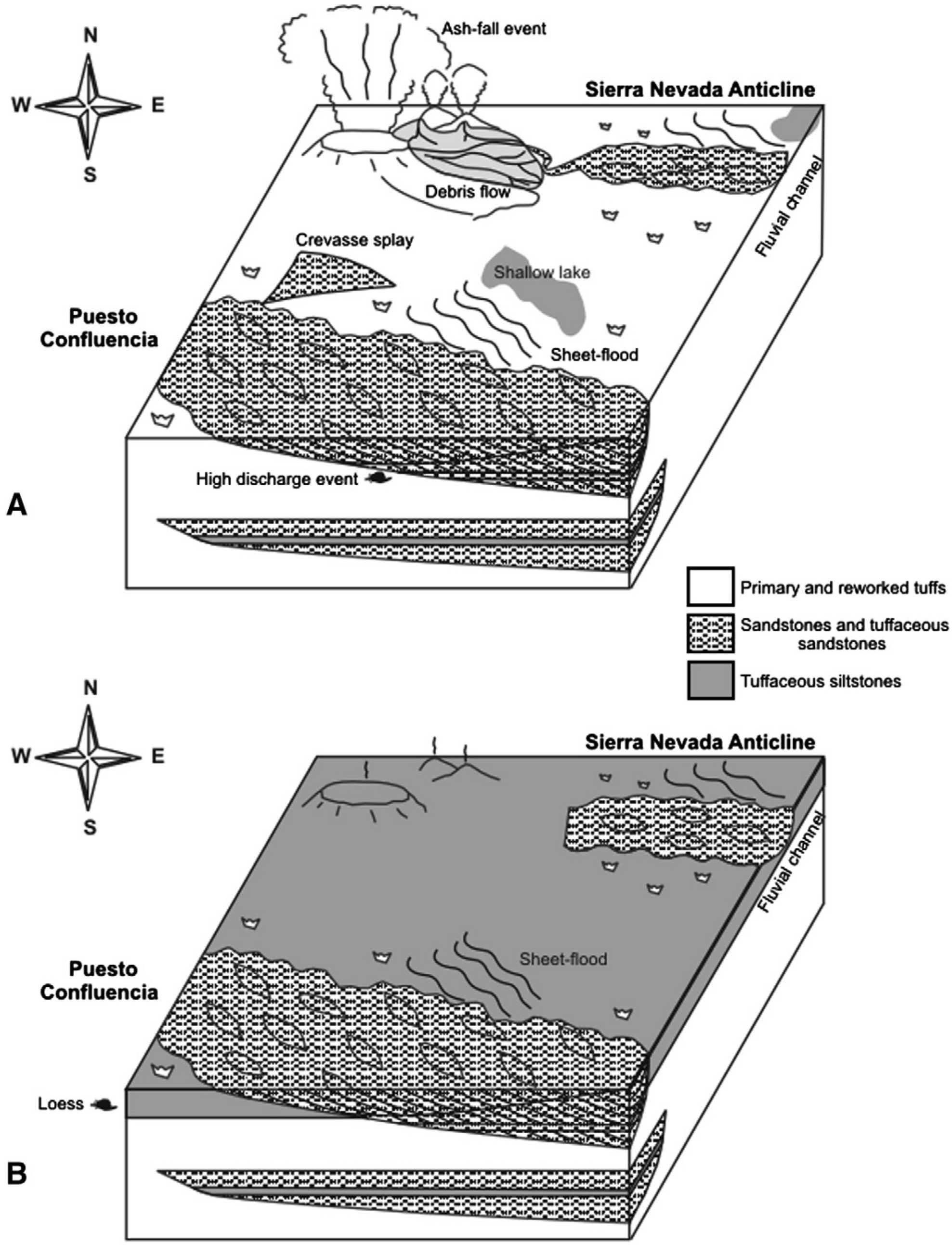

Fig. 9. Block diagram showing the depositional setting of the Bajo Barreal Formation. (A) lower member. (B) upper member.

frequent in comparison with the underlying member, partially remobilized aeolian deposits. After deposition, the sediments of these unconfined fluvial streams were colonized by soil organisms. Absence of primary pyroclastic (Fa1) and debris-flow (Fa5) deposits suggests that this section represents inter-eruptive conditions (Smith, 1991).

