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Sequence Stratigraphy in Continental to Marine Transitions. An Example from the Middle Jurassic Cuyo Group, South Neuquén Basin, Argentina

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Abstract: The Middle Jurassic Cuyo Group in the southern Neuquén Basin comprises shallow marine to continental beds up to 1200 m of thickness. Twelve sedimentary sections were measured through the succession, in which facies and sequence stratigraphic analysis have been carried out. The study allowed us to recognize eight depositional sequences, related to both third and fourth-order scales (*sensu* Exxon). Because these outcrops extend from mainly fluvial deposits on the east to coeval shallow marine deposits on the west, they allow to analyze sequence stratigraphic relationships, facies, and paleoenvironmental changes during the evolution of a depositional sequence. (1) In shallow marine environments, third-order sequences start with a major erosive and non-depositional event followed by up to 20 meters of sandy-braided fluvial to high sinuosity estuarine channel deposits linked with a late lowstand systems tract - early transgressive systems tract stage. The transgressive systems tract deposits are characterized by 2-6 meters thick shallowing upward tidal bars with a retrogradational parasequence set. Highstand systems tract deposits starts with open-shelf mudstones followed by 4-6 meters of shallowing upward cycles of input to wave dominated stream-mouth bars, with a progradational parasequence set. (2) In mainly continental areas, third order sequences begin with up to 10 meters of coarse grained braided-river deposits resting over a regional discontinuity. These deposits are interpreted as developed in early transgressive systems tract stage. The Transgressive systems tract deposits are expressed by 12-14 meters of marsh levels, with tidal influence. The highstand systems tract deposits start with off-shore marine mudstones, followed by a strongly prograding input-dominated deltaic systems, and ending with thick high-sinuosity sandy fluvial deposits.

INTRODUCTION

Sequence stratigraphic tools and methods allow the analysis of coeval deposits in different positions within a sedimentary basin. This is because the depositional sequence (the key unit for sequence stratigraphic analysis) is a relatively conformable succession of genetically related strata, bounded at its top and base by unconformities or their correlative conformities [1]. The rocks located above a sequence-bounding surface are everywhere younger than those below it, for this reason, sequence boundaries have a chronostratigraphical significance.

Recognition of depositional sequences and sequence boundaries from outcrop studies have received much attention in the last years [2,3,4,5,6,7]. A prerequisite for the successful application of sequence stratigraphic concepts in outcrops studies is that sufficient attention should be given to the study of sedimentary facies. In other words, sequence stratigraphic analysis made from outcrop data may be no better than our facies association knowledgement.

Sequence stratigraphic studies suggest that sedimentary facies associations are arranged in a predictable fashion within depositional sequences [3,8,9,10].

In this paper, the vertical stratigraphic evolution of several sequences is examined in different positions within the basin, focusing in the transition between shelfal and continental environments.

GEOLOGIC SETTING AND STUDY AREA

The Neuquén Basin is a well know back-arc basin located in western central Argentina [11]. Basin onset took place during the Late Triassic - Early Jurassic, and it was filled with up to 15,000 meters of marine to continental deposits, mainly during the Mesozoic and Early Cenozoic Eras. The Cuyo Group (also named "Cuyano")(Early - Middle Jurassic) (Fig. 1) represents the first major marine depositional episode after the configuration of the basin. The Cuyo Group comprises more than 2,500 m thick deposits, beginning with a transgressive event during Hettangian - Pliensbachian stages, follows with regressive deposits till Middle Callovian. Marine claystones, knew as Los Molles Fm. [12], are diachronologically overlaid by sand-rich shallow marine deposits assigned to Lajas Fm. [12] (Fig. 1). The succession ends with fine-grained continental red-beds referred to the

