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Research paper

Sedimentology and alluvial architecture of the Bajo Barreal Formation (Upper Cretaceous) in the Golfo San Jorge Basin: Outcrop analogues of the richest oil-bearing fluvial succession in Argentina

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A B S T R A C T

This study addresses the sedimentology, architecture and dimensions of fluvial deposits in the Bajo Barreal Formation (Upper Cretaceous) in the Codo del Senguerr anticline, Golfo San Jorge Basin, Argentina. The stratigraphic framework of the 450–650 m thick alluvial succession was carried out through description and interpretation using 18 detailed sedimentary logs along a 4.5 km wide exposure, where 314 fluvial channels were analysed. The Bajo Barreal Formation is a high-accommodation fluvial succession, dominated by fine-grained floodplain deposits, with isolated-to-vertically stacked, sheet-like, low-sinuosity or braided fluvial channels of limited lateral mobility clustered in several coeval channel belts, in which fluvial channels were relocated by avulsion. The Lower Member consists of reworked ash-fall materials preserved in floodplain areas (78%), floodplain sandstones (4%) and fluvial channels (18%). The mean thickness of sandbodies is 2.96 m (n = 118) and mean true width is 112 m (mean W:T = 43), with thicker and wider sandbodies in upper levels of the Member. The Upper Member consists of grey siltstones and mudstones preserved in extensive lowland areas (78%) and fluvial channels (19%), with scarce preservation of sandstones in the proximal floodplain (3%). Fluvial channels are narrow low-sinuosity sheets with comparable thickness (mean = 3.21 m, n = 196), but greater width than those of the Lower Member (mean width = 147 m, mean W:T = 50). Paleoflow data from 298 fluvial sandbodies indicates a paleoflow direction toward the SE (Az. 112°). Rivers flowed parallel to inherited early Cretaceous normal faults and are oriented to high-angle (>70°) to the current axis of the Codo del Senguerr anticline, suggesting that the uplift of the anticline occurred after the deposition of the formation. The variation in geometry of fluvial channels in both Members of the Bajo Barreal Formation could help in planning and developing primary and/or enhanced oil recovery projects in nearby oilfields, and provide data necessary for modelling the subsurface connectivity of hydrocarbon reservoirs.

1. Introduction

Fluvial systems are heterogeneous on a variety of scales, from microscopic to megascopic (Weber and van Geuns, 1990; Ambrose et al., 1991; Jordan and Pryor, 1992; Miall, 1996; Lynds and Hajek, 2006; Bridge, 2003, 2006), as documented in a wealth of sedimentary studies of outcrops and modern systems. Coarse-grained components of ancient fluvial systems contain more of the 20% of the remaining reserves of hydrocarbon in the world, and are an important reservoir type for the petroleum industry. Their importance has resulted in research focused on understanding the internal and external complexity of reservoir types (Miall, 1996; Bridge and Tye, 2000; Bridge, 2003; Labourdette, 2011), modelling of their behaviour (Bridge and Leeder, 1979; Karssenberg et al., 2001; Keogh et al., 2007), and recovery of hydrocarbons (Tye, 1991; MacDonald and Halland, 1993; Hamilton et al., 1998; Root et al., 2005; Kjemperud et al., 2008).

The Golfo San Jorge Basin in central Patagonia (Fig. 1A) provides 47% of the liquid hydrocarbons in Argentina. About 90% of this hydrocarbon comes from fluvial channels in the Upper Cretaceous Bajo Barreal Formation. The remaining production is obtained from the Albian Castillo Formation, with minor production from the underlying Pozo D-129 Formation. Because of its prolific

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hydrocarbon production and remaining potential, the Bajo Barreal Formation has been extensively studied since the middle of the past century (Feruglio, 1949a,b; Lesta and Ferello, 1972; Lesta et al., 1980). The analysis of outcrop exposures in the San Bernardo Fold Belt (Fig. 1B) (Sciutto, 1981; Meconi, 1990; Figari et al., 1990; Legarreta et al., 1993; Hechem et al., 1990; Hechem, 1994, 1997; Bridge et al., 2000; Bellosi et al., 2002; Umazano et al., 2008, 2009, 2012) have shown large variability in facies and environment along the exposures, and variable importance of volcaniclastic materials in different areas of the basin. A huge amount of subsurface information including seismic surveys, wireline logs and cores (Brown et al., 1982; Clavijo, 1986; Barcat et al., 1989; Fitzgerald et al., 1990; Figari et al., 1999; Uliana and Legarreta, 1999; Sylwan, 2001; Rodriguez and Littke, 2001; Hechem and Strelkov, 2002; Sylwan et al., 2008) have been used to reconstruct the tectono-stratigraphic evolution of the basin, and to define the extension of hydrocarbon reservoirs. In the last 30 years, most of the subsurface research has been conducted correlating and mapping multiple, thin, isolated and discontinuous fluvial channels, which constitute the main hydrocarbon reservoirs (Sanagua et al., 2002; Rodriguez and Aguirre, 2015; Giampaoli, 2015). Although considerable research has been conducted on the sedimentology of the unit, little data has been published on the large-scale variability of the fluvial systems, or on the changes in its sandstone-body dimensions at outcrops. Exceptions include the detailed measurements on photomosaics of Bridge et al. (2000) and Umazano et al. (2012). In this paper, we present sandstone-body dimensions measured with GPS of 312 fluvial channels in both Members of the Bajo Barreal Formation in an area close to some of the main oilfields in the basin (Fig. 1B).

The aim of this study is to document the spatial and temporal variation in the sedimentology and alluvial architecture of the Bajo Barreal Formation along a 4500 m wide exposure in the eastern limb of the Codo del Senguerr anticline, to assess its potential as an analogue of hydrocarbon reservoirs in nearby oilfields. The specific objectives of this study are (1) to analyse the alluvial sedimentology and architecture of the Lower and Upper Members, (2) to quantify the dimensions (true width/thickness) of fluvial channels of both Members, (3) to provide useful information for primary and/or enhanced oil recovery practices, and (4) to analyse the coeval tectonic scenario based in the evolution of fluvial systems and paleoflow data. The sedimentological and tectonic implications of the approach followed in this study can be of interest to geologists working in fluvial successions in other geological settings. We hope the data will be also useful to geoscientists and engineers as they consider subsurface fluid flow problems in fluvial successions.

2. Geological framework

The Golfo San Jorge basin is a dominantly extensional basin superimposed on Paleozoic continental crust formed as a response to the break-up of the Gondwana supercontinent during the Jurassic and Early Cretaceous (Barcat et al., 1989). The infill of the basin started during the Middle to Upper Jurassic (Fig. 2), with deposition of a thick succession dominated by basalts, rhyolites and ignimbrites known as the Lonco Trapial or Bahía Laura Groups (Lesta and Ferello, 1972), representing the climax of the rift event that led to the fragmentation of Gondwana in southern South America. A second extensional event took place in the uppermost Jurassic and Early Cretaceous, with the development of E–W, NNW–SSE or NE–SW striking half-grabens, filled by black shales and wedge-shaped, sandstone bodies of lacustrine origin (Figari et al., 1999). These strata composed the Las Heras Group, and are only preserved in the subsurface.

The Barremian Patagonidic tectonic phase (compressional) in the Andean Ranges resulted in an eastward shifting of the main depocentres of the basin over a regional unconformity, and the incorporation of large volumes of pyroclastic detritus. At the same time, the generation of new WNW–ESE to E–W striking normal faults (Uliana et al., 1989; Paredes et al., 2013; Ramos, 2015) resulted in the creation of accommodation space for the deposition of the Chubut Group (Barremian to Campanian?) in fluvial and lacustrine environments (Hechem et al., 1990; Hechem and Strelkov, 2002). The Chubut Group mainly crops out in the San Bernardo Fold Belt, which was formed as a result of the tectonic inversion of extensional depocentres during the Cenozoic (Peroni et al., 1995; Homovc et al., 1995), although more recent studies (Navarrete et al., 2015; Gianni et al., 2015a,b) have suggested that the uplift of the San Bernardo Fold Belt started during the deposition of the Castillo Formation (Albian).

The Chubut Group is mape up of six continental formations: Pozo D-129, Matasiete, Castillo, Bajo Barreal, Laguna Palacios and Lago Colhué Huapi formations (Fig. 2). Initial sedimentation occurred in a widely distributed lacustrine unit (Pozo D-129 Formation - Barremian to Aptian) which was sourced from the north by fluvial systems within the Matasiete Formation (Sciutto, 1981; Paredes et al., 2007). Both units are overlain by the Castillo Formation (Albian), equivalent to the Mina del Carmen Formation in the subsurface (Lesta, 1968), which contains a large proportion of

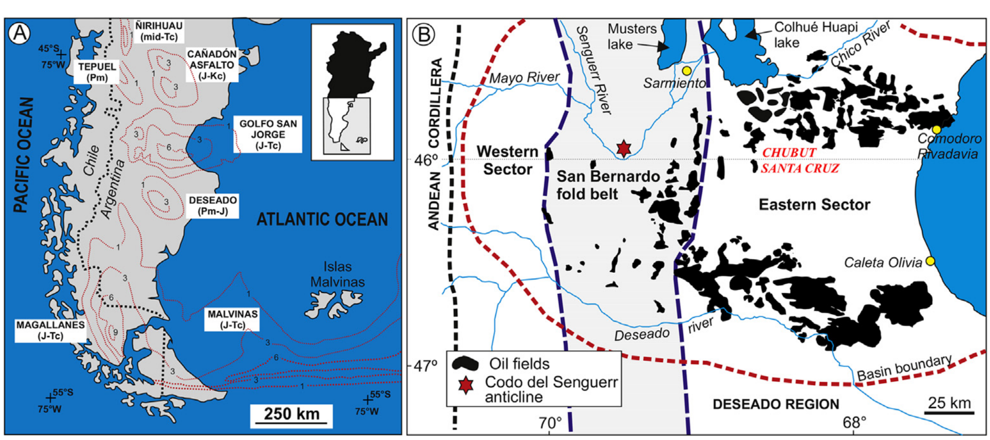

Fig. 1. **(A)** Location map of the Golfo San Jorge Basin and nearby basins in central Patagonia, Argentina. **(B)** Main structural regions of the Golfo San Jorge basin and boundaries of the basin, with indication of main localities. The major oilfields in the basin are indicated in relation to the location of the Codo del Senguerr anticline (star).

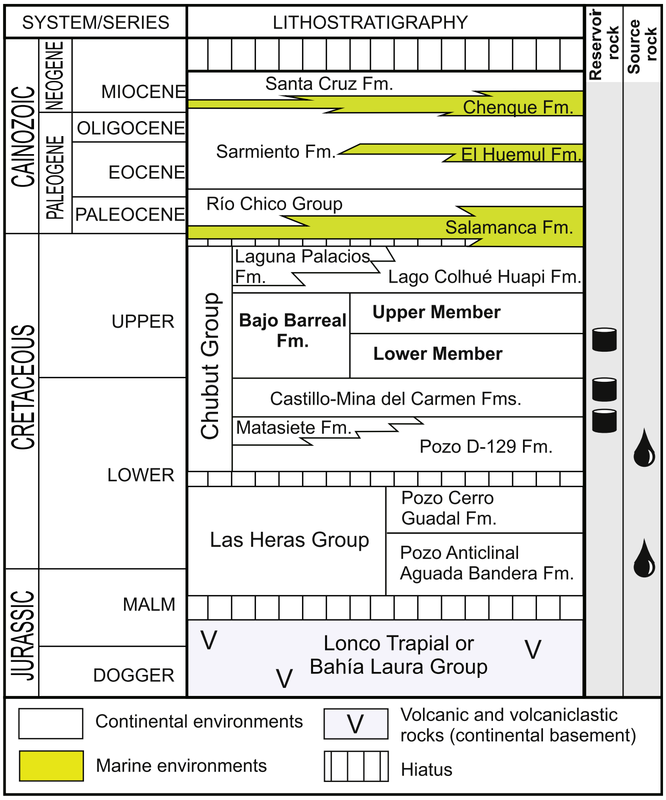

Fig. 2. Stratigraphy of the Golfo San Jorge Basin, with indication of main source and reservoir rocks.

reworked pyroclastic material mainly preserved in fluvial environments (Lesta and Ferello, 1972; Umazano et al., 2012; Paredes et al., 2015). The Castillo Formation is overlain by the fluvial Bajo Barreal Formation (Senomanian to Campanian?), which has two members. The Lower Member in outcrop is commonly composed of channelled sandstones, interbedded with thicker and finer grained (very fine sand-size) tuffaceous strata. The Upper Member is composed of isolated channel sandbodies surrounded by grey siltstones and mudstones (Figari et al., 1990; Umazano et al., 2008). The Bajo Barreal Formation (Lesta and Ferello, 1972) and its subsurface equivalents (Lesta, 1968) are distributed over an area exceeding 150000 km^2, with thicknesses from 300 m to up to 2500 m in the centre of the basin (Fitzgerald et al., 1990). Their wide distribution has allowed varied interpretations of their deposits, including lacustrine fans, volcaniclastic alluvial fans, meandering and braided rivers, and ephemeral rivers (Brown et al., 1982; Barcat et al., 1989; Hechem et al., 1990; Fitzgerald et al., 1990; Legarreta et al., 1993; Rodriguez, 1993; Hechem, 1997). Bridge et al. (2000) carried out detailed sedimentological work on the Bajo Barreal Formation; most of their data were obtained from the Cerro Ballena (Santa Cruz province), with additional data from the southern side of the Senguerr river and cerro Colorado de Galveniz (Fig. 3A). At the southern margin of the Senguerr river Bridge et al. (2000) constructed three sedimentological sections and photomosaic panels, identifying single, straight to low-sinuosity ($S < 1.2$) fluvial channels draining to SE (mean: 116°) with a channel/floodplain ratio of 0.3. The mean thickness of sandbodies was 3.96 m, lateral extent of 62.5 m, and width/thickness ratio of 23.85 ($n = 26$). Umazano et al. (2008) studied the Bajo Barreal Formation at Sierra Nevada and Puesto Confluencia (location in Fig. 3A), and considered that during deposition of the Lower Member, pyroclastic sediments that arrived as ash falls were reworked by braided rivers and deposited over wide floodplains by sheetflood processes. During deposition of the Upper Member a braided river pattern was recognized by Umazano et al. (2008) in which the associated floodplain aggraded mostly by fine-grained aeolian sedimentation (loess deposits), and less commonly as sheet floods, and primary pyroclastic-fall deposits were rare. The petrography and geochemistry of the sandstones and tuffaceous components indicate a westerly source from a coeval volcanic arc of acid to intermediate composition (Umazano et al., 2009).

The age of the Bajo Barreal formation is controversial. Ar–Ar dating of pyroclastic strata (Bridge et al., 2000) implies that the Bajo Barreal Formation was deposited between 97.9 and 91.0 Ma (Cenomanian-early Turonian). A late Albian-Cenomanian palynological association was obtained from the subsurface (Lower Bajo Barreal = Caleta Olivia Member of the Cañadón Seco Formation) by Archangelsky et al. (1994). A recent SHRIMP U–Pb zircon age of 99.7 ± 0.7 Ma (Cenomanian) was obtained dating 20 zircon grains of a tuffaceous strata of the Upper Member at Codo del Senguerr (Suárez et al., 2014); nevertheless in the same sample the authors mention the occurrence of three zircon grains with ages of 94.4 ± 1.1 Ma, 93.1 ± 1.2 and 91.7 ± 1.4 Ma (early Turonian).

