PALEOENVIRONMENTAL ANALYSIS AND ARCHITECTURE OF SANDSTONE BODIES OF THE BAJO BARREAL FORMATION (CRETACEOUS), WESTERN SAN JORGE BASIN, ARGENTINA

Aldo Martín Umazano[1], Ricardo Néstor Melchor[2] and Eduardo Sergio Bellosi[3]

[1]CONICET, Facultad de Ciencias Exactas y Naturales (UNLPam)-amumazano@yahoo.com.ar
[2]CONICET, Facultad de Ciencias Exactas y Naturales (UNLPam)-rmelchor@exactas.unlpam.edu.ar
[3]CONICET, Museo Argentino de Ciencias Naturales "Bernardino Rivadavia"-ebellosi@sei.com.ar

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Resumen: *Análisis paleoambiental y arquitectura de los cuerpos de arena de la Formación Bajo Barreal (Cretácico), oeste de la Cuenca San Jorge, Argentina.*
Los cuerpos areno-tobáceos de la Formación Bajo Barreal (Cretácico) y unidades equivalentes constituyen los principales reservorios de hidrocarburos de la Cuenca San Jorge. Los objetivos de este trabajo fueron determinar el paleoambiente depositacional de dicha formación, así como su evolución vertical y realizar el análisis arquitectural preliminar de los cuerpos arenosos en el sector oeste de la cuenca. La sucesión sedimentaria estudiada se encuentra en el occidente de la Faja Plegada San Bernardo, al norte de la confluencia de los ríos Mayo y Senguerr y muestra impregnación por hidrocarburos en los niveles medio-altos. Dicha sucesión está compuesta principalmente por tobas reelaboradas y areniscas depositadas en un ambiente fluvial efímero. Se reconocieron dos asociaciones de facies cuyas características las hacen potenciales reservorios: canales fluviales (Fa1) y crevasse splays (Fa2). Las piroclastitas reelaboradas y las areniscas finas (Fa3) fueron generadas por flujos fluviales no confinados y representan el principal mecanismo agradacional de las planicies de inundación. También se encuentran niveles limosos con menor continuidad lateral y potencia interpretados como lagos someros, ocasionalmente interestratificados con tobas conformando la asociación de facies de planicies de inundación heterolítica (Fa4). El desarrollo vertical de la sucesión estudiada sugiere un incremento de la participación piroclástica con frecuente e importante bioturbación y una menor proporción de cuerpos arenosos hacia el techo del perfil. Dicho patrón vertical estaría relacionado con un incremento de la tasa de acomodación, probablemente vinculado a una mayor tasa de subsidencia.

INTRODUCTION

The San Jorge Basin is the first and most prolific oil basin of Argentina. It is a small extensional intracontinental basin from central Patagonia (between 44-47°S and 66-71° W) (Barcat *et al.* 1989; Fitzgerald *et al.* 1990). The basin was filled with pyroclastic and epiclastic sediments from the Middle Jurassic to the Neogene. The Late Jurassic-Early Cretaceous deposits compose the first sedimentary cycle commonly associated to active faulting and extension commonly ascribed to the synrift stage (Fitzgerald *et al.* 1990; Figari *et al.* 1999; Bellosi *et al.* 2002). A new cycle of sedimentation started during the Early Cretaceous, whose deposits were named *Chubutense*, *Chubutiano* (Feruglio 1949; Hechem *et al.* 1990) or Chubut Group (Lesta and Ferello 1972). The latter deposits represent sedimentation during the sag stage (Uliana and Biddle 1987; Fitzgerald *et al.* 1990) or a new event of rifting (Figari *et al.* 1999). The filling of the basin is completed with a widespread tertiary sedimentation (Legarreta and Uliana 1994; Bellosi 1995; Bellosi *et al.* 2000).
Main petroleum reservoirs and current exploration targets correspond to fluvial sandstone bodies of the Chubut Group (e.g. Figari *et al.* 1999; Jalfin *et al.* 1999; Rodríguez and Littke 2001; Gonzalez *et al.* 2002; Salomone *et al.* 2002; Sanagua *et al.* 2002), which belong to Castillo and Bajo Barreal formations and lateral equivalents. Most stratigraphic and sedimentologic studies on these units are from the classic localities of the western part of the basin. However, there are still many unresolved aspects that are important for the characterization of the potential reservoirs, subtle traps and for the final development of many mature fields. The main controversy is the type of fluvial system that originated the sandstone bodies of the Bajo Barreal Formation: some authors suggested an ephemeral fluvial system (Hechem 1994, 1998; Sciutto 1999),

whereas other authors proposed sedimentation in a permanent fluvial system (Archangelsky *et al.* 1994; Bridge *et al.* 2000). Other poorly known aspects include the lateral facies relationships, the detailed channel sandstone body architecture and dimensions, and their petrophysical and diagenetic properties.
The goal of this paper is the paleoenvironmental characterization of the fluvial system from the lower part of the Bajo Barreal Formation and preliminary architectural analysis of some sandstone bodies in a selected locality from the western sector of the basin.