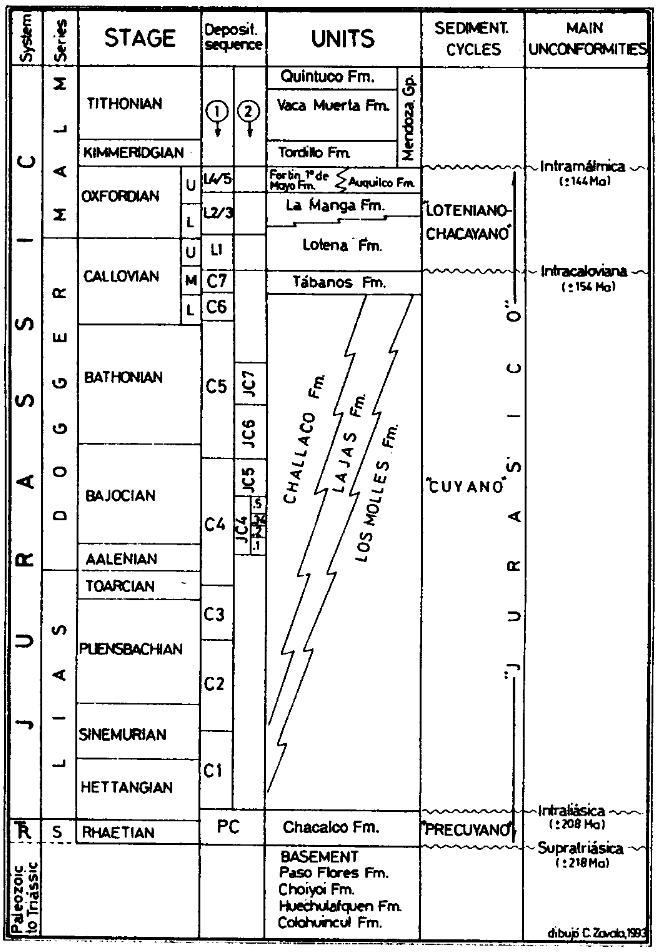

Figure 1: Stratigraphic chart for the Jurassic of the Neuquén Basin. (From Gulisano et al. [14]).

Challacó Fm. [13,14], and evaporites of the Tábanos Fm. [15] developed mainly in the center of the basin (Fig. 1). Sequence stratigraphic studies carried out in the last years allow to recognize in the Cuyo Group at least seven third-order depositional sequences [14,16] ("1" in Fig. 1).

The study area is located in the south part of the Neuquén Basin (Fig. 2), almost 40 Km south of the Zapala City. It comprises an area of about 2,800 Km^2 in which twelve detailed sections were measured (Fig. 3). Facies and sequential analysis based on outcrop observations of the Middle Jurassic Cuyo Group allow to recognize four third-order depositional sequences [17] named JC4, JC5, JC6 and JC7 ("2" in Fig. 1; Fig. 4). The JC4 sequence is in turn composed by five fourth-order sequences (JC4.1, JC4.2, JC4.3, JC4.4 and JC4.5). The main stratigraphic forestepping occurs from the south-east to the Northwest. Both the JC6 and JC7 sequences consists of continental deposits all over the study region. On the other hand, the JC4 and JC5 sequences show shallow marine facies in the west, linked with coeval continental deposits located in the east of the area. This type of exposure allows to analyze lateral sequence stratigraphic relationships in terms of facies and paleoenvironmental changes along the continental to marine transitions, both in progradational and in retrogradational settings. Based in examples from the Middle Jurassic Cuyo Group, the final aim of this paper is to propose a model for the sequence stratigraphic evolution in different positions within the basin.

SEQUENCE STRATIGRAPHIC EVOLUTION

We discuss how sequence boundaries are expressed in different basin settings, and how the sedimentological record reflects changes in accommodation, derived from relative changes in sea level. Because the main progradational trend was toward the Northwest, we have chosen an east proximal area (section 8), and a mainly shelfal area (section 2) to the west (see Fig. 3). Although only to examples are considered here, similar evolutions have been recognized for the JC5 sequence in sections 1, 2, 3, 4, 5, 6, 11 and 12 (Fig. 3).