Available information about the climate during the deposition of the Bajo Barreal Formation is limited. A palynological assemblage recovered from the Lower bajo Barreal Formation in the subsurface (Archangelsky et al., 1994) evidence humid, continental mild to warm climate during Late Albian-Cenomanian times, and similar conditions have been also reported from southernmost areas of Patagonia in the Late Albian-Cenomanian Kachaike Formation (Barreda and Archangelsky, 2006). However, as mentioned previously, most sedimentological studies indicate fluvial systems with large discharge variation or ephemeral rivers (Hechem, 1997; Umazano et al., 2008).

Toward the basin margin, the Bajo Barreal Formation is covered by the Laguna Palacios Formation (Sciutto, 1981; Genise et al., 2007), which is characterized by the stacking of pyroclastic paleosols and minor channels. Recently, the Lago Colhué Huapi Formation (Campanian?-Maastrichtian?) has been proposed as a lateral equivalent of the Laguna Palacios Formation (Casal et al., 2015), due to the occurrence of a well-preserved skull of *Aeolosaurus Colhuehuapensis* (Casal et al., 2007), a genus recorded since the Campanian in Argentina (Powell, 1987; Salgado et al., 1997).

Paleocene strata include the marine Salamanca Formation and the continental Río Chico Group. The remaining Cainozoic succession is represented by the Sarmiento, El Huemul, Chenque and Santa Cruz formations, and glaciofluvial gravels of Plio-Pleistocene age known as "Rodados Tehuelches".

3. Methodology

The studied area is located in the southernmost exposures of the San Bernardo Fold Belt in Chubut province (Figs. 2 and 3), on the eastern limb of the Codo del Senguerr anticline. The Codo del Senguerr anticline is a southward plunging fault-propagation fold associated with a buried, east-dipping reverse fault located west of the anticline (Homovc et al., 1995). The fold has a steep west-dipping limb and a broader, more shallowly-inclined eastern limb. At Codo del Senguerr anticline, the Chubut Group reach the maximum exposed thickness in the San Bernardo Fold Belt, with exposure of a 140 m thick section of the lacustrine Pozo D-129 Formation in the core of the anticline (Paredes et al., 2014) and 960 m of a fluvial succession belonging to the Castillo Formation (Paredes et al., 2015); the basal contact with the overlying Bajo Barreal Formation is gradational, and only visible in the eastern limb. The western limb of the Codo del Senguerr anticline do not expose rocks of the Bajo Barreal Formation. The 450–650 m thick

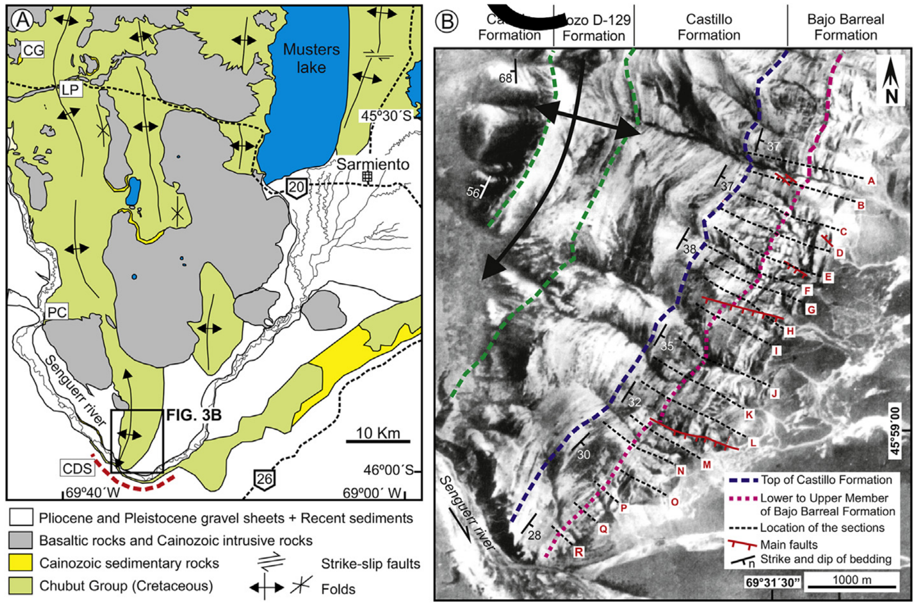

Fig. 3. (A) Simplified geological map (after Paredes et al., 2007) of the San Bernardo fold belt in exposures northward of the Codo del Senguerr anticline. Keys: PC = Puesto Confluencia, LP = Las Pulgas anticline, CG = cerro Colorado de Galveniz, CDS = Codo del Senguerr anticline. The red, dotted line in the southern side of the Senguerr river marks the area studied by Bridge et al. (2000). **(B)** Aerial photo of the Codo del Senguerr anticline. The main lithostratigraphic boundaries and tectonic structures are shown. Letters A to R represent the location of the measured sections in the eastern limb of the anticline. The sedimentological markers are displaced by high-angle faults oriented normal to the axis of the anticline.

succession (top is eroded) of the Bajo Barreal Formation was analysed along a 4.5 km width exposure, that allow the observation of multiple channel-form fluvial sandbodies. A total of 7389 m of strata thickness were measured along eighteen stratigraphic sections (Fig. 4) separated from each other by 140 m–400 m (average 291 m); 44% of the data comes from the Lower Member and 56% from the Upper Member.

Two hundred ninety-four fluvial sandstone bodies of the Lower and Upper Member were precisely measured (thickness, width) using the Jacob staff and a global positioning system (GPS) device; twenty additional channels were not sufficiently preserved to allow the measurement of the true width, due to lateral erosion in canyons and/or lack of paeoflow data, and are not included in the diagrams. The width of individual or multi-storey channels were measured using GPS point data at their margins, and correcting their apparent width using the mean of the paleocurrent data for each channel. The real width/thickness ratio of fluvial channels (hereafter abbreviated as W:T) was obtained and plotted on frequency histograms. Lithofacies and lithofacies associations were described and interpreted. Approximately 4074 paleocurrent measurements, derived primarily from several varieties of cross-bedding, supplement the lithofacies information and aid in the reconstruction of the paleogeographic setting. Paleocurrents were structurally corrected according to the geometrical methods (Ramsay, 1961) using a declination of 9°E. Two-dimensional panels of selected multi-storey fluvial channels were established to include information of bounding surfaces, cross-sectional geometry, internal lithofacies and bedding architecture in order to depict lateral and vertical lithofacies relationships. Geometry of fluvial channels were broadly classified as ribbons (W:T < 15), narrow sheets (15 > W:T < 100) and broad sheets (W:T > 100) following Gibling (2006) criteria.

4. Facies and facies associations

Detailed descriptions and interpretations of fifteen lithofacies that constitute four lithofacies associations are presented below, defined on the basis of their lithology, grain size, sedimentary structures, geometries and boundaries. A selected sedimentological log is presented in Fig. 5. A brief summary of their main attributes, flow properties and interpretation is presented in Table 1 and typical features are shown in Fig. 6. Metre-scale architectural elements, equivalent to lithofacies associations (Bridge, 1993), record short-term physical processes (Miall, 1991) providing a basis for understanding the nature of the depositional system. The main lithofacies associations are interpreted as (i) subaerial floodplains and ephemeral ponds; (ii) proximal floodplains, with three subtypes: crevasse-splay, overbank fines and crevasse channels; (iii) sheetfloods, and (iv) major fluvial channels, with three sub-types.

4.1. Facies Association A (FA-A): subaerial floodplains and ephemeral ponds

4.1.1. Description

Fine grained components represents up to 75% of the sections in both Members of the unit, and two distinctive suites of lithological components were recognized. In the *Lower Member* the lithofacies association refers to clay-sized to very-fine grained vitric ash beds with individual strata ranging from tens of centimeters to 1.2 m thick that can be traced laterally for hundreds of metres; their stacking results in aggradational successions of several tens of metres thick that can be traced laterally for up to 2000 m (Fig. 7A). It is characterized by the occurrence of massive, white-to pale green, tabular, tuffaceous strata (Tm) that may contain fossil traces, roots and/or asymmetrical ripples (Fr), or rarely tuff strata containing core-type accretionary lapilli (Tla). Silicified, tuffaceous strata with plane-lamination are common (Tl). Frequently, the tuffaceous strata contain volcanic or tuffaceous clasts (<2 cm in diameter), or variable-altered pumice clasts with dissolution cavities; thin sections of these strata show variably-altered glass shards and large proportions of siltstones or very fine-grained sandstones. Locomotion traces assigned to *Planolites* and *Palaeophycus* are occasionally preserved on bedding surfaces; vertical, cylindrical burrows were attributed to *Skolithos*. Rarely, meniscate,

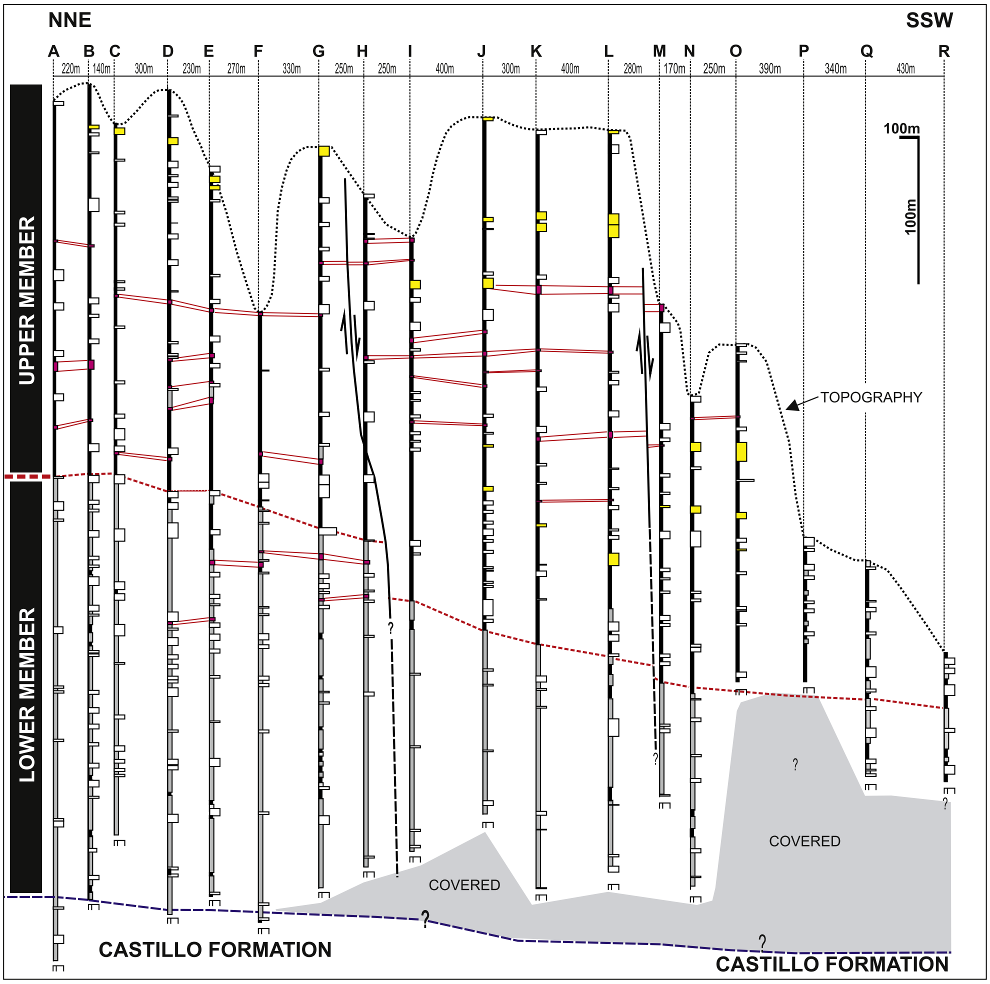

Fig. 4. Lithostratigraphic correlation of sedimentary logs (see Fig. 3 for location of the sections). Solid correlation levels (in red) are tuffaceous strata, whereas dashed correlations lines are boundaries of Formations or Members. White boxes are channel sandstones, yellow-coloured channels in the Upper Member contain extrabasinal conglomerates. Overbank deposits are shown in black or grey.

backfilled traces attributed to *Taenidium isp.* were identified. Strata may also contain vertically-oriented rhizoliths, pale grey mottling or desiccation cracks on bedding surfaces. Paleosols show no development of any typical or diagnostic horizon. In contrast, in the *Upper Member*, most of the fine-grained deposits are tabular, massive grey siltstone or mudstones (Fsm) in strata up to 1 m of thickness; their stacking produces tabular, fine-grained packages several tens of metres thick (Fig. 7B). In many cases, they contain thin intercalations of pale-grey, finely-laminated mudstone (Fsh) or rarely thin (<50 cm) strata of white, tuffaceous deposits (Tm); meniscate burrows are common.

4.1.2. Interpretation

The fine grain size of ash particles suggests a distal volcanic source for the pyroclastic materials (Walker, 1971). Their preservation as tabular, very extensive beds indicates a general low-relief floodplain environment and transportation of the material by suspension during overbank sheetfloods. Plane laminations in tuffaceous strata are due to primary deposition or can reflect reworking by aeolian currents, or floods. The aggradational pattern of the grey mudstones is produced by a combination of (mainly) overbank sedimentation during high-discharge events, although it may have been reinforced by transportation of silts by aeolian processes (Umazano et al., 2008). The occurrence of accretionary lapilli is due to contemporary rain in the basin during pyroclastic ash-fall events (Fisher and Schmincke, 1984); in distal volcaniclastic environments it is a feature only preserved in the subaerial floodplain, due to destruction of non-welded ash-aggregated particles by water (Cas and Wright, 1987). Strata containing accretionary lapilli are the single unequivocal tuff strata in the unit. This lithofacies association mainly represents a subaerial floodplain environment, although subaqueous environments are inferred in tuffaceous strata that preserve current ripples or plane-laminations with dispersed outsized clasts. Such features were likely developed in poorly-drained, ephemeral ponds, reflecting the formation of standing bodies of water laterally adjacent to the fluvial sandbodies.