GEOLOGICAL SETTING

The outcrops of the Bajo Barreal Formation were studied at an east-west orientated canyon (45º 43´ 33´´ S; 69º 41´ 11´´ W) located north of Puesto Confluencia, on the left margin of the Senguerr River, south-western of the San Bernardo Range, Chubut province (Fig. 1). These outcrops are considered as part of the Lower Member of the Bajo Barreal Formation following Sciutto (1981, 1999). The San Bernardo Range is a fold belt with a NNW-SSE orientation, a length of approximately 600 km and a width of less than 100 km at most places. The local sedimentary succession composes the western limb of a faulted anticline with an axial trace orientated approximately N-S (Homovc *et al.* 1995; Sciutto 1999; Bridge *et al.* 2000). The strata dip 5º to 8º toward the south-western and locally show low angle reverse faulting.
The measured sedimentologic profile is approximately 340 m thick and started at the canyon head (45º 43´ 24´´ S; 69º 37´ 21´´ W) near the outcrops of the underlying Castillo Formation, although the contact is covered.

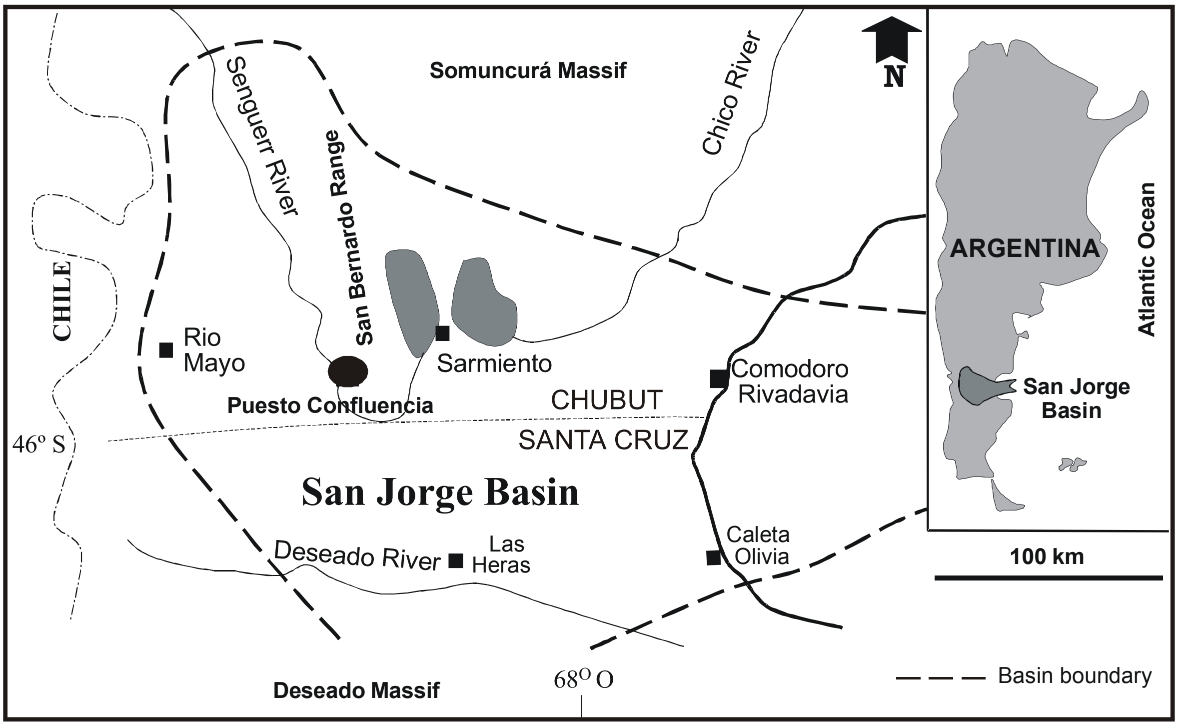

Figure 1: Location map of San Jorge Basin, Argentina.

METHODS

The measurement of the sedimentary profiles was realized using standard sedimentologic techniques. Detailed sedimentary profiles were measured at various positions along some selected sandstone bodies. For the architectural analysis, photomosaics of accessible and well exposed sandstone bodies were taken following the photographic techniques proposed by Wizevich (1991). The scales of the photomosaics were determined from direct measurements of sedimentary units at the field. The geometry and internal structure of sandstone bodies were traced on the photomosaics.

FACIES ASSOCIATIONS

The studied section of the Bajo Barreal Formation is composed of fining-upward channel-fill sandstones interbedded with primary and reworked tuffs and fine-grained sandstones. Twelve sedimentary facies were defined on the basis of lithology, texture, sedimentary structures and fossil content (Table 1), which can be grouped into four facies associations (Figs. 2 & 3).