Section 8

Section 8 comprises a 296 m thick succession that ranges from off-shore shelfal claystones at the base (Los Molles Fm) to shallow marine and fluvial sandstones at the top (Lajas Fm). Three depositional sequences have been recognized (JC4.1, JC5, and JC6) (Fig. 5a). The upper levels of sequence JC4.1 contains ammonoids of the Aalenian-Bajocian Stage boundary. The JC5 sequence shows a broad areal extension, and has been recognized in westward positions (Sierra de Chacaico), in which ammonoids content indicate an Early to Late Bajocian age (Fig. 4). JC6 sequence has no marine fauna, and its age is inferred to be Late Bajocian - Early Bathonian [17].

Of special interest are the boundaries and internal evolution of the JC5 sequence. This sequence begins with 8 meters of coarse grained braided-river deposits, resting on a sharp basal contact (sequence boundary) over lower shoreface marine claystones of the sequence JC4.1 (Fig. 5b). These basal fluvial deposits are followed, after a sharp contact, by 10 meters of interlayered claystones and sandstones, with planar lamination, hummocky cross-stratification, swaley, and climbing ripples, with abundant plant debris (Fig. 5b). These accumulations are interpreted as swamp deposits.

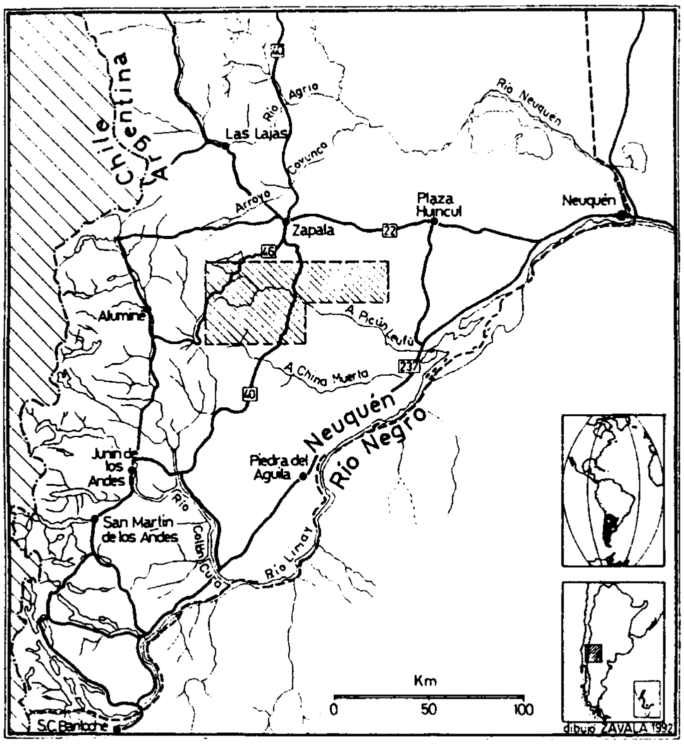

Figure 2: Location map, stippled areas show the location of Argentina, the Neuquén Basin and the study area (From Zavala, [17]).

After a discontinuity (ravinement surface), a 1,5 thick sandstone unit is recognized, with marine fossils remains at its top. This sandstone unit is interpreted as deposited in an upper-shoreface environment and grades upward into a 8 meters thick off-shore marine claystone interval, in turn followed by a 6 meters thick section of input-dominated delta front deposits (Fig. 5b). Over these deltaic deposits, a transition with high-sinuosity sandy fluvial deposits was recognized. In this locality, the fluvial deposits comprise a more than 60 meters thick succession.

The basal fluvial deposits have been interpreted as accumulated as an incised valley fill during the late lowstand systems tract and the early transgressive systems tract. The swamp and upper shoreface sandstones are assigned to the transgressive systems tract. The off-shore claystones, the input-dominated deltaic systems and the high-sinuosity fluvial deposits are interpreted as accumulated during the highstand systems tract (Fig. 5b).