4.2. Facies Association B (FA-B): proximal floodplain environment

4.2.1. Description

This lithofacies association represent on average 1.50% of the measured sections, with three distinctive sub-associations. The sub-association FA-B1 consists of moderately-sorted, coarse to very-fine grained tuffaceous sandstones interbedded with silt-to clay-sized ash beds and/or mudstone strata. The sandstones that occur in this sub-association have a plane or erosional base, with individual strata several cm to several tens of cm of thickness; they display a clear coarsening-upward trend in packages up to 3 m thick. Most of the strata are massive (Fm), but commonly include

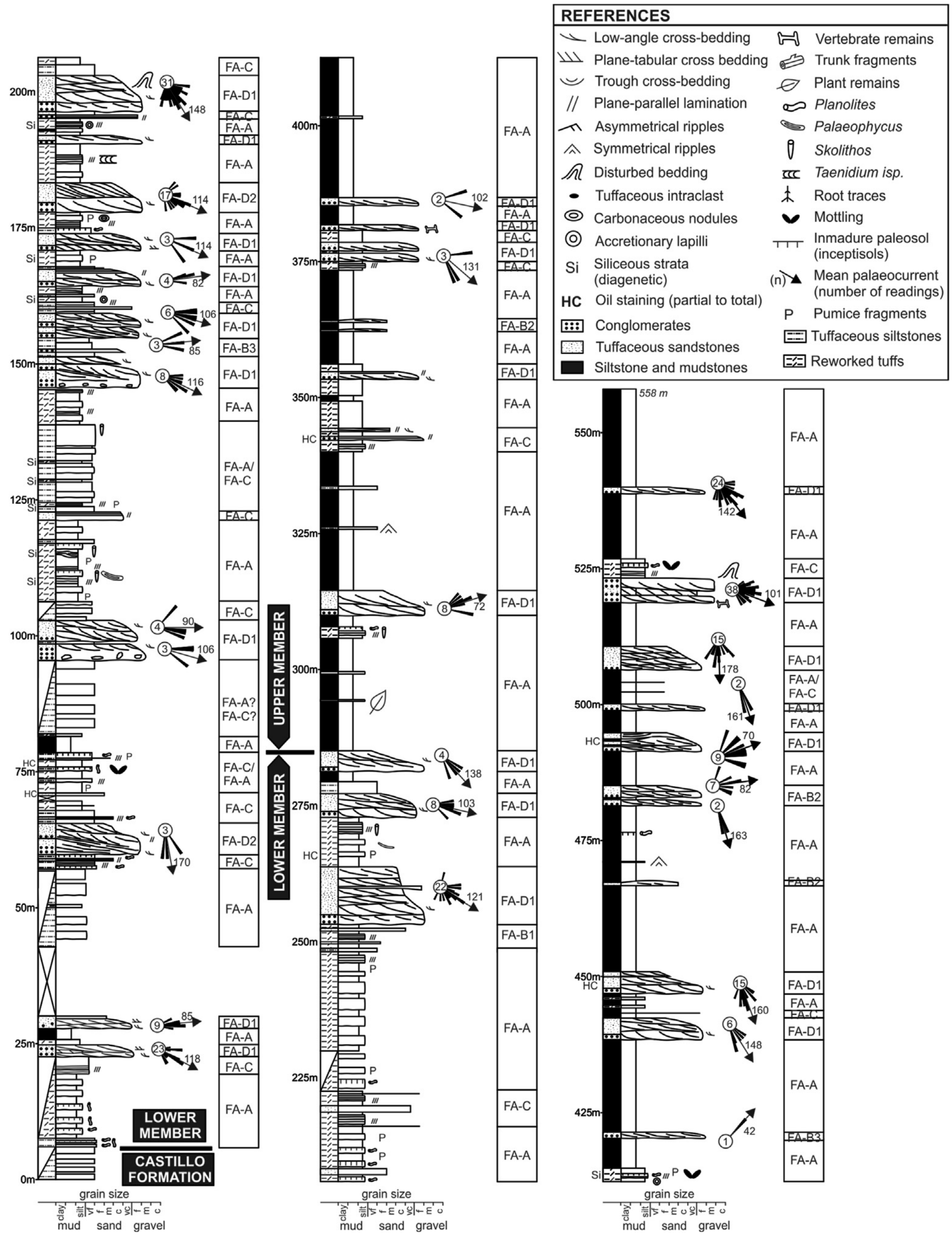

Fig. 5. Detailed sedimentological log (Section C) of the Bajo Barreal Formation in the Codo del Senguerr anticline. Location of the section in Fig. 3 and 4.

patches of plane-lamination (Fl) or low-angle cross bedding (Ft). Fossil traces are dominated by sand-filled vertical burrows of *Skolithos* and sand-filled horizontal burrows (*Palaeophycus* like), although meniscate burrows attributed to *T. isp.* are also recorded. The second sub-association (FA-B2) is integrated by moderately-sorted, coarse to very-fine grained tuffaceous sandstones of plane base and convex-upward top (Fig. 8B). Individual strata thin out laterally, but amalgamated strata show a sheet-like geometry, with, large-scale, low-angle (3–6°) surfaces that separate sandbodies with fining-upward trends and gradual thickness variations. The sandstone packages range in thickness from 0.4 to 0.8 m, and have a true width of 8 m–90 m. Internally they contain plane lamination (Fl) or low-angle cross bedding (Ft) with alternations of massive strata (Fm). The third sub-association (FA-B3) consists of tabular, fine-grained tuff strata locally dissected by coarse to fine-grained sandstones with erosive, concave-upward basal boundary and ribbon geometry (Fig. 8A), containing plane-lamination (Fl), low angle cross-bedding (Ft) and trough cross-bedding (Fx), and rarely fine sandstone with asymmetrical ripples at top (Fr). Paleoflow directions are oriented at high-angle in relation to adjacent fluvial channels. Sandstone packages can reach 1.8 m thick and 15 m of true width.

4.2.2. Interpretation

A proximal floodplain environment is inferred due to the alternation of coarse and fine-grained lithologies, the small scale of the interbedded sandstone bodies and their spatial association with fluvial channels. The coarsening-upward sub-association (FA-B1) is considered a levee deposit produced by deposition from suspension of fine-grained material in a low-energy environment, with

Table 1
Lithofacies of the Bajo Barreal Formation in Codo del Senguerr anticline.

Code	Facies and description	Interpretation
Fce	*Clast-supported extraformational conglomerate.* Common, only in the Upper Member. Crudely bedded or with trough cross-bedding, clast-supported, sub-rounded to rounded clasts of igneous (rhyolites) and pyroclastic origin. Matrix of coarse to medium-grained tuffaceous sandstones. Mean size up to 3 cm, with rounded clasts up to 20 cm in diameter. Common soft-sediment deformation.	Downstream migration of bars or migration of 3D dunes.
Fci	*Intraformational conglomerate.* Abundant. Tuffaceuos, fine conglomerates with clast or matrix supported texture. Crudely bedded or with trough cross-bedding. Matrix of coarse to medium-grained tuffaceous sandstones. Mean size up to 0.5 cm, with rounded clasts up to 7 cm in diameter.	Downstream migration of bars or migration of 3D dunes inside channels.
Fcc	*Clast-supported, tuffaceous breccia.* Rare. Poorly organized accumulation of angular to sub-rounded blocks until 0.7 m in size Erosive base, structureless. Individual blocks could contain interbedded siltstone and sandstones, and fossil traces.	Overbank sediments incorporated into a channel by gravitational bank collapse.
Ft	*Low-angle cross bedded tuffaceous sandstone.* Abundant. Slightly erosive base, moderate grain size selection, occasionally with fining upward trend from coarse to fine sandstones. Sets are <0.5 m thick and 1–4 m of lateral extent. Foresets dip less than 10°. Individual laminae show plane-parallel lamination. Interbedded with massive or trough cross-bedded strata. Trunk remains. Occasional convolute bedding.	Downstream accretion of low relief bedforms with high wavelength/amplitude ratio.
Fx and Fp	*Trough (Fx) and planar (Fp) cross-bedded tuffaceous sandstone*. Fx common, Fp subordinate. Very coarse-grained to fine-grained, sub-angular to sub-rounded clasts showing moderate sorting. Beds average 0.3–0.6 m thick, with bedset up to 2 m. Could contain trunk remains or broken dinosaur bones.	Migration of straight-crested or curved-crested bedforms in lower flow regime conditions.
Fl	*Parallel-laminated tuffaceous sandstone.* Abundant. Medium to very-fine grained sandstones, with planar base and moderate sorting, occasional outsized clasts. Laminae are few mm to 1 cm in thick and show normal grading. Laminae boundaries defined by changes in the grain size. Frequently interbedded with low-angle cross bedding and/or massive sandstones. Locally convolute lamination chaotically folded.	Deposition under upper-flow regime within a fluvial channel, or as an unconfined fluvial sheetflood.
Fb	*Burrowed tuffaceous sandstone.* Common. Medium to fine-grained sandstones with gradational base to other coarse-grained facies. Contain roots, mottling and several fossil traces, included *Skolithos* sp, *Planolites*, and *Taenidium* sp.	Destruction of structure due to bioturbation.
Fm	*Massive tuffaceous sandstone*. Subordinate. Very coarse to very fine, ungraded, structureless sandstones. Strata are tens of cm thick, with scours at base. Interbedded with plane-laminated or trough cross-bedded stata.	Rapid deposition of bedload during high-discharge conditions.
Fr	*Current-ripple laminated tuffaceous sandstone.* Rare. Very-fine to fine-grained sandstones with good sorting. Associated to several current-dominated sandstone facies or interbedded with fine-grained, massive tuffaceous material. Strata are less than 20 cm in thickness. Unimodal palaeocurrents.	Migration of small bedforms within a fluvial channel or via unconfined flows under lower flow regimes.
Fsh and Fsm	*Massive (Fsm) or horizontally laminated (Fsh) siltstone/mudstone.* Abundant in the Upper Member. Pale-grey siltstone with lower amount of mudstone. Where preserved, laminations are less than 5 mm thick. Frequent incorporation of isolated, tuffaceous clast until 1 cm in diameter or small, unorganized wood (carbonaceous) fragments.	Deposition from suspension within a fluvial channel or in a floodplain environment.
Tla	*Tuffs with accretionary lapilli.* Scarce. Fine grained, well sorted vitric tuffs containing scattered to densely-packed, core-type accretionary lapilli beds. Individual aggregated are 3–7 mm in diameter or have oval shape. Thickness of strata variable from 5 cm to 30 cm, extension variable from tens to thousands of metres. Interbedded with fine-grained plane-laminations and/or massive tuffaceous beds.	Fallout from remnants of Plinian plume on the subaerial floodplain
Tm and Tl	*Massive (Tm) or horizontally laminated (Tl), fine-grained tuffaceous sediment*. Abundant in the Lower Member, rare in the Upper Member. Laminae are few mm thick and commonly ungraded, but can be normally graded and contain clasts of coarse tuffaceous sandstones, or pumice fragments up to 1 cm in diameter. Packages can reach up to 10 m of thickness. Contain rootlets, intense mottling and several fossil traces, including *Planolites*, and *Palaeophycus sp.* Some beds contain symmetrical ripples and wood fragments on bedding surfaces.	Reworking of primary ash-fall beds by aqueous or (rarely) aeolian flows. Later pedogenesis of reworked tuffs.
Tvt	*Trough cross-bedded vitric tuffs.* Rare, only in the Upper Member. Erosive base and lenticular geometry, with coarse-grained lag, interbedded with massive or plane-laminated strata. Abundance of glass shards, with dispersed sub-angular to sub-rounded clasts. Cross-sets are 30–50 cm of thickness. Common burrowing on top of strata, and on bedding surfaces. Could grade laterally to low-angle cross bedding.	Reworked ash-fall bed inside fluvial channels by turbulent flows in lower flow regimes.
Tvl	*Horizontally laminated vitric tuffs.* Strata with planar base, thickness from few cm to several tens of cm. Laminae is <5 mm thick, but changes in the thickness laminae into the same strata are common, as well as inverse grading. Frequent low-angle truncations of laterally extensive laminae. Could contain pumice outsized clasts interbedded parallel to the planar lamination. Biotite grains oriented parallel lo the laminae are common.	Reworked ash-fall deposits inside fluvial channels by turbulent flows in upper flow regimes.

sandstone deposition during periods of increased sediment supply to the floodplain, likely associated with floods. Coarsening upward trends reflect the gradual increase in discharge or changes in the distance from an avulsed channel (Jones and Hajek, 2007). Lobate bodies (FA-B2) were deposited from unconfined flows during high-discharge events (Smith et al., 1989) as crevasse-splays; massive sandstone may also indicate rapid deposition. Scoured-based sandbodies (FA-B3) are interpreted as crevasse channels, formed as a result of the crevassing of a major river channel (Farrell, 2001).

4.3. Facies Association C (FA-C): sheetflood deposits

This facies association includes tabular sandstone strata that lack evidence of channel scouring, and dominated by plane-lamination. Excluded from this association are those coarse-grained deposits that share the geometry and internal structure, but are part of multistory channels of a known fluvial pattern (see below). Although the occurrence of this association is low (<3%), these deposits occur in both Members.

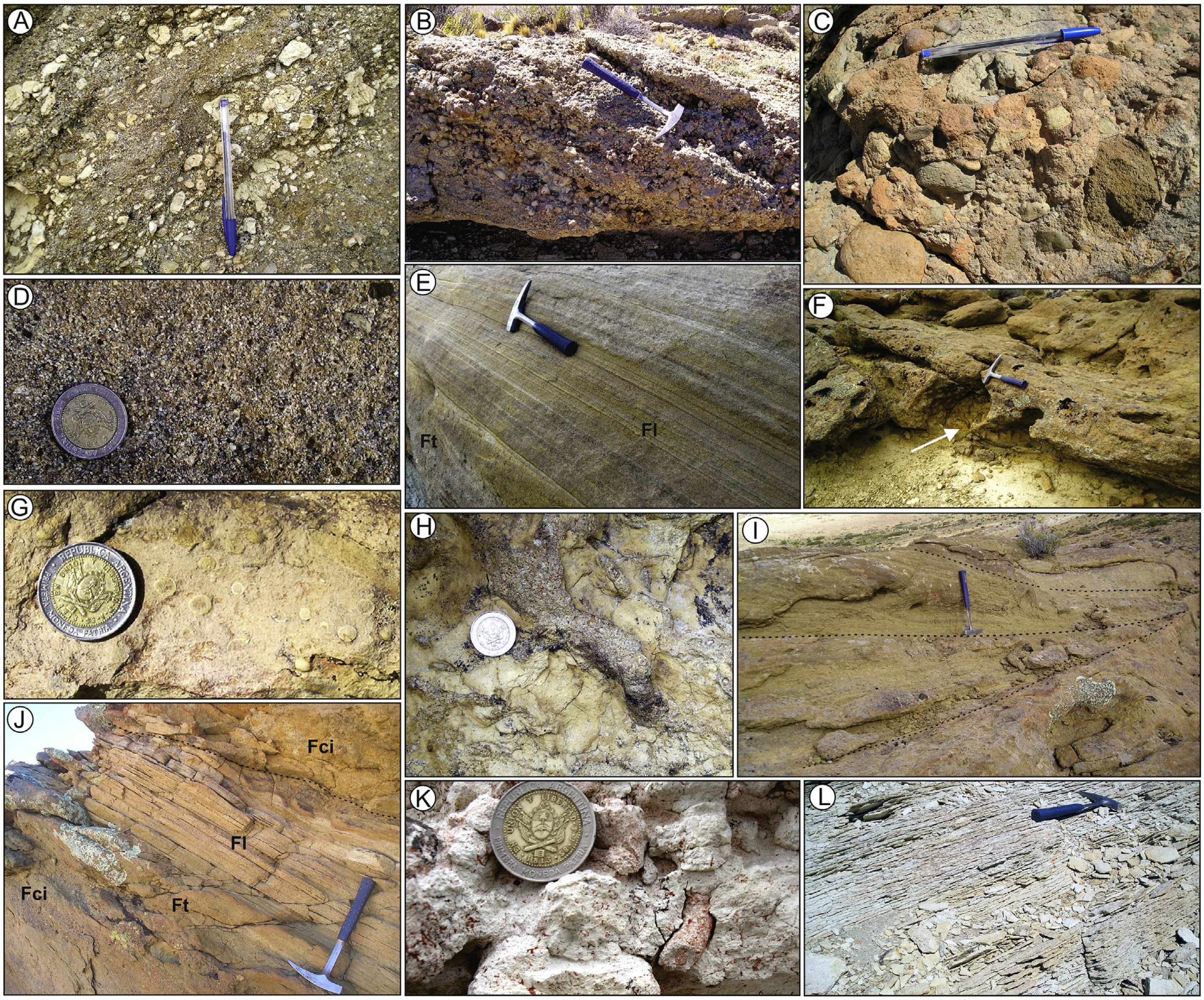

Fig. 6. Lithofacies of the Bajo Barreal Formation in the Codo del Senguerr anticline. **(A)** Clast to matrix supported intraformational conglomerate (Fci), larger clasts are subrounded, reworked tuffs. Pen is 13 cm long. **(B)** Cross-bedded, granule to small-pebble extraformational conglomerates (Fce) of the Upper Member. Hammer is 30 cm long. **(C)** Massive, large pebble conglomerates (Fce) with rounded clasts. Pen is 15 cm long. **(D)** Structureless, medium-grained tuffaceous sandstones (Fm) with open framework. Larger clasts are tuffaceous intraclasts. Coin is 13 mm in diameter. **(E)** Channel fill (FA-D1) characterized by plane-laminated sandstones (Fl) covering low-angle cross-bedded sandstones (Ft). Subtle grainsize variations between laminae and strata are highlighted by the cement contents. **(F)** Sub-rounded cobbles (arrow) of tuffaceous material (Fcc) incorporated into a sandstone-dominated channel-fill. Hammer is 30 cm long. **(G)** Massive tuffs containing accretionary lapilli (Fla), the coin is 13 mm in diameter. **(H)** Massive, fine-grained tuffaceous rocks (Tm) with multidirectional trails filled with medium-grained sandstones. The coin is 13 m in diameter. **(I)** Large-scale, low-angle inclined surfaces (dotted lines) with trough cross-bedding (Fx) in a braided sandstone body (FA-D2). Hammer is 30 cm long. **(J)** Multistorey channel fill (FA-D1), with massive, fine tuffaceous conglomerates (Fci) covered by coarse-to medium-grained sandstones with low-angle cross-bedding (Ft) in sharp contact with plane-laminated medium-sandstones (Fl). The overlying channel-fill event start over an erosional surface (dotted) with large to small-pebble conglomerate (Fci). **(K)** Cylindrical, lined burrows in fine-grained, white tuffaceous sediments. **(L)** Plane-laminated tuffaceous sediments (Tl), Lower Member. The hammer is 30 cm long.