Facies	Lithology	Sedimentary structures	Fossil content	Interpretation
G	Coarse to fine conglomerate	Trough cross bedding	Levels with very abundant logs	Migration of 3D dunes and bars
S1	Coarse to fine-grained sandstone, common tuffaceous intraclasts. Occasional Fe nodules.	Trough cross bedding	Abundant logs at certain levels, very scarce roots and vertical to horizontal burrows	Migration of 3D dunes and bars with pedogenetic alteration
S2	Coarse-grained sandstone with intraclasts at the base	Planar cross bedding		Migration of 2D dunes
S3	Coarse to fine-grained sandstone, very scarce intraclasts	Plane parallel lamination		Upper flow regime plane beds
S4	Fine-grained sandstone, occasional intraclasts at the base	Asymmetrical ripples	Scarce subvertical burrows	Migration of ripples
S5	Mostly fine-grained sandstone, occasionally medium-grained sandstone	Massive or structureless		Upper flow regime during turbulent flow
F	Siltstone	Laminated (sometimes deformed) or structureless	Scarce Skolithos and Palaeophycus	Setting from suspension
T1	Fine tuff, basal intraclasts are common	Trough cross bedding		Migration of 3D dunes
T2	Fine and medium tuff, common intraclasts and extraclasts, scarce concretions	Plane parallel lamination (sometimes deformed)	Scarce vertical burrows and Skolithos at the top	Upper flow regime plane beds
T3	Fine tuff (occasionally medium and coarse), frequent intraclasts and extraclasts	Massive or stratified	Levels with roots, vertical to horizontal burrows, logs Taenidium barretti	Upper flow regime during turbulent flow with pedogenetic alteration
T4	Coarse to fine tuffs	Grading		Setting from suspension
T5	Fine tuff with very scarce intraclasts	Massive, deformed stratification	Highly bioturbated	Destruction of primary structures by organisms

Table 1: Description and interpretation of sedimentary facies recognized for the Lower Member of Bajo Barreal Formation.

Facies association 1: fluvial channels

The facies association 1 (Fa1) consists of tabular or sheet sandstone bodies (c.f. Potter 1963; *fide* Stear 1983) of dominant very pale orange color (10YR 8/2) with multiple concave upward basal and internal erosion surfaces. These bodies have a lateral extension of tens to hundreds of meters and commonly forming fining-upward successions up to 14 m thick. Some bodies does not show vertical variation of grain size. The thicker sandstone bodies are volumetrically dominated by coarse-to-fine-grained sandstones with trough cross-bedding and frequent intraclasts (S1) and coarse-to-fine-grained sandstones with horizontal lamination (S3). The thin analysed sections show that the sandstones are feldspathic with abundant plagioclase or lithic dominated by volcanic fragments. Lens shaped and tabular conglomerate beds with trough cross-bedding (G) are also found. Internally, some sandstone bodies haves scarce fine-grained silt interbeds (F). Abundant log remains (up to 0.5 m in diameter and 2 m long) occur at the basal Fa1. At least two of the coarse sandstone-fine conglomerate bodies from the upper part of the section exhibit oil impregnation. Paleocurrent data from trough cross-bedded sandstones and conglomerates indicate a paleodrainage toward E-SE.
The fining upward cycles, unidirectional paleocurrent data, together with the concave upward basal erosion surfaces and logs suggest deposition in fluvial channels. The trough cross-bedded conglomerates and sandstones (facies G and S1) were deposited by three dimensional dunes and bars. The plane parallel laminated sandstones (facies S3) were formed as upper-flow regime plane beds from episodic and high-

energy streams. Silt interbeds signify a break in the sedimentation and may be considered pause planes formed during periods of little or no discharge. Presence of these scarce pause planes and nongraded

