LATE TRIASSIC - EARLY JURASSIC SUCCESSIONS OF THE ATUEL DEPOCENTER: SEQUENCE STRATIGRAPHY AND TECTONIC CONTROLS

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ABSTRACT

Biostratigraphic correlations of the Late Triassic - Early Jurassic successions of the Atuel depocenter allowed determining the accommodation changes and the possible tectonic controls on sedimentation. The Rhaetian - late Early Sinemurian deposits contain facies of slope-type fan deltas, braided fluvial systems and low sinuosity rivers with alternate bars deposited during a synrift phase. The late Early Sinemurian - Toarcian series host facies of intermediate (Gilbert to shelf) type fan deltas, braided and low sinuosity fluvial systems, wave-dominated estuaries, transgressive storm-dominated and turbidite-influenced marine shelves which record the sag phase. According to different criteria two stratigraphic schemes are proposed, the first one considering tectosedimentary units (TSU) and the second one using "Exxon-like" sequences. In the first scheme the synrift TSU matches the actual Precuyo Mesosequence and the sag TSU is partly equivalent to the Cuyo Mesosequence, mainly keeping the current mesosequence scheme for the Neuquén basin but assigning the fandeltaic deposits to the Precuyo Mesosequence. The second sequence scheme considers the whole Late Triassic - Early Jurassic succession as a part of the Cuyo Mesosequence, where the synrift deposits composes the detached lowstand system tract (LST) and most of the sag deposits makes the transgressive system tract (TST). The basal sequence boundary does not crop out, the flooding surface at the TST base and the maximum flooding surface at the TST top are respectively marked by the lowest estuarine levels and by black shales with suboxic-compatible bivalves (*Bositra* sp.).

Keywords: *Neuquén Basin, Precuyano, Cuyo, sequences, tectosedimentary units*

RESUMEN: *Sucesiones del Triásico Tardío - Jurásico Temprano del Depocentro Atuel: estratigrafía secuencial y controles tectónicos*. La correlación bioestratigráfica de las sucesiones del Triásico Tardío - Jurásico Temprano del depocentro Atuel permitió determinar los cambios del espacio de acomodación y los posibles controles tectónicos de la sedimentación. La sección del Retiano - Sinemuriano Temprano tardío contiene facies de abanicos deltaicos de talud, ríos entrelazados y ríos de baja sinuosidad con desarrollo de barras alternas, depositados durante una fase de sinrift. La sucesión del Sinemuriano Temprano tardío - Toarciano alberga facies de abanicos deltaicos intermedios (entre los de tipo Gilbert y los de plataforma), ríos entrelazados, ríos de baja sinuosidad, estuarios dominados por oleaje y plataformas marinas transgresivas (desde plataformas dominadas por tormentas hasta otras influídas por corrientes de turbidez), todos los cuales registran la fase de *sag*. Se proponen dos esquemas estratigráficos según diferentes criterios: el primero considerando unidades tectosedimentarias (TSU) y el segundo usando secuencias depositacionales (o de tipo "Exxon"). En el primer esquema la TSU de sinrift se corresponde con la Mesosecuencia Precuyo y la TSU de sag equivale parcialmente a la Mesosecuencia Cuyo, manteniendo en gran parte el esquema de mesosecuencias vigente para la cuenca Neuquina aunque asignando los depósitos de abanicos deltaicos a la Mesosecuencia Precuyo. En el segundo esquema se considera a toda la sucesión del Triásico Tardío - Jurásico Temprano como parte de la Mesosecuencia Cuyo, donde los depósitos de sinrift componen el cortejo de mar bajo (LST) y la mayoría de los depósitos de sag forman parte del cortejo transgresivo (TST). El límite de secuencia basal no aflora, la superficie de inundación en la base del TST y la superficie de máxima inundación en el tope del TST están marcados, respectivamente, por los niveles estuáricos más bajos y por las lutitas negras con bivalvos subóxicos (*Bositra* sp.).

Palabras clave: *Cuenca Neuquina, Precuyano, Cuyo, Secuencias, Unidades tectosedimentarias.*

INTRODUCTION

The Neuquén basin is a Mesozoic rifted back-arc basin placed on the western convergent margin of the South American plate (Uliana and Biddle 1988, Legarreta and Uliana 1991) and attributed to the extension during the fragmentation of Gondwana and the opening of the South Atlantic Ocean (Uliana and Biddle 1988).

The basin evolution began with a series of unconnected depocenters (Manceda and Figueroa 1993, 1995, Tankard *et al.* 1995) resulting from the first rifting episode in the Middle Triassic - Sinemurian (Ramos 1992, Manceda and Figueroa 1995) and finally connected in the Early Pliensbachian (Legarreta and Gulisano 1989) when most of the basin was transgressed. The unrelated depocenters were initially filled with the non-marine, mainly non-fossiliferous, siliciclastics and volcanics of the Precuyo Mesosequence (Gulisano 1981, Gulisano *et al.* 1984, Legarreta and Gulisano 1989), which were interpreted as synrift deposits (Gulisano *et al.* 1984, Legarreta and Gulisano 1989). At the same time, the deepest zone of the basin was rapidly transgressed by nearshore sandstones and offshore shales of the Cuyo Mesosequence (Legarreta and Gulisano 1989) partly due to the Sinemurian to Toarcian regional sag phase (Vergani *et al.* 1995). Features, areal distribution and basal age of the sag deposits depended on the marked basement topography, controlled by the main faults and footwall uplift. The rough paleotopography also governed the partial synchronism between continental and marine units of the Late Triassic - Early Jurassic age (Gulisano 1981, Gulisano and Gutiérrez Pleimling 1994).

One of the initial unconnected sub-basins above was the Atuel depocenter (Fig. 1), which had a different evolution because it contains the only presently known marine synrift deposit and the oldest transgressive record (Rhaetian, Riccardi *et al.* 1997, Riccardi and Iglesia Llanos 1999). In this depocenter, several detailed structural and sedimentary studies of the Late Triassic - Early Jurassic interval have been carried out during the last decade (Lanés 2002, 2005, Giambiagi *et al.* 2005a, 2005b, 2008 in press and 2008 this issue, Bechis *et al.* 2005, Spalletti *et al.* 2007).

The purpose of the present paper is to describe the Late Triassic - Early Jurassic sequences of the Atuel depocenter and their relationship to the current sequence scheme of the Neuquén basin. Identifying sequences in rifts is difficult due to the combination of eustatic sea-level changes, fault movements, changes on the sedimentary supply and the local fault-derived paleotopography on the control of the sedimentary record.

METHODS

Facies, paleocurrents and thickness variations of vertical sections were analyzed to determine the depositional systems and probable paleogeographical features (Lanés 2002, 2005). Sections were correlated along two roughly orthogonal east-west and north-south transects orientation, based on local ammonite, bivalve and brachiopod biostratigraphy (Riccardi *et al.* 2000). We used two selected datums for this correlation: the *Epophioceras* Zone at most of the sections and the *Tropidoceras* Zone to correlate Puesto Araya, Arroyo Las Chilcas and Quebrada de los Caballos sections (Figs. 1b and 2). The underlying fluvial unit lacks fossils of biostratigraphic value, being dated due to its field position. The age uncertainty of these fluvial successions obstructs the determination of hiatus inside them and between the marine and non-marine formations.

In order to identify the sequences and any tectonic or eustatic control on the Rhaetian - Toarcian successions of the Atuel depocenter, the evolution of the accommodation was evaluated and the relative sea-level changes were contrasted with the global eustatic sea-level chart (Haq *et al.* 1987, 1988) and with the tectonic evolution of the Neuquén basin (Vergani *et al.* 1995).

GEOLOGICAL SETTING

Late Triassic - Early Jurassic interval of the Atuel depocenter includes mixed, marine and non-marine deposits of the Arroyo Malo, El Freno, Puesto Araya and Tres Esquinas Formations (Figs. 1b and 3). Though a discussion on the lithostratigraphy of the study area is beyond the scope of the paper, we consider the Puesto Araya Formation divided into an upper and a lower section, as in Giambiagi *et al.* (2005a).

Analysis of these successions allowed determining a synrift phase during the Rhaetian - late Early Sinemurian followed by a sag phase in the late Early Sinemurian - Toarcian (Lanés 2002, 2005, Giambiagi *et al.* 2005b). Detailed descriptions of facies associations, depositional systems and their evolution can be found in Lanés (2002, 2005), Giambiagi *et al.* (2005b) and Spalletti *et al.* (2007), though a brief account is given below.