4.3.1. Description

The association is characterized by non-scoured sandstone packages of less than 3.2 m thick (most <1.2 m thick) and 250 m of maximum true width. They have coarse-grained laminated sandstones with differences in grain size between laminae at base, followed upward by plane-laminated, medium to fine sandstones (Fl); tops in most cases are slightly undulatory. Convolute lamination is developed locally, and rarely symmetrical ripples occur at the top (Fr), where more commonly the deposits have a massive appearance due to bioturbation (Fb). Paleoflow directions show low dispersion of flow vectors. Sandbodies have sheet geometry with W:T ratio up to 100 ($n = 8$).

4.3.2. Interpretation

Dominance of horizontal lamination reflects high-energy flow conditions and vertical aggradation of the substrate (McKee et al., 1965; Tunbridge, 1981), with transportation mainly as bed-load (Hampton and Horton, 2007) in upper-to-transitional flow regime during high-discharge events (Fielding, 2006). A non-confined to poorly-confined flow in inferred from the sheet-like geometry of the deposit. Soft-sediment deformation indicates rapid dewatering, probably due to rapid accumulation of the sand (Allen, 1977). Preservation of asymmetrical ripples on upper parts of the association represent decrease of flow velocity and/or depth as flow waters waned (North and Taylor, 1996), and the bioturbated/

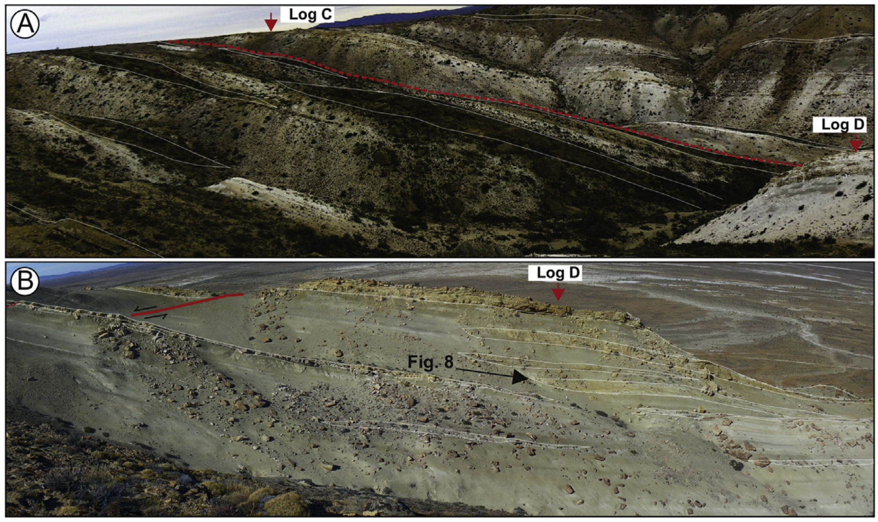

Fig. 7. **(A)** Typical distribution of fluvial channels (dotted lines) and fine-grained tuffaceous rocks preserved on wide floodplains in the Lower Member, with indication of location of some of the sedimentological logs. The approximate boundary between the Lower and Upper Member is indicated by a red, dotted line. **(B)** Field appearance of floodplain deposits and fluvial channels of the Upper Member.

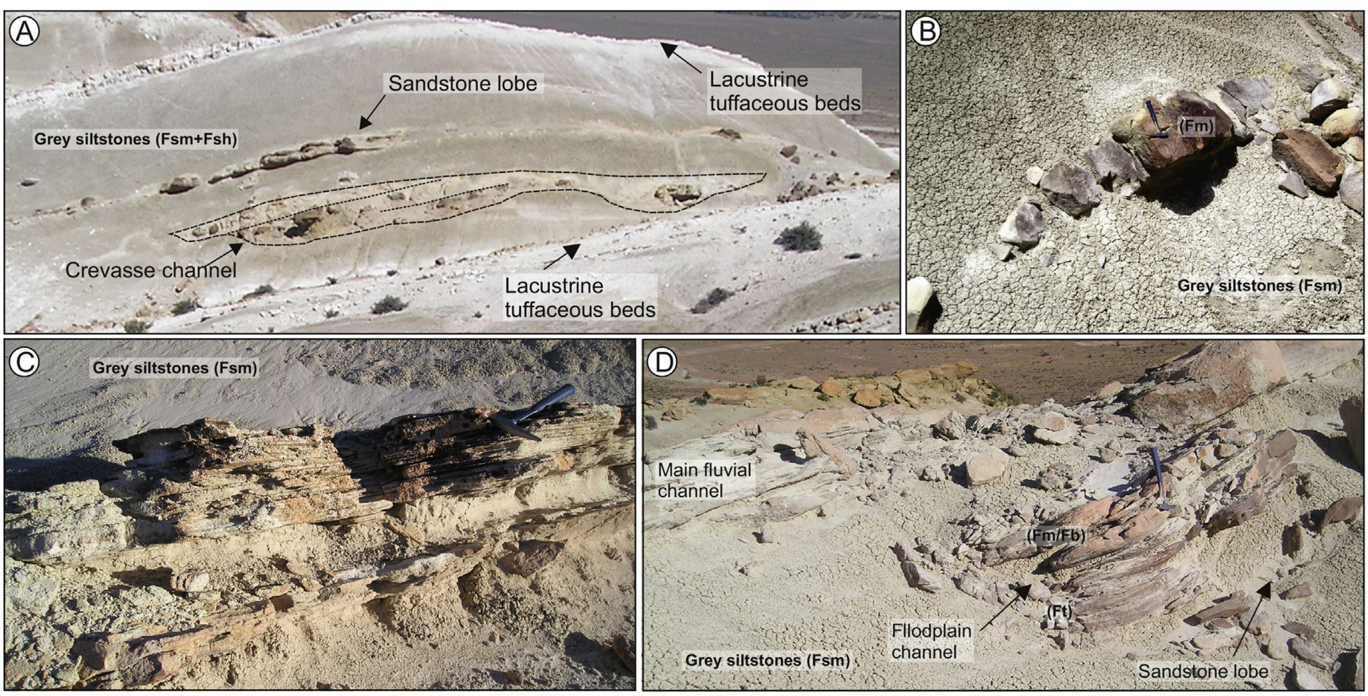

Fig. 8. Details of the proximal floodplain facies association. **(A)** Crevasse channel in the Upper Member. Three episodes of infill can be interpreted, the size of the entire sandbody is 1.4 m thick and 18 m width. **(B)** Medium-grained sandstones with plane base and convex top interbedded with grey, massive siltstones (Fsm) in the Upper Member. Hammer is 0.3 m long. **(C)** Tabular, medium-grained sandstones with plane-laminations (Fl) or massive appearance (Fm) interbedded with massive siltstones. **(D)** Small-scale fluvial channel with ribbon geometry, interbedded with laminated siltstones. Hammer is 0.3 m long.

disrupted top of some strata are evidence of post-flood organic activity. Umazano et al. (2008) reported for two localities (Sierra Nevada and Puesto Confluencia) that sheetflood processes represent the main aggradational mechanism of the floodplain in the Lower Member, being almost absent in the Upper Member.

4.4. Facies Association D (FA-D): major fluvial channels

Three hundred and twelve channels were described, measured and characterized in the study area. Three main channel types were identified: (FA-D1) low-sinuosity, (FA-D2) braided, (FA-D3) meandering. Typical features of the sub-associations are presented in Figs. 9–11. Fluvial channels can be single, although most of the sandstone bodies are multi-storey, with a ribbon or sheet geometry (Gibling, 2006).

4.5. FA-D1: low-sinuosity fluvial channels

4.5.1. Description

Fluvial channels with this pattern represent 84% of the analysed sandbodies, and are dominant in both Members. Single-thread channels are tens of metres of true width and 1.6–1.8 m thick.

Multi-storey channels can be as much as 18 m thick and 630 m of true width. The channels are characterized by a scoured, concave-upward basal surface, covered either by a coarse-grained basal lag tens of cm thick, or a poorly-organized matrix or clast-supported, crudely-bedded granule to small-pebble tuffaceous conglomerate (Fci). The basal surface is commonly in sharp contact with underlying fine-grained floodplain facies (FA-A) and only rarely grades from coarsening upward facies successions attributed to the FA-B. Upward, most of the infill consists of coarse to medium-grained tuffaceous sandstone with low-angle cross bedding (Ft) or trough cross-bedding (Fx), in many cases separated by erosional surfaces. Towards the top, medium-grained tuffaceous sandstones containing parallel-lamination (Fl) or current-ripples (Fr) are found, as well as massive, or mottled strata (Fb). Locally, clast-supported breccias (Fcc) occur near the base of the deposits. If preserved, low-angle inclined surfaces attached to channel margins dip downstream, and display low angle with paleoflow directions obtained from overlying trough cross-bedding. Paleoflow measurements display low (30–40°) dispersion on the measurements. The infill of this channel type records mostly a slightly fining-upward arrangement, although many channels are ungraded. In several cases grey mudstones (Fsh and Fsm) containing abundance of tuffaceous clasts, burrowing and/or massive appearance separate stories; these fine-grained strata are lenticular, and range in thickness from 0.3 to 1.2 m thick, and extend laterally for 20–30 m (Fig. 9).

A group of fifteen channels in the Upper Member contain extraformational, clast-supported conglomerates (Fce), that locally contain convolute lamination. These have a coarser grainsize that most of the fluvial sandbodies, and a true width (averaged) that is double the mean of the unit (see below). The clast-supported basal lag can be up to 2 m thick, containing broken bones and large trunk fragments. As in the remainder of fluvial sandbodies of low sinuosity, they contain trough cross-bedding, low-angle cross bedding, planar cross-bedding and horizontal stratification, although strata and cosets are of larger scale.

4.5.2. Interpretation

The presence of a concave-upward basal surface, lenticular to sheet-like geometries, a coarse-grained infill that fines upward, unidirectional palaeocurrents, and multiple erosional surfaces indicated repeated episodes of channel incision and infill (Bridge, 2003). Low sinuosity fluvial channels are indicated by the lack of lateral accretion surfaces, occasional preservation of downstream-migrating macroforms attached to the margin of active channel fills, and the relatively low paleocurrent variability in individual channels, all of which suggest relatively straight flow paths (Bridge et al., 2000). The clast-supported breccias can be locally associated with slumping of channel banks (Owen, 1996). Occurrence of soft-sediment deformation indicates high rates of deposition and dewatering, probably associated to quick accumulation of material (Allen, 1977). Most of the surveyed channels do not contain preserved bars, and the channel infill is constrained by a residual lag. Superimposed dunes probably represent high-stage deposits in shallow channels. Plane-lamination in single and multi-storey channels indicate transportation in upper-flow regime (Fielding,

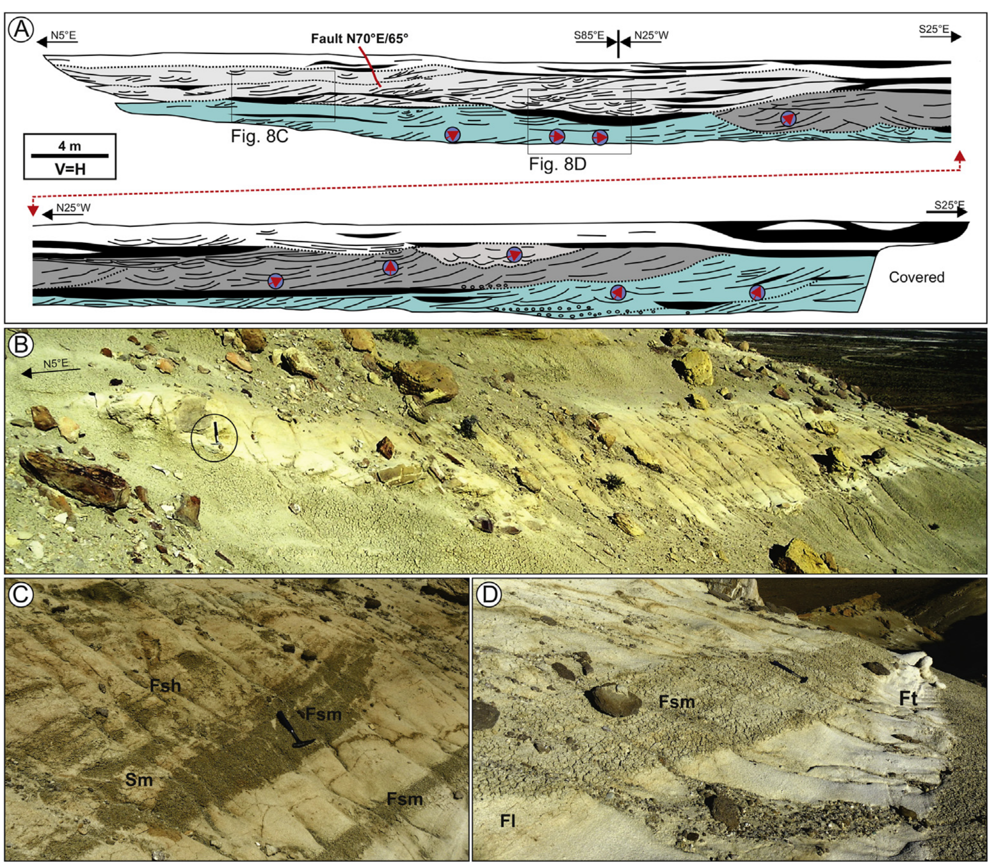

Fig. 9. Low-sinuosity, multistorey sandbody. **(A)** Line drawing following major erosional surfaces and stories. The channel contains muddy material separating the stories. **(B)** Detail of the margin of the channel. The hammer (encircled) is 30 cm long. Note the lack of proximal (sandy) heterolitic splay and levee floodplain deposits. **(C)** Massive, fine-grained material (mud plug) infillings the deeper part of a single channel (Fsm). The strata contain lenses of poorly-organized sandstones (Sm) and is locally laminated (Fsh). **(D)** Channel-shape mud plug deposits. The reoccupation of the channel erodes the top. Hammer is 30 cm long.