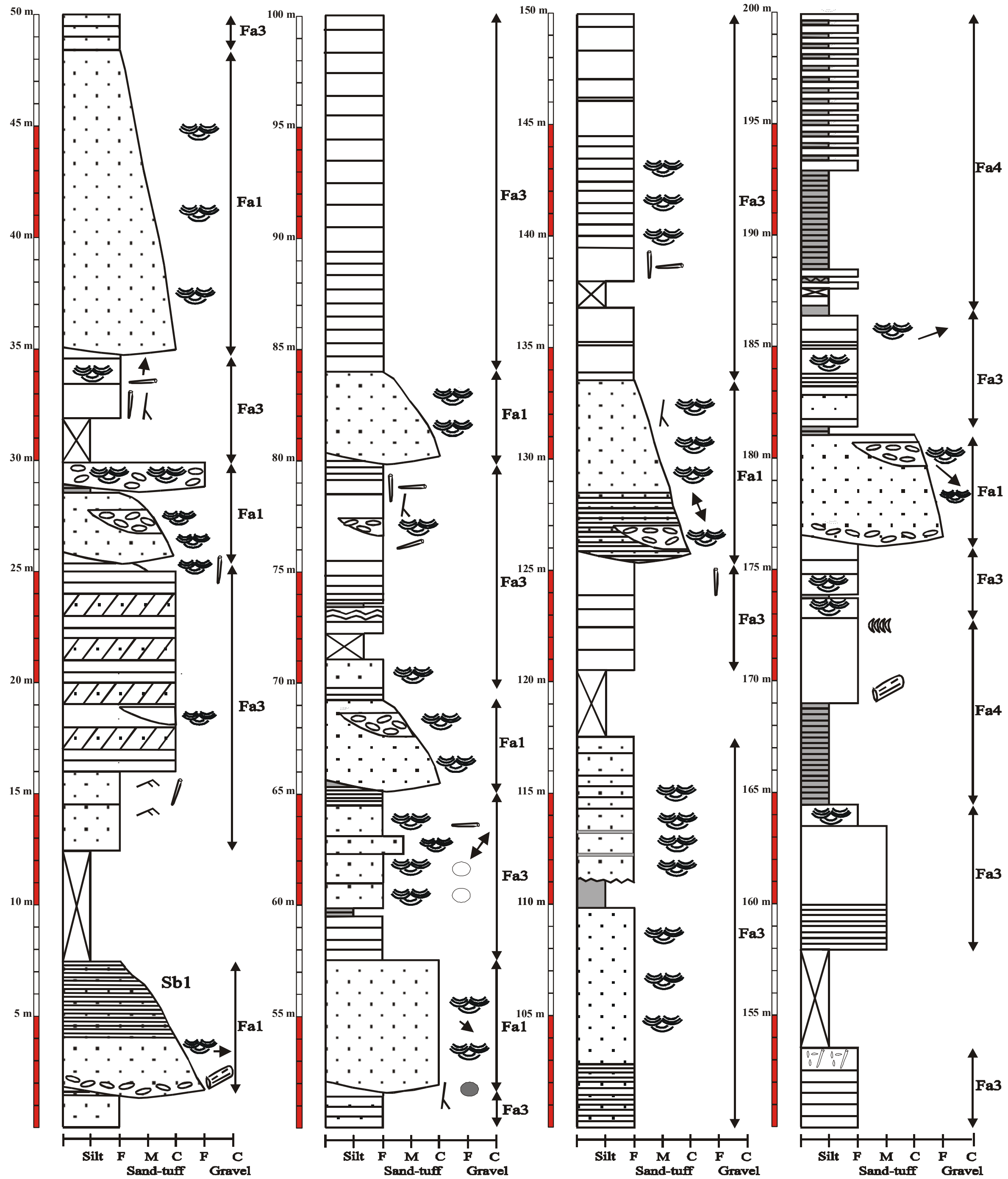

Figure 2: Sedimentary profile of Bajo Barreal Formation (Lower Member), near Puesto Confluencia. See references in Figure 3.