The oldest deposits are the fan delta successions assigned to the Arroyo Malo Formation (Rhaetian - Middle Hettangian, Riccardi *et al.* 1997, Riccardi and Iglesia Llanos 1999) and the lower section of the Puesto Araya Formation (Middle Hettangian - late Early Sinemurian). They crop out only in the Arroyo Malo halfgraben (Giambiagi *et al.* 2008, this issue), in the western part of the Atuel depocenter (Figs. 1b, 2 and 4), being well bedded, coarsening and thickening-upward turbiditic sections, with usual slump folds and synsedimentary faults, alternating with breccia and lensoidal cross-bedded sandstones and conglomerates (Fig. 4, Tables 1 and 2). Tabular beds of tangential cross-bedded sandstones, cut by lenses of trough cross-bedded sandstones exclusively occur at the top of the Arroyo Malo section (D9 in Table 2, Fig. 4). Fan delta successions were interpreted as three stacked shallowing-upward fluviodominated, transverse and normal-fault controlled, slope-type (*sensu* Ethridge and Wescott 1984 and Pos-

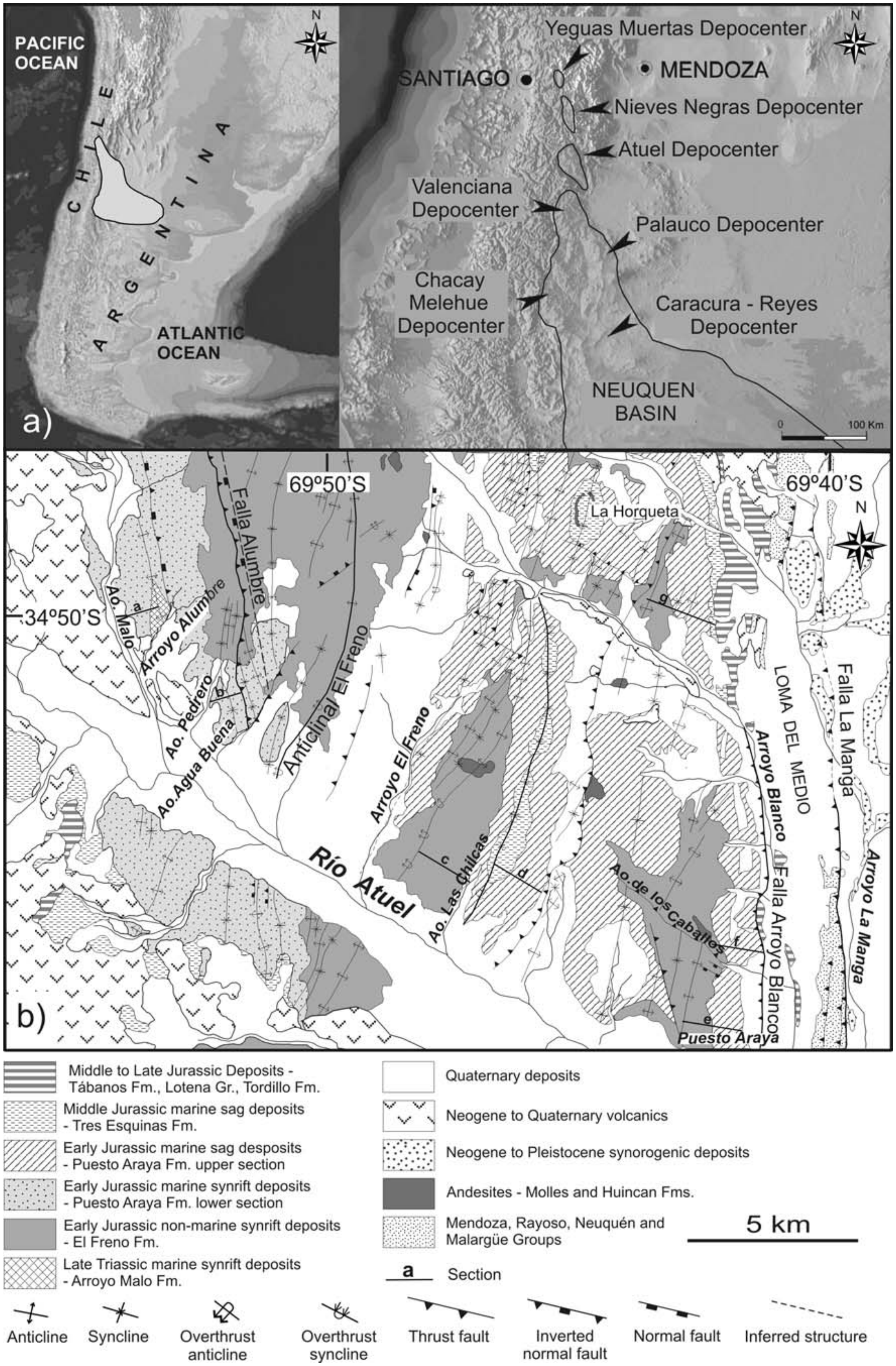

Figure 1: a) Location of the Neuquén basin and its northern depocenters (modified from Giambiagi *et al.* 2005a). b) Geological map of the study area (modified from Giambiagi *et al.* 2008 this issue). Section localities: a) Arroyo Malo, b) Arroyo El Pedrero, c) Arroyo El Freno, d) Arroyo Las Chilcas, e) Puesto Araya, f) Quebrada de Los Caballos, g) Codo del Blanco

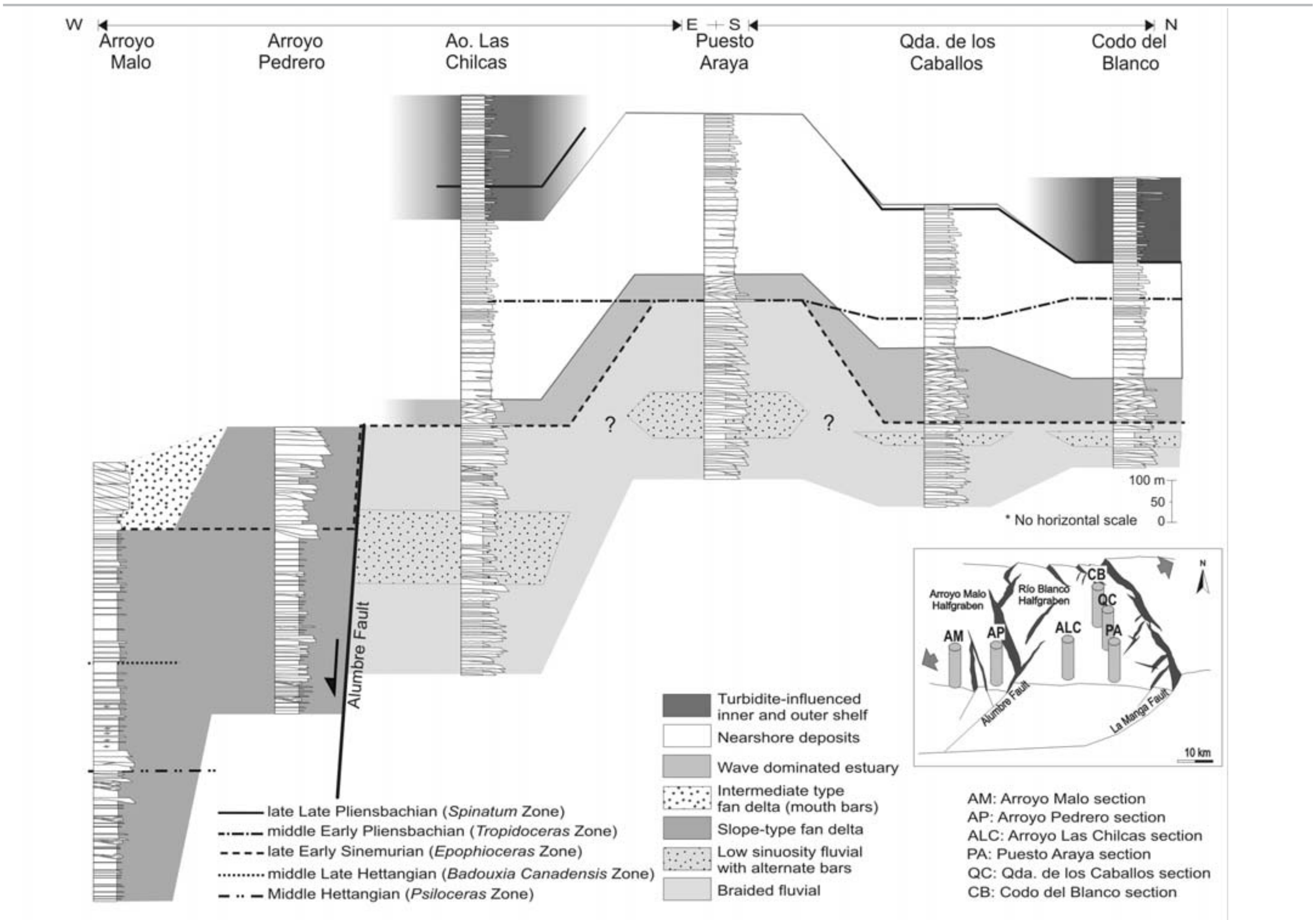

Figure 2: Biostratigraphic correlation of the studied vertical sections. Stage divisions are shown except for the Hettangian whose ammonite standard zones are present. Datums are based on the ammonite zonation for the Neuquén basin (Riccardi *et al.* 2000). Block diagram shows the inferred section sites and the ancient main faults (modified from Giambiagi *et al.* 2008 this issue).