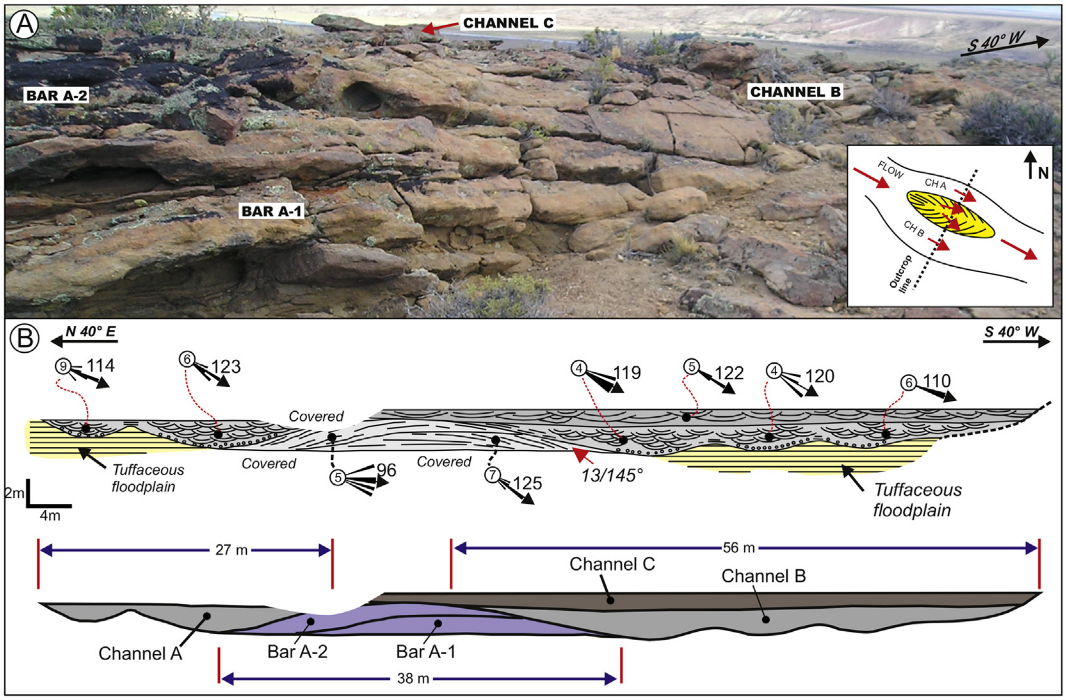

Fig. 10. Outcrop view (A) and line drawing (B) of a braided channel. The inset show the interpreted orientation of the exposure, as deduced using the paleoflow data and dip of accretion surfaces. Channel C represent a low-sinuosity, shallow channel covering the braided channel fill.

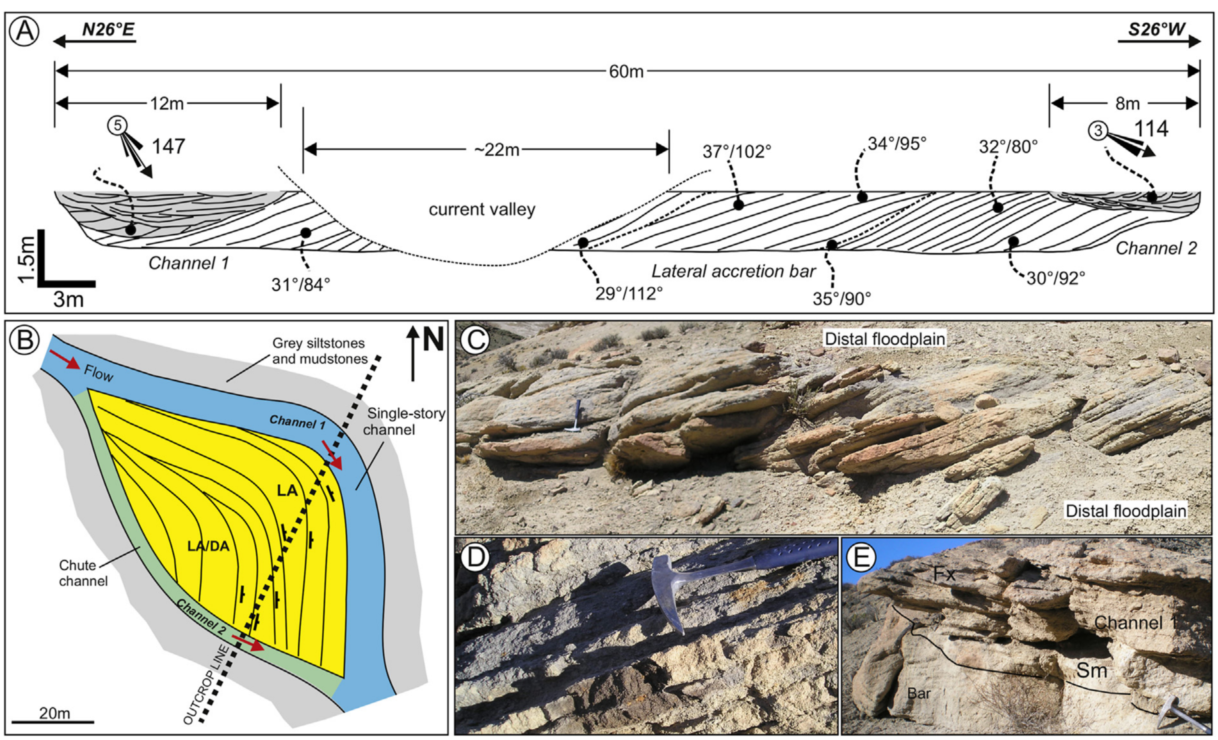

Fig. 11. Line drawing **(A)** and depositional model **(B)** of the only meandering fluvial channel identified in the study area. **(C)** Outcrop view of the lateral accretion surfaces. **(D)** The free surface (below the hammer head shows impregnation of the sandstone with hydrocarbons. **(E)** Single-channel fill containing low-angle cross bedding (Ft) up to a massive medium-grained sandstone (Fm).

2006) in the shallowest parts of the channels or over bars. Fine-grained lithologies with burrows are considered as slackwater (mud-plugs) or abandonment facies (Cant and Walker, 1976), although several fine-grained beds resemble channel-lining muds (Lynds and Hajek, 2006), indicating abandonment and later reoccupation of the channels. Avulsion or partial-to-total abandonment of the channel fill can also be inferred from muddy deposits with geometries that approximate the shape of the original channel.

Channel aggradation during the final abandonment is associated with erosional flows containing reworked tuffs or mudstones dispersed in muddy sediments associated with the peak flow, and to deposition of suspended load following the peak of the flow.

Tuffaceous conglomerates and tuffaceous sandstones have been reworked from intrabasinal areas or from highland areas in the margins of the basin (Umazano et al., 2009). The occurrence of extraformational (rhyolitic) clasts in fluvial channels with distinctive geometries in the Upper Member suggest changes in the source area, or stream capture in the headwaters, which could be due to increasing size of the drainage network or increasing discharge conditions upstream (Fraser and DeCelles, 1992; Mikesell et al., 2010). The lateral interbedding at outcrop between this two different provenance supply systems allow to infer at least two coeval drainage networks in the study area (see Discussion below).

4.6. FA-D2: braided channels

4.6.1. Description

This fluvial pattern has been identified in eleven fluvial channels of the Lower Member and in five additional channels of the Upper Member. The channels display a suite of sedimentary facies comparable to those described for low-sinuosity fluvial channels (Fci, Ft, Fx, Fl, Fp, Fr and Fb) with similar vertical arrangement. Data on thickness and true width of single and/or multistorey channel-fills are also comparable with those of the low-sinuosity pattern. Additionally, the channels contain convex-upward bounding surfaces up to 1.4 m thick and 40 m of true width, that dip in opposite direction toward adjacent channel-fills on both sides. Large-scale bounding surfaces with dips up to 13° are oriented at a low-angle (>45) to paleocurrents obtained from trough cross-bedding of the channel-fills (Fig. 10).

4.6.2. Interpretation

A braided fluvial pattern is inferred from the presence of laterally adjacent channel fills with convex-upward, large-scale inclined strata, interpreted as braid bars (Bridge, 2003, 2006). Although braided sandbodies represent a minor proportion of the fluvial channel lithofacies association, their occurrence in association with multi-storey channels of low-sinuosity origin reinforce the idea that fluvial systems of the Lower and Upper Members were subject to significant variations in discharge and flow conditions (Blodgett and Stanley, 1980; Lunt and Bridge, 2004; Bridge, 2006).

4.7. FA-D3: meandering channels

4.7.1. Description

A single meandering channel has been recognized in the Upper Member. The fluvial sandbody has a thickness of 1.5 m and a true width of 57 m. In consist of a scoured-shaped basal surface with a high angle erosional bank and gently-sloping depositional bank on the opposite side. The infill of the channel mostly consists of a poorly-organized granule to small-pebble conglomerate with subrounded clasts up to 3 cm that grade up to moderate to well-sorted, coarse to medium-grained tuffaceous sandstones with low-angle cross-bedding (Ft) and rare rippled-sandstones at top (Fr). Oil staining is abundant. Lenticular sets of strata formed by accretion of laterally-superposed medium to fine-grained sandstone that dip at angles up to 20°, they have a convex-upward shape and are separated by erosional surfaces at a lower angle; the toes of the set boundaries merge with the lower bounding surface of the entire sandstone bed (Fig. 11).

Individual convex-upward packages are about 6–9 m wide and 1.5 m thick; internally they contain inclined plane-lamination and rarely low-angle cross-bedding (Fx). Paleoflow measurements obtained from low-angle cross-bedding of the channel fill are oriented at high-angle (~80°) in relation to the dip of the accretion surfaces.

4.7.2. Interpretation

The accretion of lenticular sets dipping at high-angle in relation to paleoflow data of channel fills was developed by lateral accretion and, therefore, can be interpreted as a point bar or bench deposit associated with a helicoidal flow (Allen, 1970; Bridge, 1977). The high depositional angle of the accretion sets is likely due to low width-depth ratio of the precursor channel (Schumm, 1968). Due to the small size of the channel and its scarcity in the study area, it possibly represents a second-order channel developed on wide interfluves.

5. Channel deposits: quantitative results

In this section, we summarize the measurements of the external geometry of single and multi-storey channels. Data are presented as graphs depicting the relationship between width and thickness, and can be used to predict sandstone-body width when only thickness (obtained from well log, core or measured section) information is available. Additionally, lateral–vertical variations in the net-to-gross ratio and a summary of paleoflow data are given.

a. Width, thickness and W:T ratio

Channel dimension measurements of 294 interpreted sandbodies allowed recognizing temporal variations in the external shape of the individual channels. The results of this analysis are shown in Fig. 12A–C.

In the Lower Member, the maximum thickness of 118 single and multistorey channels was measured. Thickness values are from 0.4 to 10.5 m, with a mean thickness of 2.96 m (StD = 1.89 m). True width values, corrected according to available paleoflow data, range from 25 m to 657 m. The mean width of 113 channels is 112 m (Std = 97 m), and the mean W:T ratio is 43 (StD = 36). Five channels were excluded from the data population due to erosion of most of the (inferred) width.

For the Upper Member, a population of 196 channels provided a range of thickness data from 0.4 to 16.50 m, with a mean thickness of 3.21 m (StD = 2.32 m); thickness over 2.5 m correspond to multistorey sandbodies. The measurements of 181 channels give a mean true width of 146.8 m (Std = 142 m), with a maximum width of 630 m. The mean W:T ratio is 50 (StD = 41).

The dimensions of the 15 fluvial channels containing extraformational conglomerates (facies Fce) from the Upper Member were analysed separately. These fluvial channels, sourced from extrabasinal materials, have a mean thickness of 5.88 m, mean width of 260.7 m, and a mean W:T of 52. Grain size, thickness and width of this group of channels are larger than the average for the Upper Member, suggesting that this drainage network is associated with larger discharge conditions.

The mean thickness of sandbodies between the Lower and Upper Member is quite similar, but a statistically significant increment in the true width of the channels of the Upper Member produces a larger W:T ratio for those sandbodies.

b. Net to gross ratio and connectivity

Concepts of sequence stratigraphy and identification of systems tracts in alluvial systems is possible based mainly on the relative proportion of fluvial channel sandbodies and fine overbank deposits. Following this criteria, two main systems tracts have been proposed: the low-accommodation systems tract is characterized mainly by amalgamated channel deposits, in contrast to the high-accommodation systems tract, formed predominantly by overbank and lacustrine-dominated successions (Martinsen et al., 1999; Fanti and Catuneanu, 2010; Labourdette, 2011; Foix et al., 2013; Scherer et al., 2015). In our study area, channel deposits represent 16% and floodplain deposits 84% of the preserved sedimentary record, as calculated using thickness of sandstone versus finer-grained facies of the measured sections, suggesting a general high-accommodation setting (Fig. 12D). Sandstone bodies preserved in proximal environments represent less than 3% of the sections, although the value could be underrepresented due to exposure conditions. Fluvial sections containing a low proportion of sandstone preserved in the proximal floodplain have been formerly considered as fluvial systems of low stability, and may indicate fluvial channels with high rates of migration due to avulsion (Galloway, 1981), preventing the development of thicker heterolitic successions along the margins of the channel (Dreyer, 1993).

By representing the true width of the channels in the corresponding position of the sedimentary logs (Fig. 13), the lateral and vertical variations in the distribution of the sandstone bodies can be envisaged. In our study area no significant erosional surfaces were identified, nor can a distinctive sandstone package (or semi-regional valley) be traced, although subtle lateral variations in the proportion of the channels can be recognized. In the Lower Member there is a higher proportion of fluvial channels in the northern part of the study area in relation to the southern one, and multi-storey channels are thicker and wider toward the top of the Member. Although the increase in the channel proportion north of profile G appears to be due to a preferential stacking of channels in the paleogeomorphological scenario, southward of profile H the separation between sedimentary logs was increased due to time limitations for developing the study. Additionally, during the data collection it was apparent that several channels in the Lower Member were not intersected by any of the sedimentary logs. This

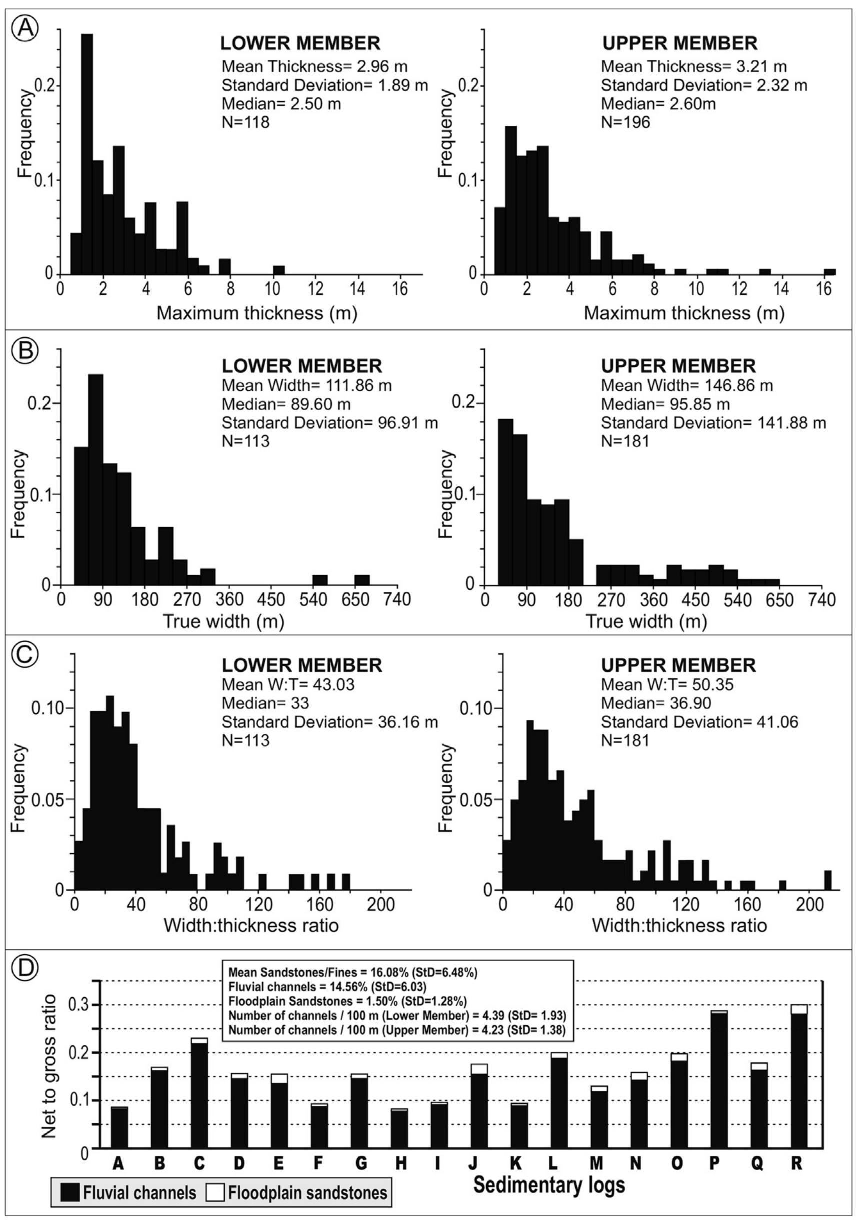

Fig. 12. Frequency histograms for **(A)** measured channel thickness, **(B)** measured channel width, and **(C)** channel width to thickness ratio for channels associated with the Lower Member (left column) and Upper Member (right column). **(D)** Channel proportion along the measured sections. Note the general low proportion of floodplain sandstones.

could partially explain the southward reduction in sandstone content. As most of the channels in the Lower Member are less than 200 m in true width, separation between sedimentary logs of about 300 m leaves some channels not intersected.