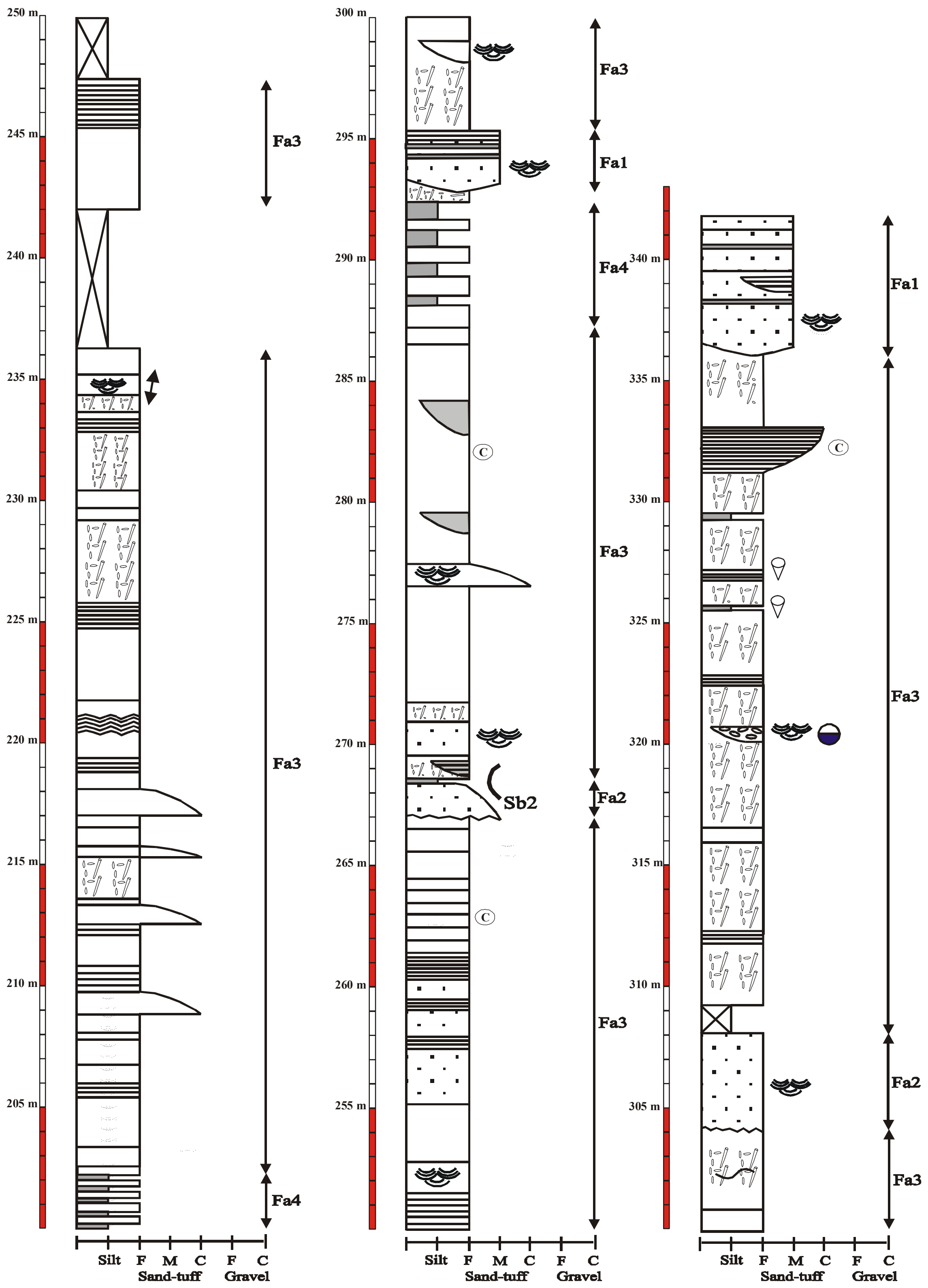

Figure 2: Sedimentary profile of Bajo Barreal Formation (Lower Member), near Puesto Confluencia. See references in Figure 3.

sandstone bodies, as well as thick beds with horizontal lamination have been considered characteristic of ephemeral fluvial deposits (i.e. Tunbridge 1984; Dreyer 1993).

Facies association 2: crevasse splays

The facies association 2 (Fa2) includes two sandstone bodies with flat erosive base, tuffaceous intraclasts, and convex upward top, composed of trough cross-bedded (S1) or massive (S5) medium-to-fine-grained sandstones. The dominant color is similar to Fa1. This facies association was recorded in the upper 80 m of the measured section. Considering the lobed geometry of facies association 2 and a similar grain size to the channel sandstone bodies assigned to Fa1, these deposits are interpreted as individual crevasse splays originated during high discharge events. Scarcity of these deposits suggest that the 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). Sandstone bodies with similar geometry and thickness have been described by Hechem (1994, 1998) for the Bajo Barreal Formation.

Facies association 3: sheet-like sandstones and tuffs

The facies association 3 (Fa3) comprises laterally continuous sheet-like beds composed of light-colored (N9, 5Y 8/4) primary and reworked tuffs and sandstones, which are interbedded with the remaining facies associations. This facies association account for most of the thickness of the measured section (approximately 65%). The volumetrically significant facies are sandstones with trough cross-bedding (S1), plane parallel lamination (S3) or massive (S5); in addition to reworked tuffs showing trough cross-bedding (T1), plane parallel lamination (T2), massive aspect (T3), grain size grading (T4), and moderate to high bioturbation (T5). Although subordinate, sandstones with planar cross-bedding (S2) or asymmetrical ripples (S4) and silt beds (F) were also recorded. Sandstone beds with fine roots and/or burrows (*Taenidium barretti* and undetermined burrows) were found within this facies association. Aligned or scattered intraclasts are common in all facies except in facies T4. Scarce paleocurrent data from trough cross- bedding sandstones and tuffs indicate two directions of paleoflow (toward NE and SW).
The facies association 3 was deposited in a floodplain setting, adjacent to the fluvial channels (Fa1) as unconfined overbank flows (c.f. Hirst 1991). In particular, massive (S5 and T3) and parallel laminated (S3 and T2) facies were deposited during sheetflood events. The origin of the material carried by these sheetflood events was as pyroclastic ash fall deposits which played an essential control on the depositional system. During sheetflood events large volumes of sediment are carried in suspension, supported by the turbulent nature of the flow. When flow velocities wane, rapid rates of sedimentation occur, leading in places to the deposition of massive, structureless or horizontally laminated deposits of granular sediment (e.g. Cas and Wright 1987). Dilute flows partially reworked sheetflood deposits, leading to development of 3D-2D dunes and asymmetrical ripples, recorded as facies S1, S2 and S4, respectively. Paleocurrent data indicate two directions of drainage (toward NE and SW), both almost perpendicular to the fluvial channels. The gradedd tuffs (T4) represent occasional sub-aqueous settling periods at ponds. However, a primary pyroclastic origin as ash fall can not be discarded for the facies T3, T4 and T5.
Horizons with fine roots and/or trace fossils and moderate-to-highly-bioturbated tuffs (T5) were developed in times of low sedimentation rates or no deposition. In the facies T5, the original structure was totally destroyed due to important biological activity.