tma 1990) and intermediate (Gilbert to shelf) type fan deltas (Lanés 2005). Sandbodies atop the Arroyo Malo section were interpreted as deposits of mouth bars and distributary channels of an intermediate (Gilbert to shelf) type fan delta. Before Middle Hettangian, the active controlling fault was located east of the present arroyo Alumbre (Arroyo Malo Fault, Giambiagi *et al.* this issue) and later, before late Early Sinemurian, it was placed farther east (Alumbre Fault, Giambiagi *et al.* 2008 this issue).

Fluvial deposits of the El Freno Formation are partly correlative to the lower section of the Puesto Araya Formation (Fig. 2). They are finning- to coarsening-upward or slightly finning- and thinning-upward successions of lenses filled with clast-supported imbricated, trough or planar cross-bedded conglomerates, trough or planar cross-bedded or plane laminated sandstones, and minor massive or plane laminated mudstones (Fig. 5, Table 3). Fines occur as mud clasts or thin lenses at the sandstone tops. Locally muddy facies increase from 10 % up to 36 % - 40 % of the whole thickness showing paleosoils, mud cracks or alternating with trough cross-bedded sandstones with lateral accretion surfaces. Considering the width/depth ratio of the conglomerate and sandstone bodies (Friend 1983), ribbon (width thickness, w/th <15, Gibling 2006) and belt (width ≈ thickness, w/th >15) types were observed. At the Arroyo El Freno section, located immediately westward of the Arroyo Las Chilcas section, these conglomerate and sandstone bodies are vertically stacked in a definite pattern (Spalletti *et al.* 2007, their Fig. 5). Ribbons dominate the basal fluvial sections with a decreasing-upward connectivity which is minimal at the middle section where fine facies dominate (*i.e.* the middle part of the Arroyo El Freno section, Fig. 5). Towards the top, the channel connectivity increases again, from isolated ribbons to belts and eventually wider mobile-channel belts (*sensu* Friend 1983). Fluvial successions resulted from the nucleation and migration of mid-channel longitudinal and transverse bars in a braided fluvial system (Giambiagi *et al.* 2005b, Spalletti *et al.* 2005, 2007), which locally evolved to a low sinuosity fluvial system with alternate bars (sensu Miall 1996), fine floodplains, crevasse channels and splays.

The upper section of the Puesto Araya

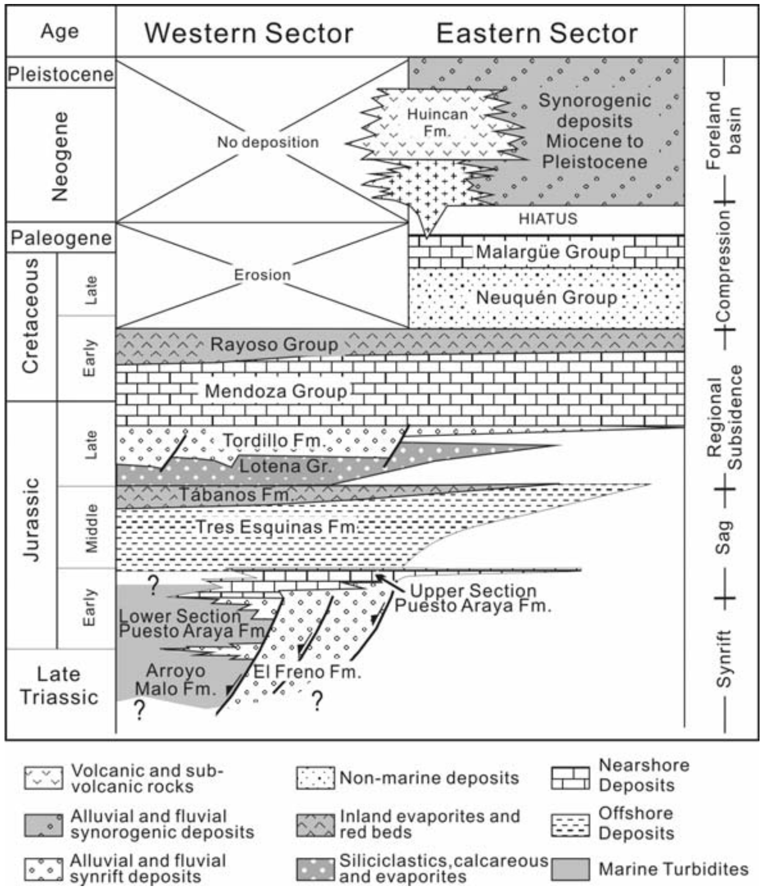

Figure 3: Stratigraphy of the study area showing the major tectonic processes, keeping the criteria by Giambiagi *et al.* 2008 (this issue). Western sector refers to the Atuel depocenter, located west of La Manga Fault (after Giambiagi *et al.* 2008 this issue).

Formation (late Early Sinemurian-Toarcian) is a tabular, well-bedded, fining- and thinning-upward sandy succession cropping out in the eastern Atuel depocenter, in the Rio Blanco halfgraben (Giambiagi *et al.* 2008 this issue) (Fig. 6, Table 4). It hosts trough cross-, swash cross-, and herringbone cross-bedded sandstones, amalgamated swaley and hummocky cross-bedded or normally graded and wave-rippled sandstones. Discrete beds of hummocky cross-bedded or normally graded, plane laminated sandstones appear towards the top, alternating with massive fine sandstones, massive mudstones and plane laminated shales. This succession records a transgressive storm-dominated shelf, from wave-dominated estuaries (Dalrymple *et al.* 1992) to inner shelf settings.

The upper section of the Puesto Araya Formation gradually evolves upwards to the shales of the Tres Esquinas Formation (late Late Pliensbachian - Bajocian), which comprise massive mudstones, and unbioturbated plane laminated black shales interfingering with Tce, Tbe and Tae turbidites (Fig. 6, Table 4). These deposits were interpreted as a turbidite-influenced anaerobic inner and outer marine shelf. Occasionally the black shales contain monoespecific pavements of *Bositra* sp., a bivalve able to live during short events of dysaerobic (O_2<0,6 ml O_2/l of H_2O, Brett and Baird 1986, Savrda *et al.* 1991) waters in usually anaerobic (O_2< 0,1 ml O_2/l of H_2O, Brett and Baird 1986) bottom waters. In the Codo del Blanco section the pavements of *Bositra* sp. occur together with ammonites of the *Spinatum* Zone (late Late Pliensbachian).

PALEOENVIRONMENTAL AND TECTONIC EVOLUTION

The evaluation of the eustatic-related changes in accommodation needs a previous identification of the tectonic controlling factors. In the Atuel depocenter the synrift phase showed a great accommodation while the sag phase evidenced a variable accommodation (Fig. 7).

The great accommodation during the synrift phase (Rhaetian - late Early Sinemurian) allowed the deposition of slope-type fan deltas, braided fluvial systems and low sinuosity fluvial systems with alternate side bars (Fig. 2). The progressive unconformities placed at the base of fining-upwards fan deltaic sequences (Fig. 2, and Giambiagi *et al.* 2008 this issue, their Fig. 8) evidence the consecutive movements of the Alumbre fault and its control on synrift sedimentation segregating the marine synrift deposits westwards from the fluvial synrift deposits eastwards, on the footwall (Figs. 2, 8, Giambiagi *et al.* 2008 this issue). Besides, the upward changes of the fluvial channel style and connectivity in the Arroyo El Freno section (Figs 1 and 5) reported by Spalletti *et al.* (2007), express an increase and a following decrease in accommodation (Emery and Myers 1996, Miall 1996, Gibling and Bird 1994, Wright and Marriott 1993 and Martinsen et al. 1999) probably controled by the synrift subsidence (Leeder and Gawthorpe 1987, Prosser 1993, Gawthorpe and Leeder 2000, Withjack *et al.* 2002).