Fluvial sandbodies in the Upper Member indicate high variation in shape, although as the connectivity is sensitive to sandstone body width (Pranter and Sommer, 2011) the widening of the channels in the Upper Member will enhance physical connectivity at similar net-to-gross ratio along the 2D section. Additionally, channel (or channel belts) disconnected in the analysed 2D cross section may be connected out of section indicating the conformation of a connected network in 3D, as has been observed in other outcrop studies (Pringle et al., 2004) and theoretical models (Hovadik and Larue, 2007).

c. Paleoflow measurements

During the research, 4074 paleoflow measurements were collected from 298 channelized bodies. The average vector mean of measurements of 107 fluvial channels of the Lower Member gives a paleotransport direction to the SE (112.6°, StD = 17°); while for the Upper Member the mean value (averaged) obtained from 191 channels is 112.9°, with a StD of 21.7°. A similar pattern of paleoflow directions (mean = 116°, StD = 16°) was obtained from data of 86 fluvial channels (number of reading = 1487) of the underlying Castillo Formation in the same locality (Paredes et al., 2015), and are consistent with paleoflow data in the southern side of the Senguerr river obtained by Bridge et al. (2000), where a mean of 116° (n = 51) was measured.

6. Discussion

a. Alluvial system

Previous sedimentological studies in other localities of the basin have found evidences of ephemeral rivers (Rodriguez, 1993; Hechem, 1994, 1997), perennial river with single-channel, low sinuosity channels (Bridge et al., 2000) or braided pattern (Umazano et al., 2008). The overall organization of the Bajo Barreal Formation in the Codo del Senguerr anticline is one of vertical floodplain aggradation in a high-accommodation fluvial setting with laterally and vertically discrete sandstone bodies of limited movility associated to one or more major channel belts. From the above data, both Members are characterized by the presence of low-sinuosity fluvial channels that locally developed a braided pattern, showing sheet-like geometry with wide variation in

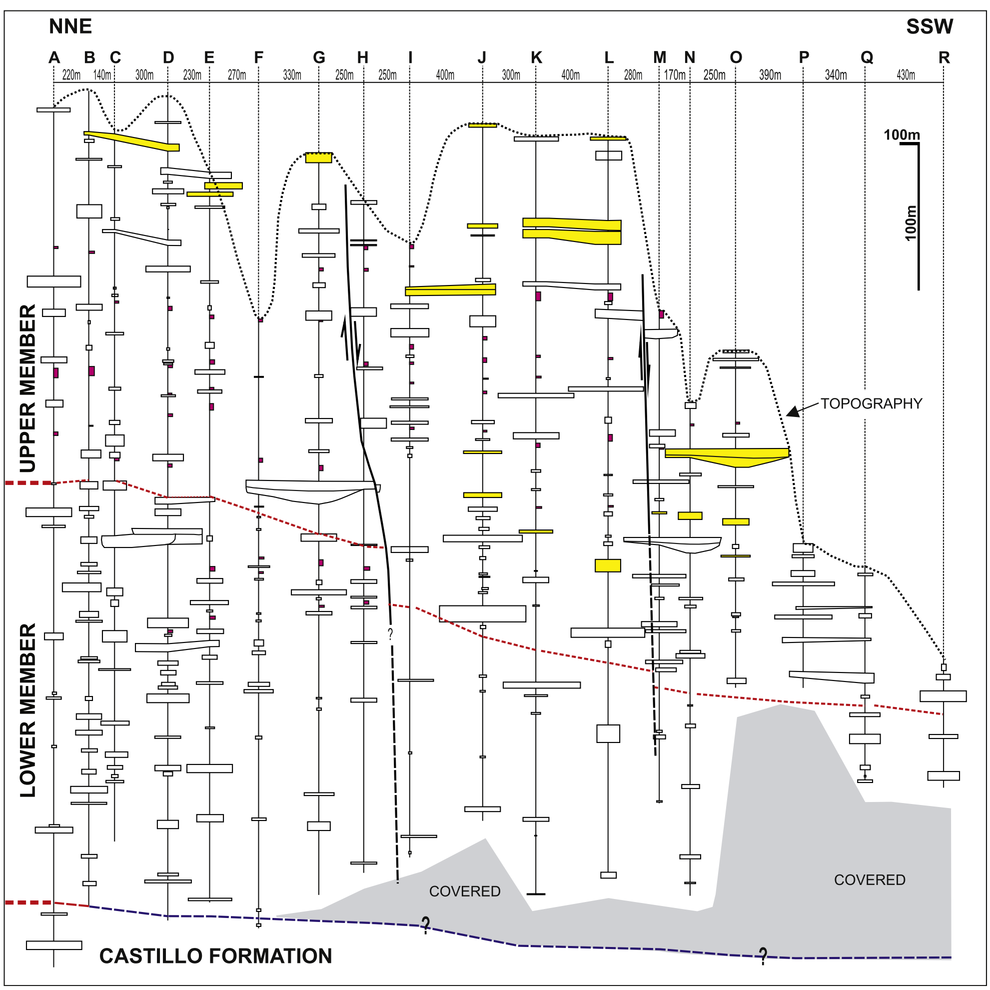

Fig. 13. Schematic representation of the lateral and vertical distribution of fluvial channels in the Bajo Barreal Formation, and their dimensions (thickness, width). The section orientation is near orthogonal to the paleoflow data. Most of the channels in the Lower Member can not be correlated to the adjacent sedimentological sections, with the exception of the uppermost part of the member. In spite of a large variation in geometry, there are a large number of wider channels in the Upper Member. Note that the channels containing extrabasinal clasts (yellow coloured) are generally wider and thicker. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dimensions. Channel banks appear to have been quite muddy and therefore stable. The occurrence of numerous small-scale channel bodies at the same level suggests the presence of a multiple-channelled (anabranching) fluvial system (Nanson and Knighton, 1996), although the demonstration that channels fills were formed by coeval rivers remain unproved. The larger, multistorey bodies up to 600 m of true width are the result of channel amalgamation in zones where channels were more closely spaced or due to repetitive reoccupation of the same site by the channels, combined with overall vertical accretion through time (cf. Stear, 1983; Mohrig et al., 2000). Those amalgamated sandstones could be considered as channel belts, but lack of fully preserved barforms on top of the multistorey sandbody, a criteria that is indicated by McLaurin and Steel (2007) as evidence of preservation of a channel belt.

Of particular interest for identifying the dynamics of the fluvial systems is the low percentage of floodplain sandstones, and the observation that many channels in the study area lie directly above of fine-grained floodplain material lacking the classical heterolitic succession that characterizes the levee-splay deposits preserved if the channels gradually migrate in the floodplain. This pattern of migration has been associated with stratigraphically abrupt avulsion (Jones and Hajek, 2007), in which the fluvial channels relocate through incisional style avulsion, and a similar interpretation can be made for the Bajo Barreal Formation. This mechanism of channel migration has been also proposed for fluvial channels in the overlying Lago Colhué Huapi Formation (Casal et al., 2015). Our research confirm that fluvial systems in the study area were subject to wide variation in discharge, since silt and mud layers intercalated with the conglomerate (Fig. 9) suggest long tranquil periods with virtually empty river channels punctuated by flooding. Furthermore, the abundance of plane-laminations in channel fills and occurrence of sheetflood processes can be associated to variable and episodic delivery of water and sediments, likely associated to seasonal distribution of the precipitations.

High variability in the channel geometries, a relatively uniform internal organization (and fluvial pattern) of single and multistorey channels and, to a lesser extent, grainsize and clast composition allows the Bajo Barreal Formation to be interpreted as an equi-style plural sedimentation system in the sense of Lewin and Ashworth (2014), with several independent channel systems occupating the alluvial valley floor. A likely actual analogue of the analysed succession can be found in several reaches of the Diamantina river in Australia (Fig. 14).

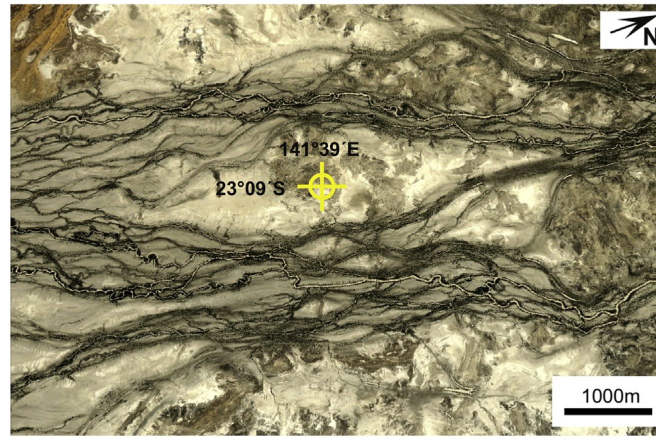

Fig. 14. A reach of the Diamantina river, a possible actual analogue of the multichanneled fluvial system that deposited the Bajo Barreal Formation in the Codo del Senguerr anticline.

b. Local tectonic scenario

Data on the fluvial sedimentology and paleoflow distribution can be used to analyse the coeval tectonic scenario in the San Bernardo Fold Belt, which has been traditionally considered as extensional during the Upper Cretaceous (Homovc et al., 1995; Figari et al., 1999), although more recent studies suggest a compressional scenario since deposition of the Castillo Formation (Navarrete et al., 2015; Gianni et al., 2015a,b). As fluvial systems are highly sensitive to subtle changes in grade due to tectonic activity, the creation of relief during deposition of the Bajo Barreal Formation might have resulted in longitudinal or lateral tilting of alluvial river profiles (Schumm, 1993; Holbrook and Schumm, 1999), features that can be preserved in the sedimentary record. Common fluvial responses to creation of tectonic slopes are 1) changes in the flow direction, 2) incision or aggradation close to tectonic structures, or 3) changes in fluvial styles and dimension of channels in the area under deformation (Ouchi, 1985; Alexander and Leeder, 1987; Leeder, 1993; Burbank et al., 1996; Keller et al., 1999). The study area is located on the eastern limb of the Codo del Senguerr anticline, and uplifting of the anticline during deposition of the Bajo Barreal Formation should have produced 1) southward deflection of the palaeoflow, associated with the propagation of the fold, 2) a sustantial reduction of the size of the channels due to diversion of the flow, 3) deposition of local-sourced alluvial fans in response to changes in the geomorphic scenario, or 4) incision and persistence of the valleys crossing the axis of the anticline, among other plausible responses of the fluvial system. As mentioned above, no incision or significative erosional surfaces were identified in the study area, neither preferential stacking or cyclic shift of channels were observed. The lack of alluvial fan deposits in the study area is attributed to the lack of creation of local relief in the Codo del Senguerr anticline.

The palaeoflow direction of the analysed succession (Az ~ 112°) and of the underlying Castillo Formation (Az ~ 116°, Paredes et al., 2015) are highly oblique (~70°) to the current axis of the Codo del Senguerr anticline, and parallel to the orientation of early Cretaceous normal faults (Fig. 15) identified in the subsurface (Homovc et al., 1995), probably reflecting the occurrence of antecedent valleys. Subsurface mapping of channel belts using seismic attributes (Foster and Iovine, 2008) eastward of the Codo del Senguerr anticline also show a dominant SE paleoflow trend in the Lower Bajo Barreal Formation. The persistence of sediment routes at high angle with the axis of the Codo del Senguerr anticline, the lack of deflection in the paleoflow plus lack of large-scale incisional surfaces or entrenched valley fills are indirect evidence of limited tectonic control at this locality during the deposition of both formations, suggesting that the uplift of the anticline should have occurred after the deposition of the analysed succession of continental units (Burbank et al., 1996). From this, no sedimentological evidence support a compressional scenario coeval with the sedimentation in the study area.

d. Implications for hydrocarbon recovery

As in many petroleum basins around the world, the historical development of oilfields in the Golfo San Jorge basin has gone from surficial to deeper units. Oilfield development in the last decades has been concentrated on recovery of hydrocarbons from both Members of the Bajo Barreal Formation, although there are more productive wells in the Upper Member. The separation between wells is typically 250–300 m, based mainly in the efficient extraction of hydrocarbons of the Upper Member of Bajo Barreal Formation. Due to the large population of channels measured in the

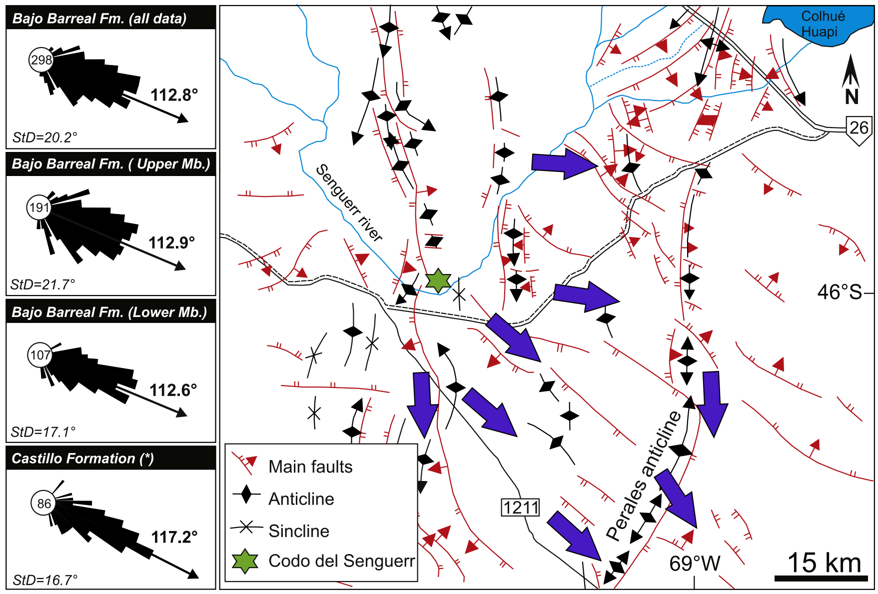

Fig. 15. Palaeoflow measurements of the Bajo Barreal Formation at Codo del Senguerr anticline, based in averaged vectors of 298 channels. Data from the Lower and Upper Member show a similar paleoflow trend, and are comparable to those obtained from paleoflow measurements in the underlying Castillo Formation by Paredes et al. (2015). The map shows the location of the Codo del Senguerr anticline (green star) and the averaged vector mean of channel belts mapped in the subsurface for the Upper Castillo and Lower Bajo Barreal succession by Foster and Iovine (2008), reflecting the general drainage direction west of the Perales anticline area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Codo del Senguerr anticline, the outcrop study can be used as a robust analogue for prediction of the dimensions of oil reservoirs in nearby oilfields; the utility is reinforced because in the subsurface of the Golfo San Jorge basin most of the fluvial reservoirs are below of the available resolution of current 3D seismic surveys (~15–20 m). A critical step during oilfield development of fluvial basins is defining an efficient well spacing between wells based in the assumed shape of the sandstone reservoirs. This research has demonstrated changes in the cross-sectional area of the sandbodies between the Lower and Upper Member, with averaged areas of 331 m^2 and 471 m^2, respectively. The reduction in the area of the sandbodies of the Lower Member is mainly due to lower true width values, as shown above. Furthermore, the geometries of the fluvial channels in the Lower Member are quite similar to those observed in the underlying Castillo Formation at Codo del Senguerr anticline (Paredes et al., 2015), indicating that planning of efficient distribution of wells to produce hydrocarbons from Castillo and Lower Member of Bajo Barreal Formations should consider a similar geometry for the potential reservoirs. Sandstone body width data indicate that a significant part of channel sandstones are smaller than the distance between wells (~250 m), suggesting that reserves will be added with infill drilling. This downward reduction in the width of the potential reservoirs will require different strategies for recovery the hosted hydrocarbons in deeper reservoirs, and also waterflooding projects or infill drilling operations should consider the observed difference in external geometry of the sandstones in order to make more appropriated decisions for location of injection and producing wells.