Facies association 4: heterolithic floodplain

The heterolicthic floodplain facies association (Fa4) is composed of interbedded siltstone and tuff, which can be stacked reaching a thickness of 16 meters. This facies association does not constitute an important proportion of the succession (approximately 7%) and lacks an extended areal continuity. This facies association include two sedimentary facies: massive or laminated siltstones with scarce burrows assigned to *Skolithos* and *Palaeophycus* (F) and massive or stratified tuffs with abundant intraclasts (T3).
The facies F was deposited by settling from suspension in floodplain ponds with episodic clastic input and may represent the most distal floodplain facies (Rust 1978; *fide* Miall 1996). The facies T3 was produced by

turbulent flows during sheetflood events (e.g. Cas and Wright 1987). The interstratification of siltstone and tuffaceous beds suggests alternate periods of torrent flows and deposition from settling in floodplain ponds.

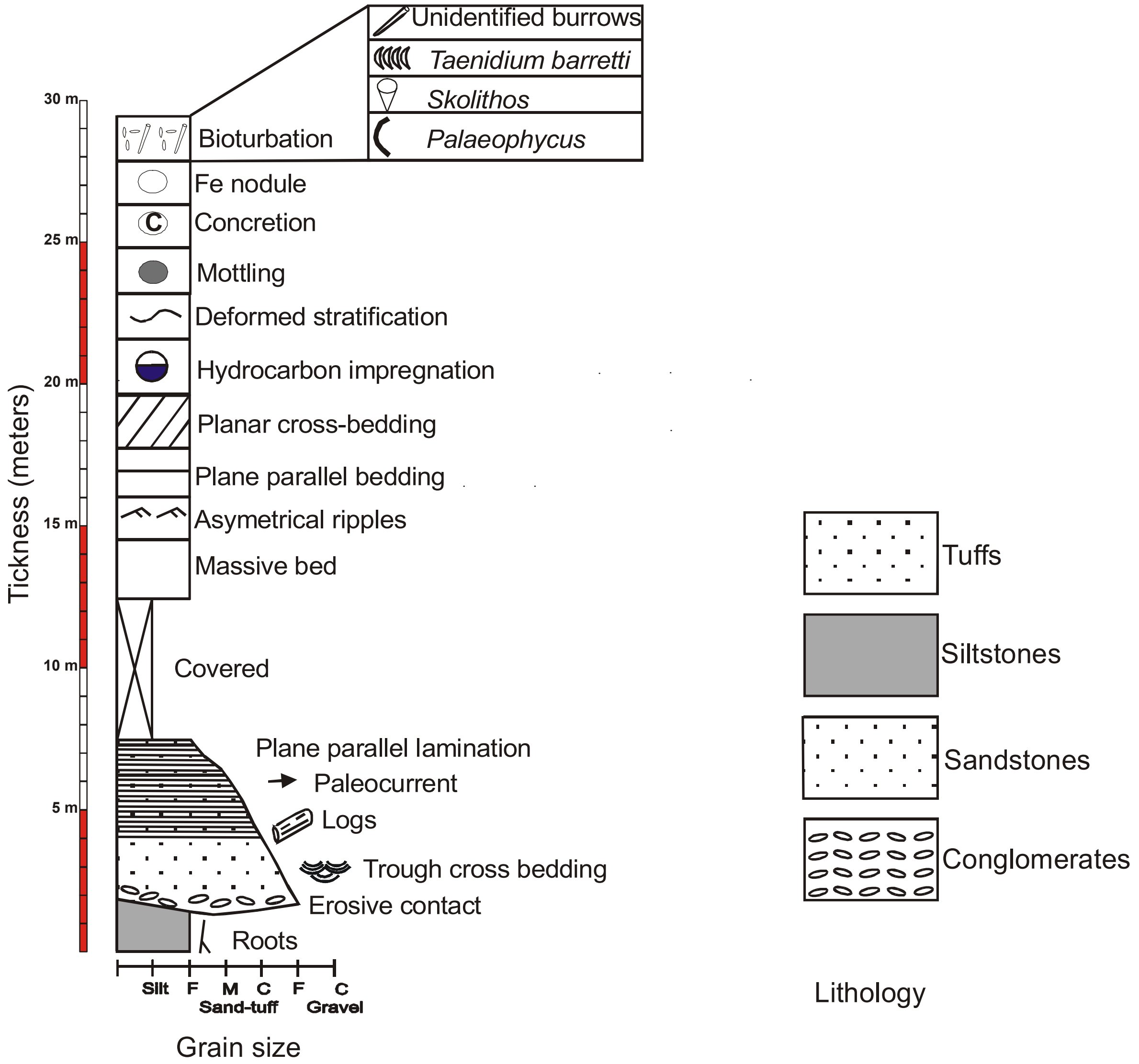

Figure 3: References to the sedimentary profile (see Fig. 2).