The similar age of the overlaying marine deposits and similar sedimentary trends of accommodation (Spalletti *et al.* 2007) of the fluvial portions in the Codo del Blanco, Quebrada de los Caballos and Arroyo Las Chilcas sections allow assigning these deposits to the synrift phase. Besides, there are independent evidences to support the synrift origin of the fluvial strata, based on structural analysis of the architecture of the depocenter (Giambiagi *et al.* 2008, this issue), kinematic analysis of small-scale normal faults (Be-

TABLE 1: : Rhaetian - Middle Hettangian fandeltaic facies associations of Arroyo Malo Formation.

Name	Deposits	Depositional processes and paleoenvironment
D1	Plane laminated mudstones, Tde and Tce turbidites, mudstone concretions	Low-density turbidity currents and mud deposition. Basin area far from fan delta front.
D2	Tce, Tbe and Tde turbidites, plane laminated mudstones, mudstone concretions.	Low-density turbidity currents and mud deposition. Prodelta of a slope-type fan delta.
D3	Tae, Tac, Tbe, Tce and Tde turbidites, laminated mudstones, massive pebbly mudstones, intraformational breccias, massive clast-supported and mud-supported conglomerates. Tae and Tac turbidites with dense lithics. Lenses of trough-cross bedded sandstones. Sediment deformation (slumps, slump folds, faults, convolute lamination, fluid escape structures, pseudonodules, load deformation, clastic dykes and syneresis cracks).	Low-density and high-density turbidity currents, mud deposition, cohesive debris flows (some of them derived from slumps or re-sedimented fluvial deposits). Channelized low-regime traction flows. Lower part of a steeply slope-type fan delta front.
D4	Usually amalgamated tabular deposits and lenses (10-20 m wide, 0.4-1 m thick) filled with massive pebbly mudstones, Tbe, Tde, Tce, Tae turbidites and plane laminated mudstones. Lenses cut stackings of Tbe, Tde and Tce turbidites.	Cohesive debris flows, low-density and high-density turbidity currents and mud deposition. Chutes and inactive interchute areas in the slope-type fan delta front, below wave base.
D5	Lenses (10-100 m wide, 0.5-3 m thick) filled with basal trough-cross bedded sandstones, shell lenses, normally graded clast-supported conglomerates, massive pebbly sandstones, Ta turbidites with mudclasts or shells or Tac and Tae turbidites with dense lithics at the lense bases; and Tce, Tde, Tbe turbidites and plane laminated mudstones at the lense tops. Lenses alternate with tabular beds of intraformational breccia and massive mud-supported conglomerates.	Hyperconcentrated flows, high-density and low-density turbidity currents and channelized low-regime traction flows. Unconfined cohesive debris flows derived from the slumping of turbidite or fluvial successions. Braided distributary channels, inactive interdistributary areas and levees in the slope-type fan delta upper front, below wave base.

* Modified from Lanés 2005.

TABLE 2: Middle Hettangian - late Early Sinemurian fandeltaic facies Associations of lower section of the Puesto Araya Formation.

Name	Deposits	Depositional processes and paleoenvironment
D6	Tbe, Tce, Tde turbidites, plane laminated mudstones and less Tae turbidites. Mudstone concretions.	Low-density and high-density turbidity currents, and mud deposition. Prodelta of a slope-type fan delta.
D7	Tabular beds and lenses filled with Tae, Ta, Tbe, Tce and Tde turbidites, massive sandstones, intraformational breccias and sandstones with isolated tangential 2-D dunes. Sediment deformation (slump folds, convolute lamination, faults, fluid escape structures, sedimentary boudinage, pseudonodules, load deformation, clastic dykes and syneresis cracks).	Low-density and high-density turbidity currents, high-density turbidity currents after the hydraulic jump and small amount of slump-derived cohesive debris flows. Inactive interchute areas and some chutes in the slope-type fan delta lower front.
D8	Usually amalgamated Tae, Tac and Ta turbidites, massive pebbly mudstones and less Tbe, Tce and Tde turbidites.	High-density and low-density turbidity currents, cohesive debris flows. Slope-type fan delta lower front.
D9	Tabular beds of tangential cross-bedded sandstones cut by lenses of trough-cross bedded, plane laminated and parting lineated sandstones. Tabular Tce, Tde and Tbe turbidites.	Unconfined and channelized low-regime traction flows, low-density turbidity currents.
D10	Tabular beds or usually amalgamated lenses of Ta and Tae turbidites. Multiepisodic or simple lenses (10-100 m wide, 1-3 m thick) filled with normal graded and plane laminated clast-supported conglomerates (sometimes with mud clasts and inversely-graded laminae) or trough-cross bedded sandstones. Stacked Tce, Tbe and Tde turbidites, and some sandstones with isolated tangential 2-D dunes.	Mouth bars and distributary channels of an intermediate (shelf to Gilbert-type) fan delta front. High-density and low-density turbidity currents, high-density turbidity currents after the hydrau-lic jump, channelized hyperconcentrated flows and some channelized low-regime traction flows. Chutes, some distributary channels and inactive interdistributary areas of a slope-type fan delta front.
D11	Multiepisodic or simple lenses (10-100 m wide, 0.5-3 m thick) filled with normally graded clast-supported conglomerates, trough-cross bedded conglomerates or trough-cross bedded sandstones with shell lenses, underlaying Tbe and Tce turbidites. Interfingering with stacked Tbe and Tce turbidites.	Channelized low-regime and upper-regime traction flows and channelized hyperconcentrated flows. Braided distributary channels, levees and inactive interdistributary areas of a slope-type fan delta front, below wave base.

* Modified from Lanés 2005.

chis and Giambiagi 2008), and provenance studies (Tunik *et al*. 2008, this issue). The lack of biostratigraphic valuable fossils in the fluvial deposits inhibits the evaluation of hiatus inside the fluvial succession or between the fluvial and the marine units. However, the local facies variations, and the convergence and amalgamation of the fluvial deposits towards the Puesto Araya section (Fig. 2) obstruct the segregation of the synrift fluvial deposits from the sag fluvial deposits in this section at the moment. Future studies considering the local effect of the faulted block topography on the fluvial accommodation and sediment supply, will allow improving such identification.

By the late Early Sinemurian a change in accommodation occurred. According to the biostratigraphic correlation (Fig. 2) the slope-type fan delta deposits at the