7. Discussion

The fluvial systems of the Bajo Barreal Formation in the studied localities had perennial channels (c.f. Archangelsky et al., 1994; Bridge et al., 2000), although they experienced major variations in water discharge. However, in other localities of the basin, several authors interpreted that the fluvial channels were ephemeral and with poorly defined margins (Rodríguez, 1992, 1993; Hechem, 1994, 1998). The fluvial pattern was braided, at least at Puesto Confluencia, and differs from those described as single-channel, low-sinuosity channels (sinuosity less than 1.2) in outcrops of the formation located southward of the study area (Bridge et al., 2000).

Recent contributions on sedimentation in alluvial settings strongly influenced by explosive volcanism (e.g. Nakayama and Yoshikawa, 1997; Manassero et al., 2000; Kataoka and Nakajo, 2002; Martina et al., 2006) consider the alternation between syn-eruptive and inter-eruptive conditions as the most conspicuous factor affecting sedimentation in this kind of environment. These contributions agree with the classic model of Smith (1991), which includes meandering perennial streams dominated by a more lithologically diverse bedload during inter-eruptive periods. During syn-eruptive periods, the impact of the sudden influx of tremendous volumes of volcaniclastic debris into the sedimentary basin induces a rapid change of the drainage pattern to a braided configuration (e.g. Vessell and Davies, 1981; Palmer, 1997; Kataoka and Nakajo, 2002), and the sediment composition is dominated by pyroclastic sediments (Smith, 1988). The record of contemporaneous pyroclastic eruptions in the lower member and its absence or rarity in the upper member suggests that a comparison with the Smith model is possible. In particular, the lower member would represent a fluvial system developed in a syn-eruptive period and the upper member reflects the adjustment of the fluvial system to an inter-eruptive period. Nevertheless, one difference with Smith's model is the apparent similarity of the channel pattern in the syn-eruptive and inter-eruptive periods. The stability of the fluvial pattern indicates that the geomorphic threshold for aggradation was continuously exceeded (Smith, 1991). In the lower member this effect could be explained by short-time intervals between successive eruptions, which is consistent with the dominance of very poorly developed palaeosols and abundance of sheet-flood deposits at both localities. In the upper member, the persistence of the fluvial channel pattern can be explained by a high input of aeolian sediments.

8. Conclusions

The Upper Cretaceous Bajo Barreal Formation records sedimentation in two successive fluvial systems with contrasting features. During deposition of the lower member, pyroclastic sediments arrived as frequent ash falls derived from a volcanic arc located to the west. Tephra deposits were reworked by braided rivers with highly variable discharge and overbank sheet-floods. Records of reduced sediment accumulation are represented by poorly developed palaeosols.

During deposition of the upper member, the aeolian input of silt-sized pyroclastic–epiclastic detritus was very significant and primary pyroclastic-fall deposits were rare to absent. The river pattern apparently remained unchanged and the floodplain aggraded mostly by fine-grained aeolian sedimentation (loess deposits) and less commonly by sheet-floods.

The lithofacies of the lower and upper members of the Bajo Barreal Formation are similar in the two studied localities and are also similar to those described from other localities of the basin, suggesting that the changes in aggradational mechanisms occurred at a basinal scale. However, the previously inferred channel patterns for other locations include ephemeral rivers and perennial, single-channel, low-sinuosity rivers. These different channel patterns probably reflect local conditions, although further studies are necessary to test this hypothesis. The presence of primary tuffs bearing accretionary lapilli in the lower member at Sierra Nevada Anticline suggests that this locality was closer to the volcanic edifices than Puesto Confluencia.

Although the Bajo Barreal Formation represents an excellent example of fluvial systems that interacted with explosive volcanism, one important difference with the classic model of syn-eruptive and inter-eruptive conditions is inferred: the possible presence of a braided fluvial pattern during the inter-eruptive condition. This difference could be explained by a high influx of loessic sediments that would have surpassed the geomorphic threshold for aggradation, thus favoring the development of a braided pattern during periods of volcanic quiescence.

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