7. Conclusions

The sedimentology, geometry and alluvial architecture of the 450–650 m thick Bajo Barreal Formation (Upper Cretaceous) have been investigated along a 4.5 km natural exposure in the Codo del Senguerr anticline. It consists of a high-accommodation fluvial succession dominated by vertical floodplain aggradation associated to sheetfloods, with isolated-to-vertically stacked, sheet-like, low-sinuosity or braided fluvial channels of limited lateral movility. Fluvial channels were relocated mainly by incisional-style avulsions during floods, and contain sedimentological evidence of large discharge variations.

The Lower Member consists of reworked ash-fall materials preserved in floodplain areas (78%), floodplain sandstones (4%) and fluvial channels (18%); the mean thickness of sandbodies is 2.96 m (n = 118) and mean true width is 112 m (mean W:T = 43, n = 113), with thicker and wider sandbodies in upper levels of the Member. Most of the fluvial channels are of low-sinuosity with preservation of alternate bars, braided sandbodies are scarce (11%) and sheetflood deposits are uncommon (2%).

The Upper Member consists of grey siltstones and mudstones preserved in extensive lowland areas (78%), and large-scale fluvial channels (19%), with scarce preservation of sandstones in the proximal floodplain (3%). Fluvial channels (mean thickness = 3.21 m, mean width = 147 m, n = 196) are narrow sheets of low-sinuosity (mean W:T = 50, n = 181), with scarce development of braided pattern (2%) and rare occurrence of either meandering channels or sheetflood deposits. Two coeval provenance supply systems were recognized in the study area.

In addition to providing quantitative data on sediment routes, channel geometries and dimensions, this study has shown that during deposition of the Lower and Upper Members of the Bajo Barreal Formation, channels flowed to high-angle (>70°) in relation to the current axis of the Codo del Senguerr anticline. The stacking of the channels, their geometry and fluvial patterns do not record evidence of coeval tectonic activity associated to the growth of the anticline. Field data suggest the uplift of the anticline ocurred after the deposition of the involved units.

The dimensional dataset compiled during the research provides insight into the spatial and temporal variation of geometries (thickness, true width and W:T ratio) of fluvial channels in both Members of the Bajo Barreal Formation, and will be useful to geoscientists and engineers for planning and developing primary and/or enhanced oil recovery projects, as well as a source of data necessary for modelling subsurface connectivity of hydrocarbon reservoirs in nearby oilfields.

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References

Alexander, J., Leeder, M.R., 1987. Active tectonic control on alluvial architecture. SEPM Spec. Publ. 39, 243–252.
Allen, J.R.L., 1970. Physical Processes of Sedimentation. Allen and Unwin, London, p. 248.
Allen, J.R.L., 1977. The possible mechanics of convolute lamination in graded sand beds. J. Geol. Soc. Lond. 134, 19–31.
Ambrose, W., Tyler, N., Parsley, M., 1991. Facies heterogeneity, pay continuity, and infill potential in barrier-island, fluvial and submarine-fan reservoirs; examples from the Texas Gulf Coast and Midland Basin. In: Miall, A.D., Tyler, N. (Eds.), The Three-dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery, SEPM Concepts in Sedimentology and Paleontology, 3, pp. 13–23.
Archangelsky, S., Bellosi, E., Jalfin, G.A., Perrot, C., 1994. Palynology and alluvial facies from mid-Cretaceous of Patagonia, subsurface of San Jorge Basin, Argentina. Cretac. Res. 15, 127–142.
Barcat, C., Cortiñas, J., Nevistic, V., Zucchi, H., 1989. Cuenca Golfo San Jorge. In: Chebli, G., Spalletti, L.A. (Eds.), Cuencas Sedimentarias Argentinas, Universidad Nacional de Tucumán, Serie Correlación Geológica, 6, pp. 319–345.
Barreda, V., Archangelsky, S., 2006. The southernmost record of tropical pollen grain in mid-Cretaceous of Patagonia, Argentina. Cretac. Res. 27, 778–787.
Bellosi, E.S., Gonzalez, M., Genise, J., 2002. Paleosuelos y sedimentación cretácica de la cuenca San Jorge (Grupo Chubut) en la Sierra de San Bernardo, Patagonia Central. In: 15th Congreso Geológico Argentino, Actas 2, pp. 747–753 (Calafate).
Blodgett, R.H., Stanley, K.O., 1980. Stratification, bedforms and discharge relations of the Platte braided river system, Nebraska. J. Sediment. Petrol. 50, 139–148.
Bridge, J.S., 1977. Flow, bed topography, grain size and sedimentary structures in open channel bends: a three-dimensional model. Earth Surf. Process. 2, 401–416.
Bridge, J.S., 1993. The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers, Geological Society of London, Special Publication 75, pp. 13–71.
Bridge, J.S., 2003. Rivers and Floodplains: Forms, Processes and Sedimentary Record. Blackwell, pp. 1–491.
Bridge, J.S., 2006. Fluvial Facies Models: Recent Developments. In: SEPM Special Publication 84, pp. 1–85.
Bridge, J.S., Leeder, M.R., 1979. A simulation model of alluvial stratigraphy. Sedimentology 26, 617–644.
Bridge, J.S., Tye, R.S., 2000. Interpreting the dimensions of ancient fluvial channel bars, channels, and channel belts from wireline-logs and cores. AAPG Bull. 84, 1205–1228.
Bridge, J.S., Jalfin, G.A., Georgieff, S.M., 2000. Geometry, lithofacies, and spatial distribution of Cretaceous fluvial sandstone bodies, San Jorge Basin, Argentina: outcrops analog for the hydrocarbon-bearing Chubut Group. J. Sediment. Res. 70, 319–337.
Brown, L.F., Barcat, C., Fisher, L.W., Nevistic, A., 1982. Seismic stratigraphic and depositional systems analysis: new exploration approaches applied to the Gulf of San Jorge basin, Argentina. In: 1st Congreso Nacional de Hidrocarburos, Petróleo y Gas, pp. 127–156 (Mar del Plata).
Burbank, D., Meigs, A., Brozovic, N., 1996. Interaction of growing folds and coeval depositional systems. Basin Res. 8, 199–223.
Cant, D.J., Walker, R.G., 1976. Development of a facies model for sandy braided-fluvial facies for the Devonian Battery Point Sandstone, Quebec. Can. J. Earth Sci. 13, 102–119.
Cas, R.A.F., Wright, J.V., 1987. Volcanic Successions, Modern and Ancient. Allen & Unwin, London, 528 pp.
Casal, G.A., Martínez, R.D., Luna, M., Sciutto, J.C., Lamanna, M.C., 2007. Aeolosaurus colhuehuapensis sp. nov. (Saurópoda, Titanosauria) de la Formación Bajo Barreal, Cretácico Superior de Argentina. Rev. Bras. Paleontol. 10, 53–62.
Casal, G.A., Allard, J.O., Foix, N., 2015. Análisis estratigráfico y paleontológico del Cretácico superior en la cuenca del Golfo San Jorge: nueva unidad litoestratigráfica para el Grupo Chubut. Rev. Asoc. Geol. Argent. 72, 81–99.
Clavijo, R., 1986. Estratigrafía del cretácico inferior en el sector occidental de la Cuenca Golfo San Jorge. Bol. Inf. Pet. 9, 15–32 (Buenos Aires).
Dreyer, T., 1993. Quantified fluvial architecture in ephemeral stream deposits of the Esplugafreda Formation (Palaeocene), Tremp-Graus basin, northern Spain. In: Marzo, M., Puidefábregas, C. (Eds.), Alluvial Sedimentation: International Association of Sedimentologists Special Publication, 17, pp. 337–362.
Fanti, F., Catuneanu, O., 2010. Fluvial sequence stratigraphy: the Wapiti Formation, West-Central Alberta, Canada. J. Sediment. Res. 80, 320–338.
Farrell, K.M., 2001. Geomorphology, facies architecture, and high-resolution, non-marine sequence stratigraphy in avulsion deposits, Cumberland Marshes, Saskatchewan. Sediment. Geol. 139, 93–150.
Feruglio, E., 1949a. Descripción Geológica de la Patagonia. Yacimientos Pet. Fisc. 1, 1–334 (Buenos Aires).
Feruglio, E., 1949b. Descripción geológica de la Patagonia. Yacimientos Pet. Fisc. 2, 1–349 (Buenos Aires).
Figari, E.G., Hechem, J.J., Homovc, J.F., 1990. Arquitectura depositacional de las "Areniscas Verdes" de la Formación Bajo Barreal, provincia del Chubut, Argentina. In: 3rd Reunión Argentina de Sedimentología, 1, pp. 130–138.
Figari, E., Stelkov, E.E., Laffitte, G., Cid de la Paz, M., Courtade, S., Celaya, J., Vottero, A., Lafourcade, P., Martinez, R., Villar, H., 1999. Los sistemas petroleros de la Cuenca del Golfo San Jorge: Síntesis estructural, estratigráfica y geoquímica. In: 4th Congreso de Exploración y Desarrollo de Hidrocarburos, pp. 197–237 (Buenos Aires).
Fielding, C.R., 2006. Upper flow regime sheets, lenses and scour-fills: extending the range of architectural elements for fluvial sediment bodies. Sediment. Geol. 190, 227–240.
Fitzgerald, M.G., Mitchum, R.M., Uliana, M.A., Biddle, K.T., 1990. Evolution of the San Jorge Basin, Argentina. AAPG Bull. 74, 879–920.
Fisher, R.V., Schmincke, H.U., 1984. Pyroclastic Rocks. Springer-Verlag, Berlin, 472 pp.
Foix, N., Paredes, J.M., Giacosa, R.E., 2013. Fluvial architecture variations linked to changes in accommodation space: Río Chico Formation (Late Paleocene), Golfo san Jorge basin, Argentina. Sediment. Geol. 294, 342–355.
Foster, M., Iovine, G., 2008. Geometría y paleodrenaje regional de los sistemas de la Formación Castillo y Sección Tobácea, Cuenca del Golfo San Jorge. In: 7th Congreso de Exploración y Desarrollo de Hidrocarburos, Trabajos Técnicos, pp. 575–586 (Mar del Plata).
Fraser, G.S., DeCelles, P.G., 1992. Geomorphic controls on sediment accumulation at margins of foreland basins. Basin Res. 4, 233–252.
Galloway, W.E., 1981. Depositional architecture of Cenozoic Gulf coastal plain fluvial systems. SEPM Spec. Publ. 31, 127–155.
Genise, J.F., Melchor, R., Bellosi, E.S., Gonzalez, M.G., Krause, M., 2007. New insect pupation chambers (Pupichnia) from the Upper Cretaceous of Patagonia, Argentina. Cretac. Res. 28, 545–559.
Giampaoli, P., 2015. Caracterización de sistemas de fallas extensionales utilizan do perfiles y mapas de desplazamiento: ejemplos del Cretácico de la cuenca del Golfo San Jorge. Rev. Asoc. Geol. Argent. 72, 111–123.
Gianni, G., Navarrete, C., Orts, D., Tobal, J., Folguera, A., Gimenez, M., 2015a. Patagonian broken foreland and related synorogenic rifting: the origin of the Chubur Group Basin. Tectonophysics 649, 81–99.
Gianni, G.M., Navarrete, C.G., Folguera, A., 2015b. Synorogenic foreland rifts and transtensional basins: a review of Andean imprints on the evolution of the San Jorge Gulf, Salta Group and Taubaté Basins. J. S. Am. Earth Sci. 64, 288–306.
Gibling, M.R., 2006. Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. J. Sediment. Res. 76, 731–770.
Hamilton, D.S., Holtz, M.H., Ryles, P., Lonergan, T., Hillyer, M., 1998. Approaches to identifying reservoir heterogeneity and reserve growth opportunities in a continental-scale bed-load fluvial system: Hutton Sandstone, Jackson field, Australia. AAPG Bull. 82, 2192–2219.
Hampton, B.A., Horton, B.K., 2007. Sheetflow fluvial processes in a rapidly subsiding basin, Altiplano plateau, Bolivia. Sedimentology 54, 1121–1147.
Hechem, J.J., 1994. Modelo predictivo de reservorios en un sistema fluvial efímero del Chubutiano de la cuenca del Golfo San Jorge, Argentina. Rev. Asoc. Argent. Sedimentol. 1, 3–14.
Hechem, J.J., 1997. Arquitectura y paleodrenaje del sistema fluvial efímero de la Formación Bajo Barreal, cuenca del Golfo San Jorge, Argentina. In: 1st Congreso Latinoamericano de Sedimentología, Actas 1, pp. 315–323 (Isla Margarita, Venezuela).
Hechem, J.J., Strelkov, E.E., 2002. Secuencia sedimentaria mesozoica del Golfo San Jorge. In: Haller, J.M. (Ed.), Geología y Recursos Naturales de Santa Cruz, Relatorio del 15th Congreso Geológico Argentino, 1, pp. 129–147 (Buenos Aires).
Hechem, J.J., Homovc, J.F., Figari, E.G., 1990. Estratigrafía del Chubutiano (Cretácico) en la Sierra de San Bernardo, cuenca del Golfo San Jorge, Argentina. In: 11th Congreso Geológico Argentino, Actas 3, pp. 173–176 (San Juan).
Holbrook, J., Schumm, S.A., 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings. Tectonophysics 305, 287–306.
Homovc, J.F., Conforto, G.A., Lafourcade, P.A., Chelotti, L.A., 1995. Fold belt in the San Jorge Basin, Argentine: an example of tectonic inversion. In: Buchanan, J.G., Buchanan, P.G. (Eds.), Basin Inversion, Geological Society of London, Special Publication, 88, pp. 235–248.
Hovadik, J.M., Larue, D.K., 2007. Static characterizations of reservoirs: refining the concepts of connectivity and continuity. Pet. Geosci. 13, 195–211. http://dx.doi.org/10.1144/1354-079305-697.
Jones, H.L., Hajek, E.A., 2007. Characterizing avulsion stratigraphy in ancient alluvial deposits. Sediment. Geol. 202, 124–137.
Jordan, D.W., Pryor, W.A., 1992. Hierarchical levels of heterogeneity in a Mississippi river meander belt and application to reservoir systems. AAPG Bull. 76,