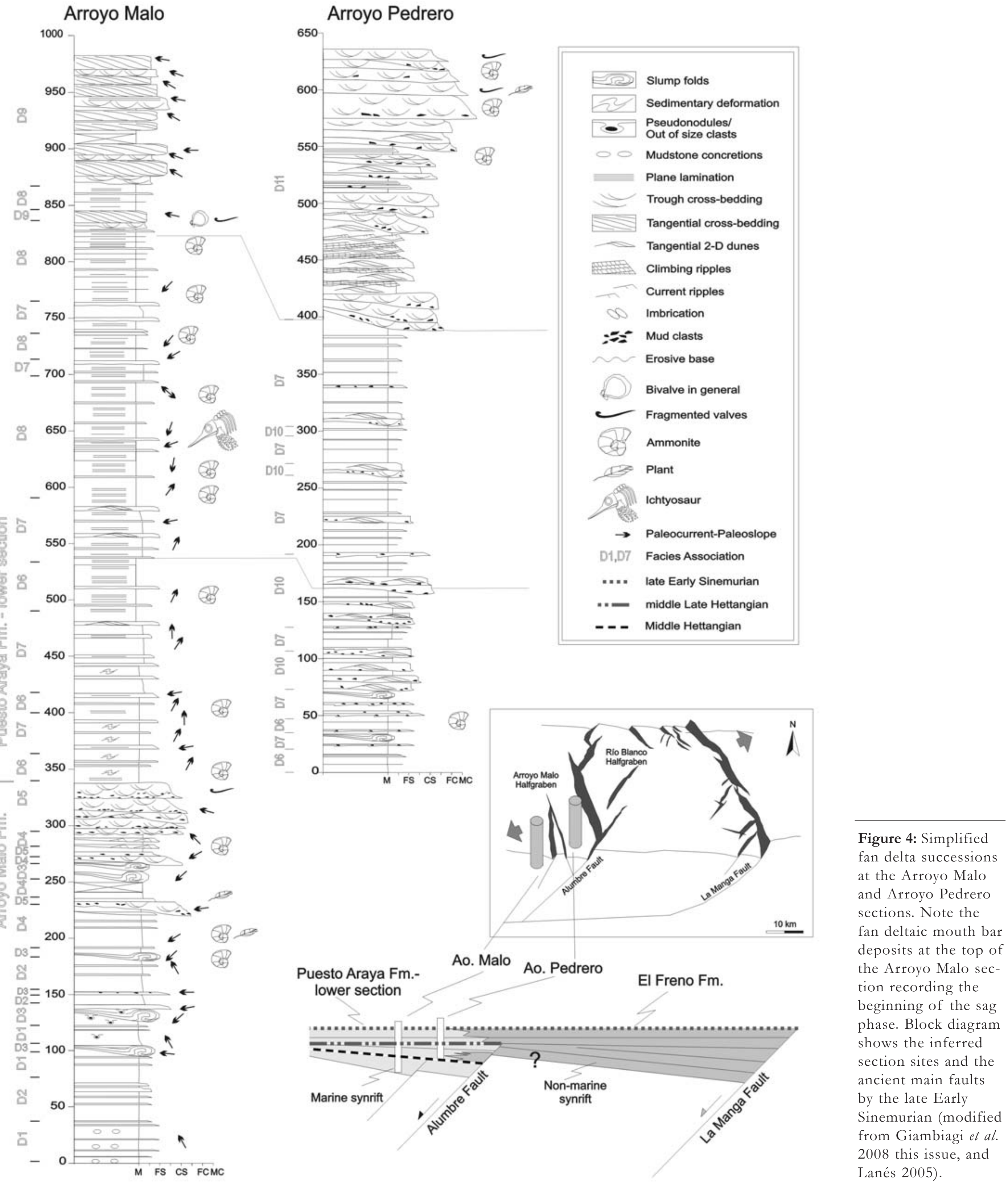

Figure 4: Simplified fan delta successions at the Arroyo Malo and Arroyo Pedrero sections. Note the fan deltaic mouth bar deposits at the top of the Arroyo Malo section recording the beginning of the sag phase. Block diagram shows the inferred section sites and the ancient main faults by the late Early Sinemurian (modified from Giambiagi *et al.* 2008 this issue, and Lanés 2005).

top of the Arroyo Pedrero section, the intermediate fan delta mouth bars and the estuarine deposits are contemporaneous and belong to the *Epophioceras* Zone. However those deposits require different accommodations to be formed. Slope-type fan deltas require a great accommodation (accommodation >> supply), the intermediate fandelta mouth bars are

TABLE 3: Late Triassic-Early Jurassic fluvial facies associations of El Freno Formation.

Name	Deposits	Depositional processes and paleoenvironment
F1	Lenses (0.3-15 m or 75-100 m wide, 0.2-2 m thick) filled with 3 different internal stacking patterns. a) Basal trough cross-bedded conglomerates, pebbly sandstones or sandstones (Gt, GSt or St) underlying trough cross-bedded sandstones (St), massive or normally graded sandstones (Sm or Sg), and plane laminated and current rippled sandstones (Sh and Sr). b) Basal planar cross-bedded conglomerates (Gp) and planar cross-bedded sandstones (Sp). c) Basal massive conglomerate or pebbly sandstones (Gm or GSm) underlying trough or planar cross-bedded sandstones (St or Sp).	a and b) Nucleation and active downstream migration of transversal bars. c) Nucleation and active downstream migra-tion of subordinate longitudinal bars. Braided fluvial system.
F2	Lenses (0.3-15 m wide, 0.2-2 m thick) filled with trough cross-bedded and current rippled sandstones (St and Sr), occasional fluid escape structures. Lateral acretion surfaces cut trough the whole bed thickness.	Alternating side bars with limited lateral migration. Low sinuosity fluvial system with alternate bars (sensu Miall 1996).
F3	Tabular single beds (0.1 to 3 m thick) of massive silt (Fsm) and minor heterolithic plane laminated or rippled sand-silt couplets (Fl), with occasional desiccation cracks and rootlets (Fr). Lenses (up to 2 m wide, up to 0.5 m thick) and tabular single beds (up to 0.4 m thick) of normal graded, massive or plane laminated coarse to medium-grained sandstones (Sg, Sm or Sh respectively) underlying plane laminated and current rippled fine sandstones (Sh and Sr).	Overbank deposits (floodplain of a mixed-load fluvial system). Crevasse-channel and crevasse splay deposits. (floodplain of a mixed-load fluvial system).
F4	Lenses (up to 2 m wide, up to 0.5 m thick) filled with massive silt (Fsm) and minor heterolithic plane laminated sand-silt couplets (Fl). Occasional mud cracks.	Abandoned channel deposits on transverse and longitudinal bars tops. Braided fluvial system.

Lithofacies codes after Miall (1978, 1996).

TABLE 4: Sag marine facies associations of late Early Sinemurian - Toarcian age.

Name	Deposits	Depositional processes and paleoenvironment
M1	Lenses (occasionally multiepisodic) of herringbone cross-bedded sandstones and shell lags, basal massive or normally graded clast-supported conglomerates and trough-cross bedded sandstones at the top. Tabular tangential cross-bedded sandstones with mud drapes; trough cross-bedded sandstones, swash cross-bedded sandstones with plane lamination and parting lineation. Quebrada de los Caballos section: also trough cross-bedded sandstones with wave ripples and shell lags, swaley cross-stratified sandstones. Codo del Blanco section: Amalgamated tabular hummocky cross-bedded, swash cross-bedded and trough cross-bedded sandstones with wave ripples and shell lags, plane laminated and parting lineated sandstones, planar cross-bedded sandstones. Lensoidal bipolar imbricated conglomerates, tabular massive or normally graded shelly sandstones, minor massive fine sandstones, massive mudstones and plane laminated shales.	Tidal inlets and tidal sand waves in the subtidal to lower intertidal area of a wave-dominated estuary. Conglomeratic tidal inlets, fairweather and storm wave and current deposits above fairweather wave base. Quebrada de los Caballos section: also scarce fairweather and storm wave deposits above fairweather wave base. Wave-dominated estuary. Codo del Blanco section: External wave dominated estuary, and scarce mudstones and washover fans of the central wave-dominated estuary.
M2	Amalgamated tabular massive or normally graded shelly sandstones, hummocky and swaley cross-bedded sandstones. Tabular trough cross-bedded sandstones with wave ripples, swash cross-bedded sandstones and less massive fine sandstones.	Deposits of fairweather and storm waves and currents around the fairweather wave base. Shoreface to upper offshore-shoreface transition zone of a storm-dominated shelf.
M3	Tabular single beds of hummocky cross-bedded sandstones; massive fine sandstones with epifaunal bivalves or brachiopods in life position; normally graded and plane laminated coarse sandstones. Scarce massive sandstones with groups of brachiopods in life position and massive mudstones.	Storm waves and currents, low energy fair-weather currents and mudstone deposition around the storm-wave base. Offshore-shoreface transition zone and upper offshore of a storm-dominated shelf.
M4	Massive mudstones and plane laminated black shales, normally graded and plane laminated medium sandstones. Scarce Tce, Tde, Tbe, Tae and Tac turbidites.	Mudstone deposition and scarce low- and high-density turbidity currents below storm wave base. Turbidity current-influenced offshore on the inner-shelf.
M5	Tce, Tbe and Tde turbidites, massive mudstones and laminated shales. Occasional Tae and Tac turbidites, tabular massive sandy mudstones and wide lenses filled with normally graded clast-supported conglomerates and trough cross-bedded sandstones.	Mudstone deposition, high-density and low-density turbidity currents, sandy debris flows, hyperconcentrated flows with tops reworked by low-regime traction currents. Turbidity current-influenced outer shelf.

*Deposits belonging to the Tres Esquinas Formation (modified from Lanés 2005).