SANDSTONE BODY ARCHITECTURE

Two sandstone bodies located at the base of the section and at about 267 m from the base were selected for architectural analysis. The basal sandstone body (Sb1 in Fig. 2) is located in the left margin of a secondary gulch orientated N15º E that cuts the main canyon. The view analysed is perpendicular to the paleoflow (see paleocurrent data in Fig. 4), although a face parallel to paleoflow is also available. This body display a general tabular shape, although a thinning toward the north was observed (Figure 4). The measured length is 170 m, although the south end is truncated by the canyon, and the maximum thickness is 6.50 m. Internally, two bodies with concave upward basal erosion surfaces and flat tops were recognized. For this reason and considering the paleoenvironmental analysis, Sb1 represent a channel complex and their bounding surfaces coincide with fifth and sixth order surfaces as proposed by Miall (1995) and Bridge (1993), respectively. The 60 m wide channel 1 (Ch1) is composed of facies S1 and G (at the base) and shows abundant logs. The 130 m wide channel 2 (Ch2) is composed of facies S1 and S3 (the latter toward the top), and also displays very abundant log remains. The presence of a central bar in both channels indicates a multichannelled river (c.f. Rust 1978; *fide* Miall 1996). An apparent cross bar channel was identified in the Ch2. Sandstone bodies with similar dimensions were recognized by Bridge *et al.,* (2000) in other outcrops of the San Bernardo Range (Senguerr River Elbow and Cerro Colorado de Galvéniz).

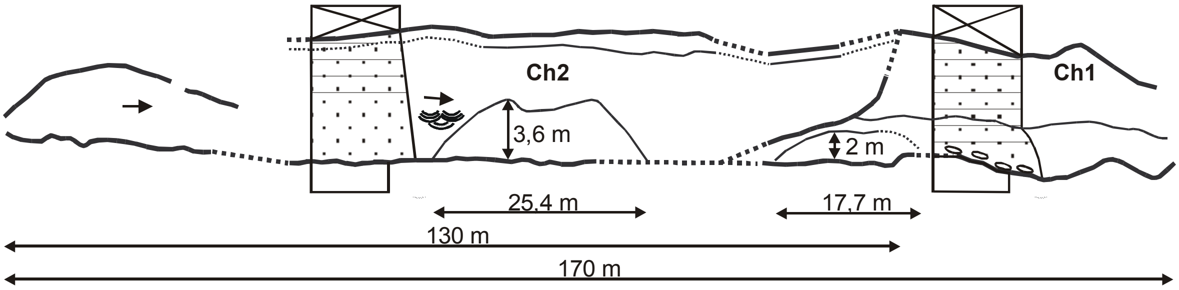

Figure 4: Architecture and synthetic sedimentary profile of a sandstone body corresponding to channel complex (Sb1 in Fig. 2). The vertical scale is exaggerated. Orientation of outcrop: N 15º E.

Sandstone body 2 (Sb2 in Fig. 2) is an individual crevasse splay deposit over the left (southern) margin of the canyon, where the outcrop face is orientated N45º E. The Sb2 displays an erosive flat base with tuffaceous intraclasts similar to the underlying bed and a convex upward top (Fig. 5). Maximum measured thickness is 1.50 m. It is composed by massive sandstones with fining-upward trend from medium-to-fine-grained sand. The sandstone body displays internal discontinuous surfaces parallel the convex upward morphology of the top of the body. Sb2 is similar to those bodies described by Hechem (1994, 1998) as lobes originated from hyperconcentrated and no-channelized flows. Nevertheless, in this contribution Sb2 is interpreted as an individividual crevasse splay deposit on the basis of its geometry and grain size similar to channel fill sandstones (Stear 1983).