1601–1624.
Karssenberg, D., Tornqvist, T.E., Bridge, J.S., 2001. Conditioning a process-based model of sedimentary architecture to well data. J. Sediment. Res. Sect. B, Stratigr. Glob. Stud. 71, 868–879.
Keller, E.A., Gurrola, L., Tierney, T.E., 1999. Geomorphic criteria to determine direction of lateral propagation of reverse faulting and folding. Geology 27, 515–518.
Keogh, K.J., Martinius, A.W., Osland, R., 2007. The development of fluvial stochastic modelling in the Norwegian oil industry: a historical review, subsurface implementation and future directions. Sediment. Geol. 202, 249–268.
Kjemperud, A.V., Schomacker, E.R., Cross, T.A., 2008. Architecture and stratigraphy of alluvial deposits, Morrison Formation (Upper Jurassic), Utah. AAPG Bull. 92, 1055–1076.
Labourdette, R., 2011. Stratigraphy and static connectivity of braided fluvial deposits of the lower Escanilla Formation, south central Pyrenees, Spain. AAPG Bull. 95, 585–617.
Leeder, M.R., 1993. Tectonic control upon drainage basin development, river channel migration and alluvial architecture: implication for hydrocarbon reservoir development and characterization. In: North, C.P., Prosser, D.J. (Eds.), Characterization of Fluvial and Aeolian Reservoirs, Geological Society Special Publication 73, pp. 7–22.
Legarreta, L., Uliana, M.A., Larotonda, C.A., Meconi, C.A., 1993. Approaches to nonmarine sequence stratigraphy, theoretical models and examples from Argentine basins. In: Eschard, R., Doligez, B. (Eds.), Subsurface Reservoir Characterization from Outcrop Observations. Editions Technip, Paris, pp. 125–144.
Lesta, P., 1968. Estratigrafía de la Cuenca del Golfo San Jorge. In: 3rd Jornadas Geológicas Argentinas, Actas 1, pp. 251–280 (Buenos Aires).
Lesta, P., Ferello, R., 1972. Región Extraandina del Chubut y norte de Santa Cruz. In: Leanza, A. (Ed.), Geología Regional Argentina. Academia Nacional de Ciencias, Córdoba, pp. 601–654.
Lesta, P., Ferello, R., Chebli, G., 1980. Chubut extraandino. In: Turner, J.C. (Ed.), 2nd Simposio de Geología Regional Argentina, vol. 2. Academia Nacional de Ciencias, Córdoba, pp. 1307–1387.
Lewin, J., Ashworth, P.J., 2014. Defining large alluvial river channel patterns: alluvial exchange and plurality. Geomorphology 215, 83–98.
Lunt, I.A., Bridge, J.S., 2004. Evolution and deposits of a gravelly braid bar, Sagavanirktok River, Alaska. Sedimentology 51, 415–432.
Lynds, R., Hajek, E., 2006. Conceptual model for predicting mudstone dimensions in sandy braided-river reservoirs. AAPG Bull. 90, 1273–1288.
MacDonald, A.C., Halland, E.K., 1993. Sedimentology and shale-modeling of a sandstone-rich fluvial reservoir: Upper Statfjord Formation, Statfjord Field, North Sea. AAPG Bull. 77, 1016–1040.
Martinsen, O., Ryseth, A., Hansen, W.H., Fleshe, H., Torkildsen, G., Idil, S., 1999. Stratigraphic base level and fluvial architecture: Ercson Sandstonw (Campanian), Rock Springs Uplift, SW Wyoming, USA. Sedimentology 46, 235–259.
McKee, E.D., Crosby, E.J., Berryhill Jr., H.J., 1967. Flood deposits, Bijou Creek, Colorado, June 1965. J. Sediment. Petrol. 37, 829–851.
McLaurin, B.T., Steel, R.J., 2007. Architecture and origin of an amalgamated fluvial sheet sand, lower Castlegate Formation, Book Cliffs, Utah. Sediment. Geol. 197, 291–311.
Meconi, G., 1990. Facies, arquitectura fluvial y paleoambientes del Grupo Chubut en el Codo del Río Senguer, límite provincial de Chubut-Santa Cruz. In: 3rd Reunión Argentina de Sedimentología, Actas 1, pp. 193–196 (San Juan).
Miall, A.D., 1991. Hierarchies of architectural units in clastic rocks, and their relationship to sedimentation rate. In: Miall, A.D., Tyler, N. (Eds.), The Three-dimensional Facies Architecture of Terrigenous Clastic Sediments, and its Implications for Hydrocarbon Discovery and Recovery, SEPM Concepts in Sedimentology and Paleontology, 3, pp. 224–232.
Miall, A.D., 1996. The Geology of Fluvial Deposits. Springer, Berlín, p. 582.
Mikesell, L.R., Weissmann, G.S., Karachewski, J.A., 2010. Stream capture and piracy recorded by provenance in fluvial fan strata. Geomorphology 115, 267–277.
Mohrig, D., Heller, P.L., Paola, C., Lyons, W.J., 2000. Interpreting avulsion process from ancient alluvial sequences; Guadalope-Matarranya system (northern Spain) and Wasatch Formation (western Colorado). Geol. Soc. Am. Bull. 112, 1787–1803.
Nanson, G.C., Knighton, A.D., 1996. Anabranching rivers: their cause, character and classification. Earth Surf. Process. Landforms 21, 217–239.
Navarrete, C.R., Gianni, G.M., Folguera, A., 2015. Tectonic inversion events in the western San Jorge Gulf Basin from seismic, borehole and field data. J. S. Am. Earth Sci. 64, 486–497.
North, C.P., Taylor, K.S., 1996. Ephemeral-fluvial deposits: integrated outcrop and simulation studies reveal complexity. AAPG Bull. 80, 811–830.
Ouchi, S., 1985. Response of alluvial rivers to slow active tectonic movement. Geol. Soc. Am. Bull. 96, 504–515.
Owen, G., 1996. Experimental soft-sediment deformation; structures formed by the liquefaction of unconsolidated sands and some ancient examples. Sedimentology 43, 279–293.
Paredes, J.M., Foix, N., Colombo, F., Nillni, A., Marquillas, R., 2007. Volcanic and climatic control on fluvial style in a high energy systems: the Lower Cretaceous Matasiete Formation, Golfo San Jorge basin, Argentina. Sediment. Geol. 202, 96–123.
Paredes, J.M., Plazibat, S., Crovetto, C., Stein, J., Cayo, E., Schiuma, A., 2013. Fault kinematics and depocenter evolution of oil-bearing, continental successions of Mina del Carmen Formation (Albian) in the Golfo San Jorge basin, Argentina. J. S. Am. Earth Sci. 46, 63–79.
Paredes, J.M., Allard, J.O., Foix, N., Alvarez, B., Olazábal, S.X., 2014. Sedimentología y perfiles de rayos gamma de la Formación Pozo D-129 en la Sierra de San Bernardo, Chubut. In: 9th Congreso de Exploración y Desarrollo de Hidrocarburos, Trabajos Técnicos, pp. 455–479 (Mendoza).
Paredes, J.M., Foix, N., Allard, J.O., Colombo, F., Tunik, M., 2015. Alluvial architecture of reworked pyroclastic deposits in peri-volcanic basins: Castillo Formation (Albian) in the Golfo San Jorge basin, Argentina. Rev. Asoc. Geol. Argent. 72, 42–62.
Peroni, G., Hegedus, A., Cerdan, J., Legarreta, L., Uliana, M., Laffite, G., 1995. Hydrocarbon accumulation in an inverted segment of the Andean Foreland: San Bernardo Belt, Central Patagonia. In: Tankard, A., Suarez, R.Y., Welsink, H. (Eds.), Petroleum Basins of South America, AAPG Memoir, 62, pp. 403–419 (Tulsa).
Powell, J.E., 1987. The Late Cretaceous Fauna from Los Alamitos, Patagonia, Argentina. Part. VI. The titanosaurids. Rev. Mus. Argent. Ciencias Nat. 3, 147–153.
Pranter, M.J., Sommer, M.K., 2011. Static connectivity of fluvial sandstones in a lower coastal-plain setting: an example from the Upper Cretaceous lower Williams Fork Formation, Piceance Basin, Colorado. AAPG Bull. 95, 899–923.
Pringle, J.K., Westerman, A.R., Clark, J.D., Drinkwater, N.J., Gardiner, A.R., 2004. 3-D high-resolution digital models of outcrop analog study sites to constrain reservoir model uncertainty: an example from Alport Castles, Derbyshire, UK. Pet. Geosci. 10, 343–352. http://dx.doi.org/10.1144/1354-079303-617.
Ramos, V.A., 2015. Evolución de la cuenca del Golfo San Jorge: su estructuración y régimen tectónico. Rev. Asoc. Geol. Argent. 72, 16–24.
Ramsay, J.G., 1961. The effects of folding upon the orientation of sedimentary structures. J. Geol. 69, 84–100.
Rodríguez, J.F., 1993. La depositación de las areniscas verdes (Formación Bajo Barreal-Cretácico Tardío) y sus implicancias tafonómicas. In: 12th Congreso Geológico Argentino and 2nd Congreso de Exploración de Hidrocarburos. Asociación Geológica Argentina, Mendoza, pp. 194–199.
Rodriguez, J.F.R., Littke, R., 2001. Petroleum generation and accumulation in the Golfo San Jorge Basin, Argentina: a basin modeling study. Mar. Pet. Geol. 18, 995–1028.
Rodriguez, R.J., Aguirre, H.D., 2015. Analogía entre yacimientos como soporte para la ubicación de pozos de avanzada de alto riesgo: un caso de estudio en la cuenca del Golfo San Jorge, Patagonia Central. Rev. Asoc. Geol. Argent. 72, 124–139.
Root, R.S., Lang, S.C., Harrison, D., 2005. Reservoir scale sequence stratigraphy for hydrocarbon production and development: Tarbat–Ipundu Field, south-west Queensland, Australia. In: Blum, M.D., Marriot, S.B., Leclair, S.F. (Eds.), Fluvial Sedimentology VII, IAS Special Publication, 35, pp. 531–556.
Salgado, L., Coria, R.A., Calvo, J.O., 1997. Presencia del género Aeolosaurus (Sauropoda, Titanosauridae) en la Formación Los Alamitos, Cretácico Superior de la Provincia de Río Negro, Argentina. Rev. Univ. Guarulhos 2, 44–49.
Sanagua, J., Hlebszevitsch, J., Suarez, F., 2002. Los reservorios del Flanco Oeste. In: Schiuma, M., Hinterwimmer, G., Vergani, G. (Eds.), Rocas Reservorio de las Cuencas Productivas de la Argentina. 5th Congreso de Exploración y Desarrollo de Hidrocarburos, pp. 175–198 (Mar del Plata).
Scherer, C.M.S., Goldberg, K., Bardola, Tatiana, 2015. Facies architecture and sequence stratigraphy of an early post-rift fluvial succession, Aptian Barbalha Formation, Araripe Basin, northeastern Brazil. Sediment. Geol. 322, 43–62.
Schumm, S.A., 1968. Speculations concerning palaeohydrologic controls of terrestrial sedimentation. Geol. Soc. Am. Bull. 79, 1573–1588.
Schumm, S.A., 1993. River response to baselevel change: implications for sequence stratigraphy. J. Geol. 101, 279–294.
Sciutto, J.C., 1981. Geología del Codo del Río Senguerr, Chubut, Argentina. In: 8th Congreso Geológico Argentino, Actas 3, pp. 203–219 (San Luis).
Smith, N.D., Cross, T.A., Dufficy, J.P., Clough, R.S., 1989. Anatomy of an avulsion. Sedimentology 36, 1–23.
Stear, W.M., 1983. Morphological characteristics of ephemeral stream channel and overbank splay sandstone bodies in the Permian Lower Beaufort Group, Karoo Basin, South Africa. In: Collinson, J.D., Lewin, J. (Eds.), Modern and Ancient Fluvial Sediments, International Association of Sedimentologists Special Publication, 6, pp. 405–420.
Suárez, M., Márquez, M., De La Cruz, R., Navarrete, C., Fanning, M., 2014. Cenomanian-? Early Turonian minimum age of the Chubut Group, Argentina: SHRIMP U-Pb geochronology. J. S. Am. Earth Sci. 50, 67–74.
Sylwan, C.A., 2001. Geology of the Golfo San Jorge Basin, Argentina. J Iber. Geol. 27, 123–157.
Sylwan, C.A., Rodríguez, J.F., Strelkov, E.E., 2008. Petroleum systems of the Golfo San Jorge Basin, Argentina. In: Cruz, C.E., Rodríguez, J.F., Hechem, J.J., Villar, H.J. (Eds.), Sistemas petroleros de las Cuencas Andinas. 7th Congreso de Exploración y Desarrollo de Hidrocarburos, Actas, pp. 53–77 (Mar del Plata).
Tunbridge, I.P., 1981. Sandy high-energy flood sedimentation – some criteria for recognition, with an example from the Devonian of S.W. England. Sediment. Geol. 28, 79–95.
Tye, R., 1991. Fluvial-sandstone reservoirs of the Travis Peak Formation, East Texas Basin. In: Miall, A.D., Tyler, N. (Eds.), The Three-dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery, SEPM Concepts in Sedimentology and Paleontology, 3, pp. 172–188.
Uliana, M.A., Legarreta, L., 1999. Jurásico y Cretácico de la cuenca del Golfo San Jorge. In: Caminos, R. (Ed.), Geología Argentina. Subsecretaría de Minería de la Nación, Buenos Aires, pp. 496–510.
Uliana, M.A., Biddle, K.T., Cerdán, J., 1989. Mesozoic extension and the formation of Argentine Sedimentary Basins. In: Tankard, A.J., Balkwill, H.R. (Eds.),

Extensional Deformation and Stratigraphy of the North Atlantic Margins, AAPG Memoir 46, pp. 599–614 (Tulsa).
Umazano, A.M., Bellosi, E.S., Visconti, G., Melchor, R.N., 2008. Mechanism of aggradation in fluvial systems influenced by explosive volcanism: an example from the Upper Cretaceous Bajo Barreal Formation, San Jorge Basin, Argentina. Sediment. Geol. 203, 213–228.
Umazano, A.M., Bellosi, E.S., Visconti, G., Jalfin, G.A., Melchor, R.N., 2009. Sedimentary record of a Late Cretaceous volcanic arc in Central Patagonia: petrography, geochemistry and provenance of fluvial volcaniclastic deposits of the Bajo Barreal Formation, San Jorge Basin, Argentina. Cretac. Res. 30, 749–766.
Umazano, A.M., Bellosi, E.S., Visconti, G., Melchor, R.N., 2012. Detecting allocyclic signals in volcaniclastic fluvial successions: facies, architecture and stacking pattern from the Cretaceous of central Patagonia, Argentina. J. S. Am. Earth Sci. 40, 94–115.
Walker, G.P.L., 1971. Grain size characteristics of pyroclastic deposits. J. Geol. 79, 696–714.
Weber, K.J., van Geuns, L.C., 1990. Framework for constructing clastic reservoir simulation. J. Pet. Technol. 42, 1248–1297.