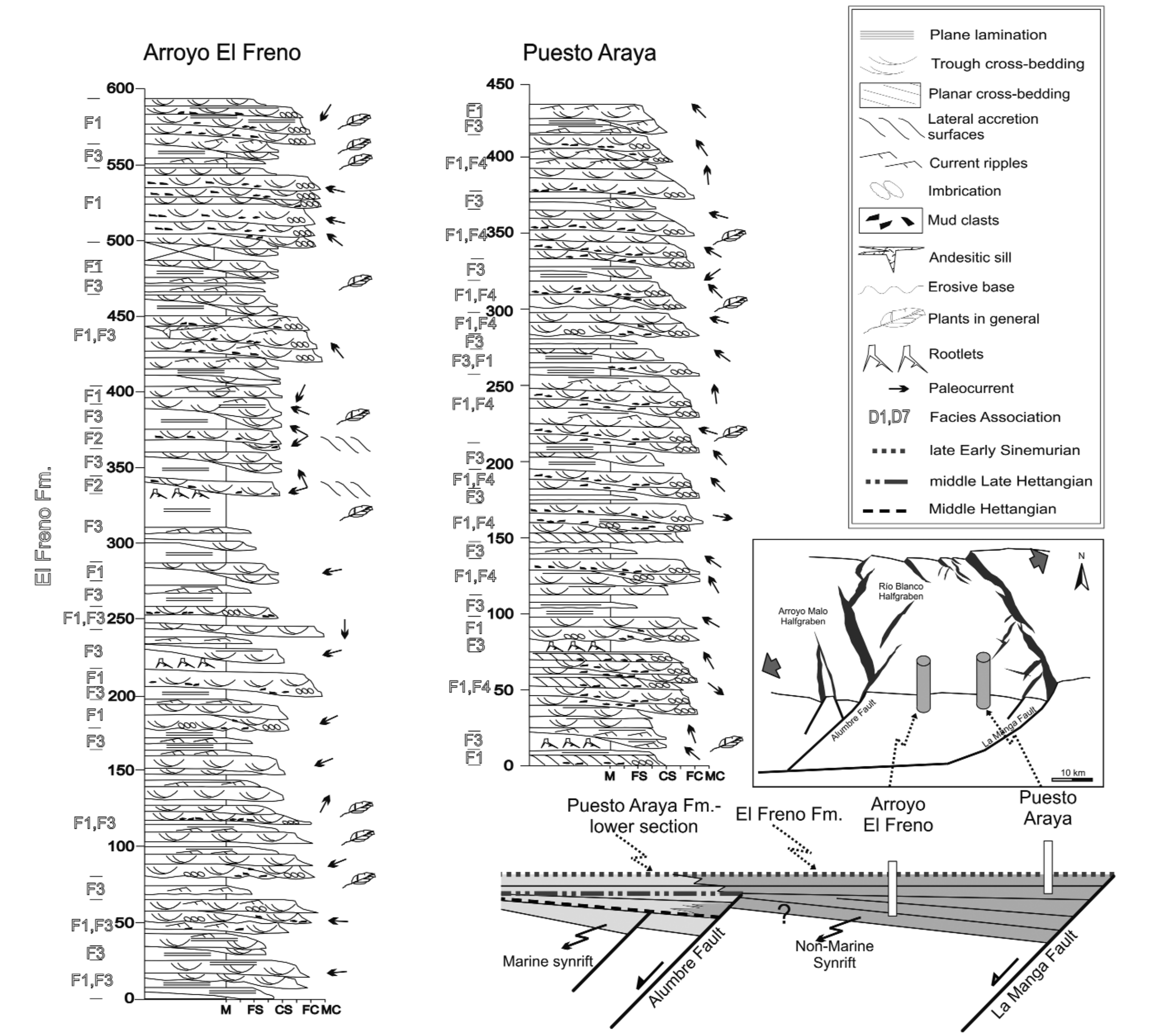

Figure 5: Simplified fluvial successions tentatively attributed to the synrift and sag phases at Arroyo El Freno and Puesto Araya section respectively. Block diagram show the inferred section sites and the ancient main faults by the late Early Sinemurian (modified from Giambiagi *et al.* 2008 this issue and Lanés 2005).

strongly prograding and need a greater supply (accommodation << supply), and the estuarine deposits require a transgressive event and increasing accommodation to be formed. This paradox can be explained considering the duration of 3 My of the *Epophiceras* Zone, long enough to allow a sea level fall and a consequent sea level rise to occur (Fig. 7). These sea level changes coincide with a lowstand and a sea level rise of the short term eustatic curve by Haq *et al.* (1987, 1988). We propose that the late Early Sinemurian sea level fall led to fluvial incision on the shelf and fan deltaic conglomerate deposition at the top of the Arroyo Pedrero section. A subsequent slow sea level rise increased the accommodation on the Alumbre fault hangingwall, allowing the fan deltaic mouth bars to prograde. The change from a fault-controlled subsidence to a thermal regime by the late Early Sinemurian explains the restricted accommodation needed to the progradation of the intermediate fan delta mouth bars. Later, a faster sea level rise led the flooding of the incised valleys and estuarine deposition in the Arroyo Blanco halfgraben. Global eustatic cycles suggest the late Early Sinemurian sea-level rise in the Atuel depocenter probably resulted from the combination of an eustatic sea-level rise with a regional sag (Lanés 2005). Afterwards an accommodation exceeding the supply, the widespread marine depositional area and a slower

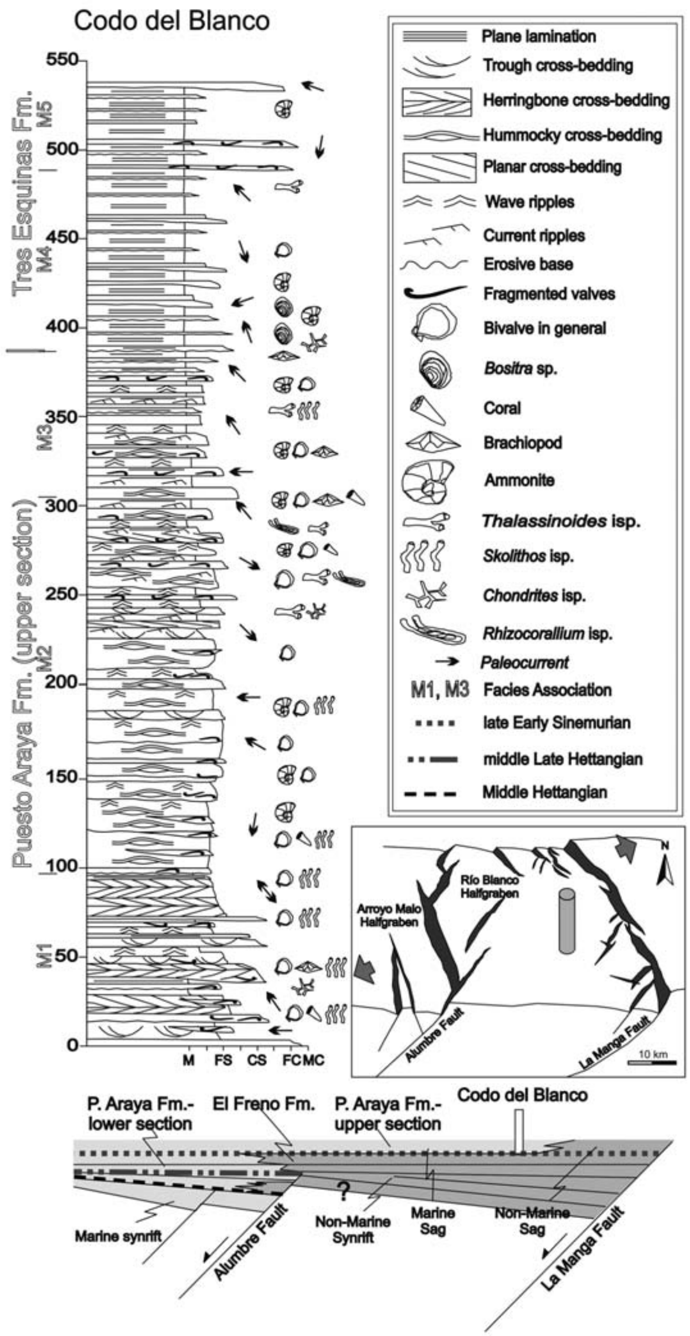

Figure 6: Simplified sag marine succession in the Codo del Blanco section. Block diagram shows the inferred section site and the ancient main faults by the late Early Sinemurian (modified from Giambiagi *et al.* 2008 this issue and Lanés 2005).

creation of accommodation led to the development of the estuaries and transgressive marine shelf. The accommodation on the marine shelf reached its maximum by the latest Pliensbachian (*Spinatum* Zone from the ammonite standard zones) in the Codo del Blanco section, when anoxic bottom waters and short dysaerobic events were recorded in laminated black shales with monoespecific pavements of *Bositra* sp.

SEQUENCE STRATIGRAPHIC SCHEMES

In tectonically active basins, the classical sequence-stratigraphic model (Vail *et al.* 1977, Van Wagoner *et al.* 1988, 1990), originally developed in passive margins, is difficult to apply due to the continuous interplay between eustasy and tectonics (Howell and Flint 1996). Tectonic movements may occur over shorter time scales than eustatic changes and may cause local unconformities which are more evident than unconformities related to eustatic sea-level changes (Mutti 1990, Bruhn and Walker 1995, Gawthorpe *et al.* 1994, 2000 a, 2000b, Burns *et al.* 1997). Then the superposition of tectonically controlled cycles may locally obscure the eustatic signal.