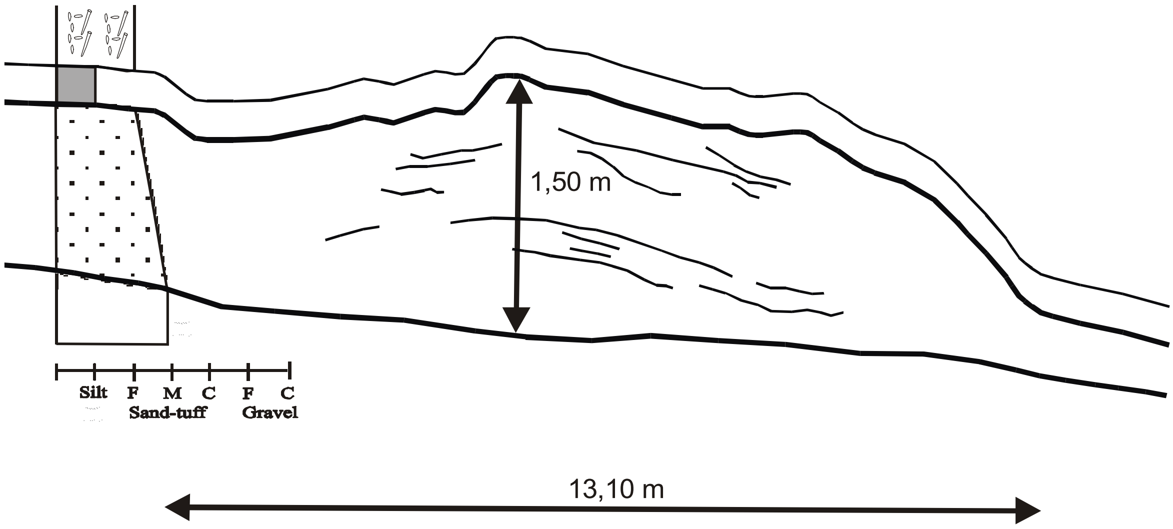

Figure 5: Architecture and synthetic sedimentary profile of a sandstone body corresponding to crevasse splay deposit (Sb2 in Fig. 2). Orientation of outcrop: N 45º E.

PALEOENVIRONMENTAL SETTING

The sedimentary succession of Lower Member of Bajo Barreal Formation at the studied locality was deposited in an alluvial setting with common ash fall events. The ephemeral streams dominated by coarse-to-fine-grained sandstones flowed toward E-SE as episodic and high-energy flows (c.f. Hechem 1994, 1998; Sciutto 1999) with scarce breaks in the sedimentation. A probably braided pattern is inferred from the presence of central bars and absence of lateral accretion surfaces (Bridge *et al.* 2000). The vertical accretion of the adjacent floodplains occurred commonly from sand and tuffaceous sheetfloods events. During periods of low or no deposition, these deposits were colonized by organisms and/or pedogenized. The sheetflood events flowed toward NE and SW and supplied fine sediment at ponds located in distal topographic depressions (Rust 1978; *fide* Miall 1996). Very scarce crevasse splays have occurred and represent the minor aggrading mechanism of the floodplain.

Despite the proposed paleoenvironmental interpretation, some features of the channel deposits are frequent in permanent rivers (for example: absence of bioturbation within the channels). Nevertheless, the presence of scarce pause planes, thicker beds with parallel lamination and some non-graded sandstone bodies suggest ephemeral flows.

The larger participation of fine-grained floodplain sediments upward succession and the poor development of paleosols suggest an increasing of the rate of accommodation, which can be linked to an increase in the tectonic subsidence rate and abundant input of pyroclastic materials. Nevertheless, highly-bioturbated tuff beds are more common in the uppermost part of the succession, which might suggest a progressive decrease in the rate of creation of accommodation.

RESERVOIR POTENTIAL

Sciutto (1999) noted the presence of oil impregnation in different outcrops from the southwestern flank of the San Bernardo Range, with no further details. The analysed succession of the Lower Member of the Bajo Barreal Formation near the confluence of Senguerr and Mayo rivers display some attributes that warrant further studies to ascertain its reservoir potential. The mentioned features include the presence of sandstone bodies with good lateral continuity and a thickness similar to the average reservoir thickness of the formation (e.g. Sanagua *et al.* 2002), and the presence of oil impregnation in coarse-grained bodies from the upper part of the analysed succession.

CONCLUSIONS

Near the confluence of the Senguerr and Mayo rivers, located in the western sector of San Jorge Basin, the Lower Member of Bajo Barreal Formation is mainly composed of massive tuffs and channel sandstones. The sedimentary succession was deposited in an ephemeral fluvial system. Tabular sandstone bodies with basal and internal erosive surfaces have been generated by successive confined streams during episodic and high-energy discharge events. These streams flowed toward the E-SE. Adjacent floodplain settings aggraded mainly during sheetflood events, responsible for deposition of the common sheet-like beds of tuffs and sandstones. Paleocurrent data from the latter deposits indicate a paleoflow perpendicular to the fluvial channels. Deposition in ponds and crevasse splays have also participated in the development of the floodplain. The proportion of sandstone bodies decrease upward in the measured section and concomitantly the amount of pyroclastic participation increase, sometimes with very important bioturbation. These vertical pattern could be related with an increasing of the rate of creation of accommodation space.

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