Therefore two different approaches were used to analyze the Late Triassic - Early Jurassic succession of the Atuel depocenter: a) the tectonosedimentary units and b) the sequences (sensu Mitchum *et al.* 1977).

a) Tectonosedimentary units

Tectosedimentary units (TSU, *sensu* Garrido-Megias 1982) are stratigraphic units composed by a succession of strata, not necessarily conformable, deposited within a concrete interval of geological time and under a tectonic and sedimentary dynamic of definite polarity, bounded by sedimentary breaks of basinal extent. Such sedimentary breaks were later defined as surfaces which can be conformable everywhere, or conformable in the basin center and correlative to an unconformity of any type at the basin margins (González *et al.* 1988, Pardo *et al.* 1989). Their conformable or unconformable boundaries allow relating the TSU with the depositional sequences (sensu Mitchum *et al.* 1977) though the last ones are conformable stakings of strata. On the other hand, the unconformable boundaries of some TSU make them comparable to the sequences (sensu Sloss 1963) and the unconformity-bounded units, including the subsynthems (Chang 1975, Salvador 1994). Finally the TSU are similar to the pre-rift, syn-rift and post-rift megasequences defined by Hubbard (1988) to analyze the stratigraphy of rift-related basins and passive margins.

In the Late Triassic - Early Jurassic of the Atuel depocenter, a synrift TSU and a sag TSU were identified (Fig. 8). The synrift TSU includes the fan deltaic and fluvial synrift deposits of Rhaetian - late Early

Sinemurian age. As it was mentioned above, the local facies variations and the convergence and amalgamation of the fluvial deposits towards the Puesto Araya section (Fig. 2) obstruct the segregation of the synrift fluvial deposits from the sag fluvial deposits in this section at the moment. However, there are independent evidences to support the synrift origin of the fluvial strata, based on structural analysis of the architecture of the depocenter (Giambiagi *et al.* 2008, this issue), kinematic analysis of small-scale normal faults (Bechis and Giambiagi 2008), and provenance studies (Tunik *et al.* 2008, this issue). Future studies considering the local effect of the faulted block topography on the fluvial accommodation and sediment supply, together with the age of the basal nearshore successions would allow the extrapolation of the synrift TSU to other localities.

Due to its tectonic origin and despite of the fandeltaic origin of part of its deposits, the synrift TSU is comparable to the Precuyo Mesosequence (Legarreta and Gulisano 1989), Precuyano Cycle (Gulisano 1981) and Sañicó Subsynthem (Riccardi and Gulisano 1990). The three units were defined as including occasional siliciclastics of non-marine (alluvial fan, fluvial, playa lake) origin, which crop out without a definite position inside the sequence (Gulisano *et al.* 1984). However the authors emphasized that the Precuyano Cycle, Precuyo Mesosequence or Sañicó Subsynthem include the initial infilling of extensional depocenters in the basement of the Neuquén basin, which were later covered non-marine and marine sedimentary rocks of the Cuyo Mesosequence.

As the sag TSU recognized in the Atuel Depocenter is partly equivalent to the Cuyo Mesosequence, the TSU scheme mainly keeps the current mesosequence scheme for the Neuquén basin but assigning the fandeltaic deposits to the Precuyo Mesosequence.

b) Depositional sequences

Sequence stratigraphy of the Late Triassic - Early Jurassic succession of the Atuel depocenter and its relationship with the current sequence scheme of the Neuquén basin (Legarreta *et al.* 1993, Legarreta and Gulisano 1989) were determined, considering the current "Mesosequences" as second order sequences (9-10 My, Haq *et al.* 1987, Mitchum and Van Wagoner 1991).

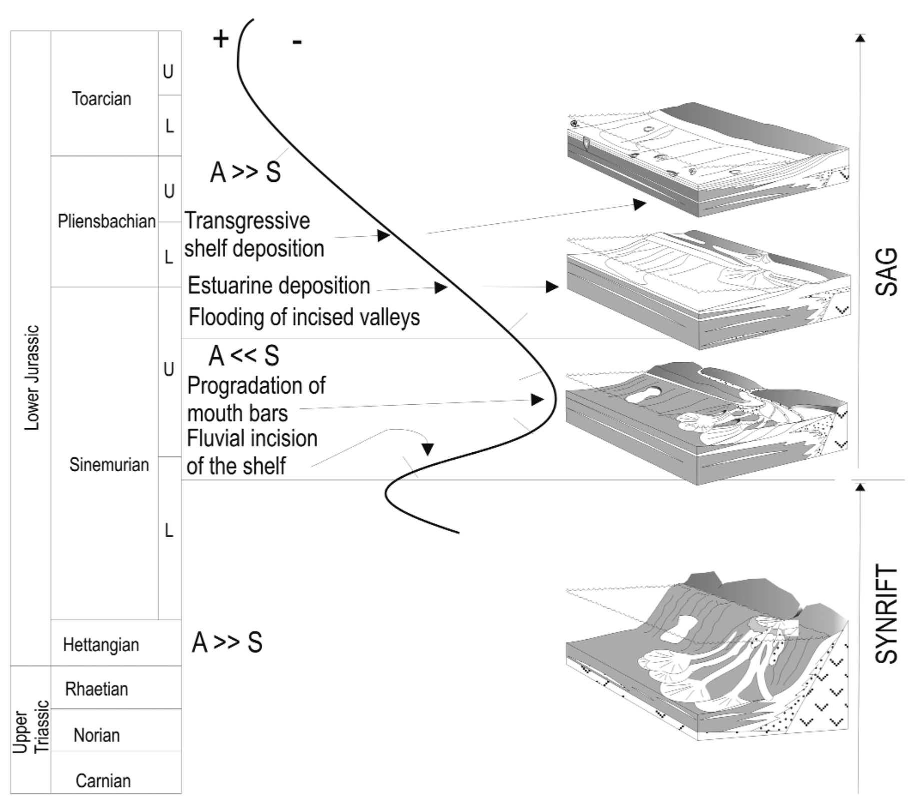

Figure 7: Late Triassic - Early Jurassic evolution of the accommodation (A) vs. sediment supply (S) proposed in this paper. A part of a hypothetical eustatic curve is given to show the eustasy-controlled changes of accommodation. Fluvial incision of the shelf refers to the erosion of the bases of the estuaries. Blocks illustrate the different depositional systems related to definite portions of the curve (from base to top: slope-type fan delta, intermediate fan delta with prograding mouth bars, wave-dominated estuary, storm-dominated shelf).

The whole Late Triassic - Early Jurassic succession is part of the Cuyo Mesosequence (Legarreta and Gulisano 1989) showing a lowstand system tract (LST), transgressive system tract (TST) and highstand system tract (HST) (Fig. 9). Each system tract reflects a definite portion of the hypothetical eustatic curve on Fig. 7.

The lowstand system tract (LST) includes deposits of fan deltas and of their feeding fluvial systems, of Rhaetian - late Early Sinemurian age, which crop out in the Arroyo Malo halfgraben. Aggrading slope-type fan delta deposits located on the Arroyo Malo and Alumbre fault hangingwalls, at the base of the fault slope, are comparable to the slope fans of the LST (SF, Fig. 9), while the prograding fan deltaic mouth bars at the Arroyo Malo section represent the prograding lowstand wedge (PLW, Fig. 9). The second order sequence boundary, placed at the base of the LST, does not crop out. However, the detachment between the LST and TST deposits, which occurs outcropping in the hangingwall and in the footwall of the Alumbre fault respectively, allow considering a type 1-sequence boundary.

The TST includes estuarine, nearshore and minor offshore deposits of Late Sinemurian - Late Pliensbachian age. It begins with a flooding surface (FS) at the base of the estuarine deposits, marked by

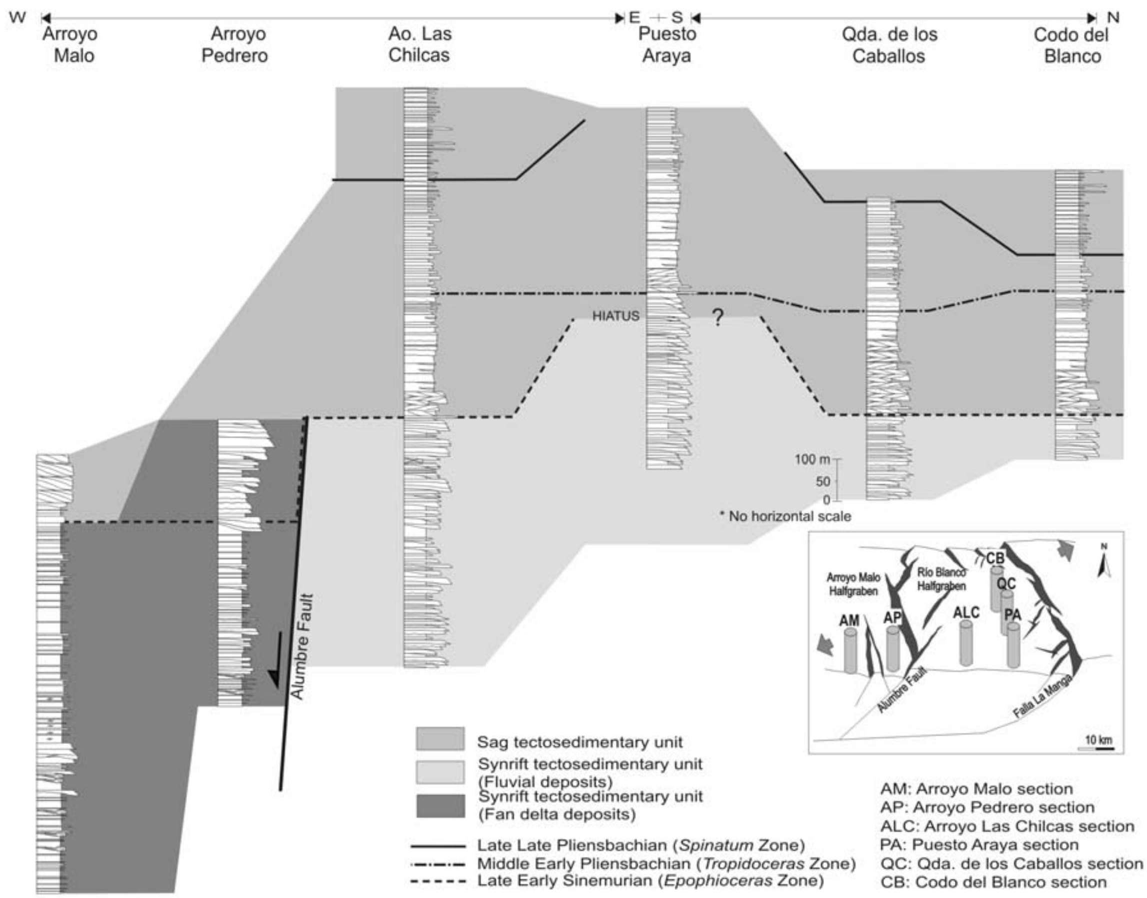

Figure 8: Tectosedimentary units (TSU) of the Late Triassic - Early Jurassic succession of the Atuel depocenter. Note the uncertain attribution of fluvial deposits at the Puesto Araya section to the synrift phase. Block diagram shows the inferred section sites and the ancient main faults.

a shell lags at the base of tidal inlets (Lanés 2002). The ravinement surface (RS) at the base of the nearshore deposits coincides with the base of bioclastic massive storm deposits, dividing the nearshore and the estuarine deposits. The age of the basal marine deposits decrease eastwards, due to the paleotopographic control (Fig. 8), emphasizing the onlap of the marine deposits and the varying age of the flooding surface, estuarine beds and ravinement surface.

The maximum flooding surface (MFS) at the top of the TST is clearly identifiable in the Codo del Blanco section, where it is represented by the laminated black shales containing pavements of *Bositra* sp. together with ammonites from the *Spinatum* Zone (Late Pliensbachian, Fig. 8). The pavements of *Bositra* sp. confirm the occurrence of short events of dysaerobic bottom waters in an usually anaerobic marine shelf, and of rapid burial processes at the end of the transgression and the beginning of the highstand (Brett 1995) mainly in highly subsiding basins (Kidwell 1993). Finally the HST includes fine deposits of a turbidite-influenced inner and outer shelf, belonging to the Tres Esquinas Formation (late Late Pliensbachian - late Early Bajocian) (Lanés 2002).

CONCLUSIONS

Biostratigraphic correlations of the Late Triassic - Early Jurassic succession of the Atuel depocenter allowed segregating the synrift deposits (Rhaetian - late Early Sinemurian) from the sag deposits (late Early Sinemurian - Toarcian).

As the study area show evidences of synsedimentary extensional tectonics, two different approaches were used to analyze such succession The first one considering tectosedimentary units (TSU) and the second one applying sequences (*sensu* Mitchum *et al.* 1977).

In the first scheme the synrift TSU of Rhaetian - late Early Sinemurian age matches the actual Precuyo Mesosequence and the sag TSU (late Early Sinemurian - Toarcian) is partly equivalent to the Cuyo Mesosequence, mainly keeping the current mesosequence scheme for the Neuquén basin but assigning the fandeltaic deposits to the Precuyo Mesosequence.

The second sequence scheme considers the whole Late Triassic - Early Jurassic succession as a part of the Cuyo Mesosequence, a second order sequence, where the synrift deposits composes the lowstand system tract (LST) and most of the sag deposits makes the transgressive system tract (TST). The basal sequence boundary does not crop out, the flooding surface at the TST base and the maximum flooding surface at the TST top are respectively marked by the lowest estuarine levels and black shales with suboxic-compatible bivalves (*Bositra* sp.). The HST begins with the turbidite-influenced shelf deposits of the black Tres Esquinas Formation (late Late Pliensbachian - late Early Bajocian).

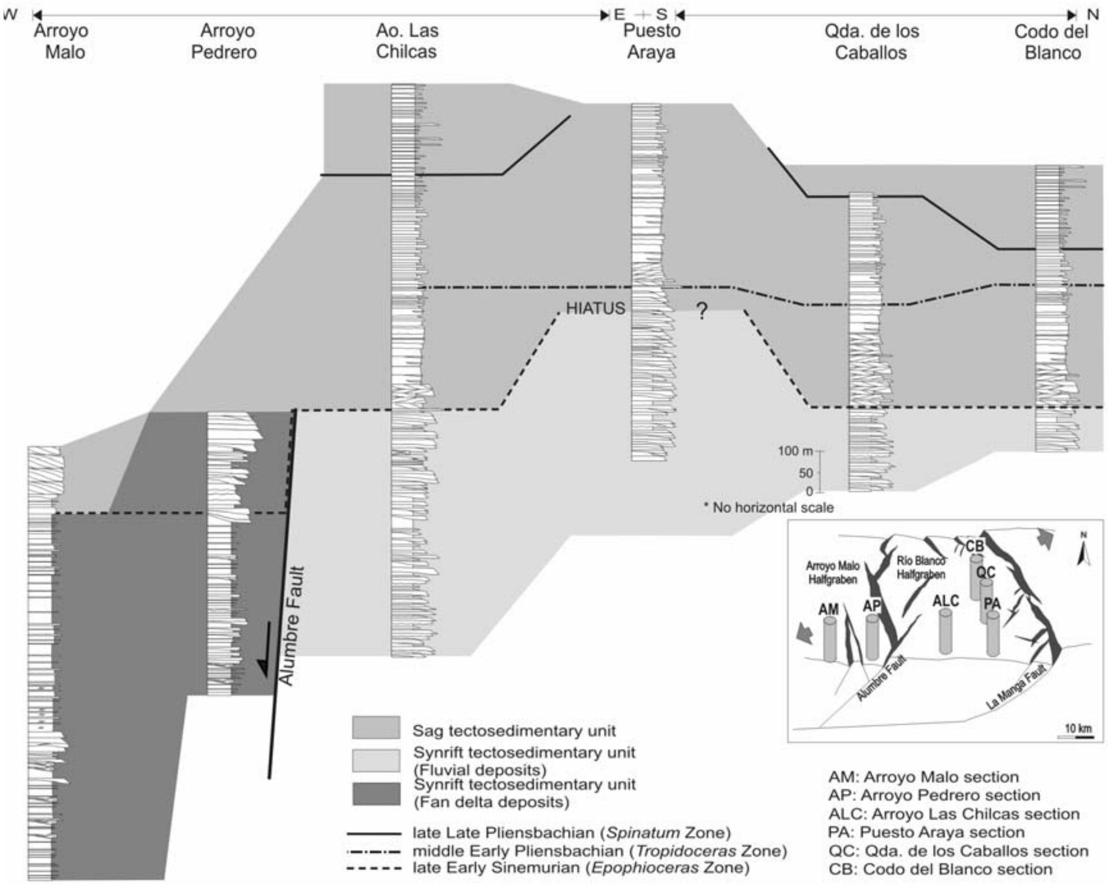

Figure 9: Second order sequence stratigraphy of the Late Triassic - Early Jurassic succession of the Atuel depocenter. Block diagram shows the inferred section site and the ancient main faults.

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