Section 2

Section 2 comprises a 750 meters thick succession that ranges from off-shore claystones (Los Molles Fm), to shallow marine sandstones (Lajas Fm) and into continental red-beds deposits (Challacó Fm). In this section, sequence stratigraphic analysis allows to recognize five depositional sequences: JC4.1, JC4.2, JC5, JC6 and JC7 (Fig. 6a).

Both JC4.1 and JC4.2 sequences carry ammonoids indicating an Early Bajocian age. The JC5 sequence contains ammonoids remains indicating an Early to Late Bajocian age. The JC6 and JC7 sequences are continental red-beds of the Challacó Fm. all over the Sierra de Chacaico area, and no fossils remains other than silicified tree trunks have been found.

The JC4.2 sequence begins with 3 meters (locally may be thicker) of channelized sandstone deposits unconformably resting on lower delta-front sandstones of the JC4.1 sequence, that bear no evidences of tidal influence (Fig. 6b). Internally, the basal JC4.2 channelized deposits show a suite of tide-

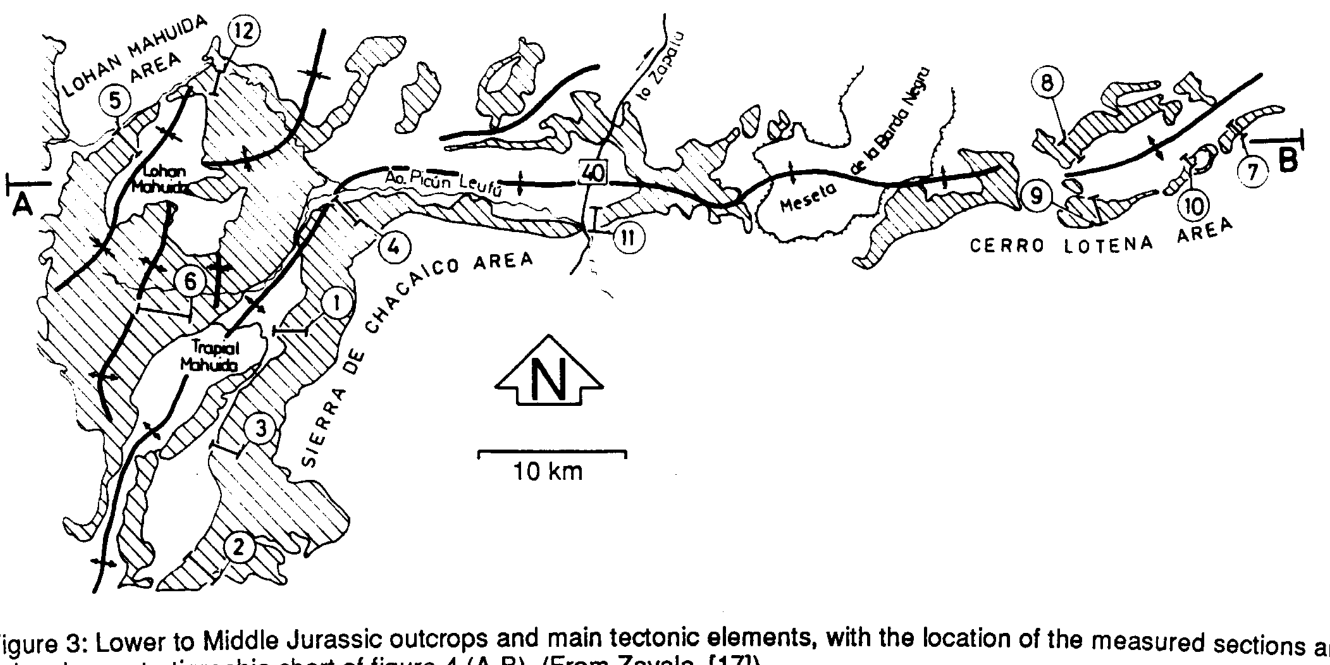

Figure 3: Lower to Middle Jurassic outcrops and main tectonic elements, with the location of the measured sections and the chronostratigraphic chart of figure 4 (A-B). (From Zavala, [17]).

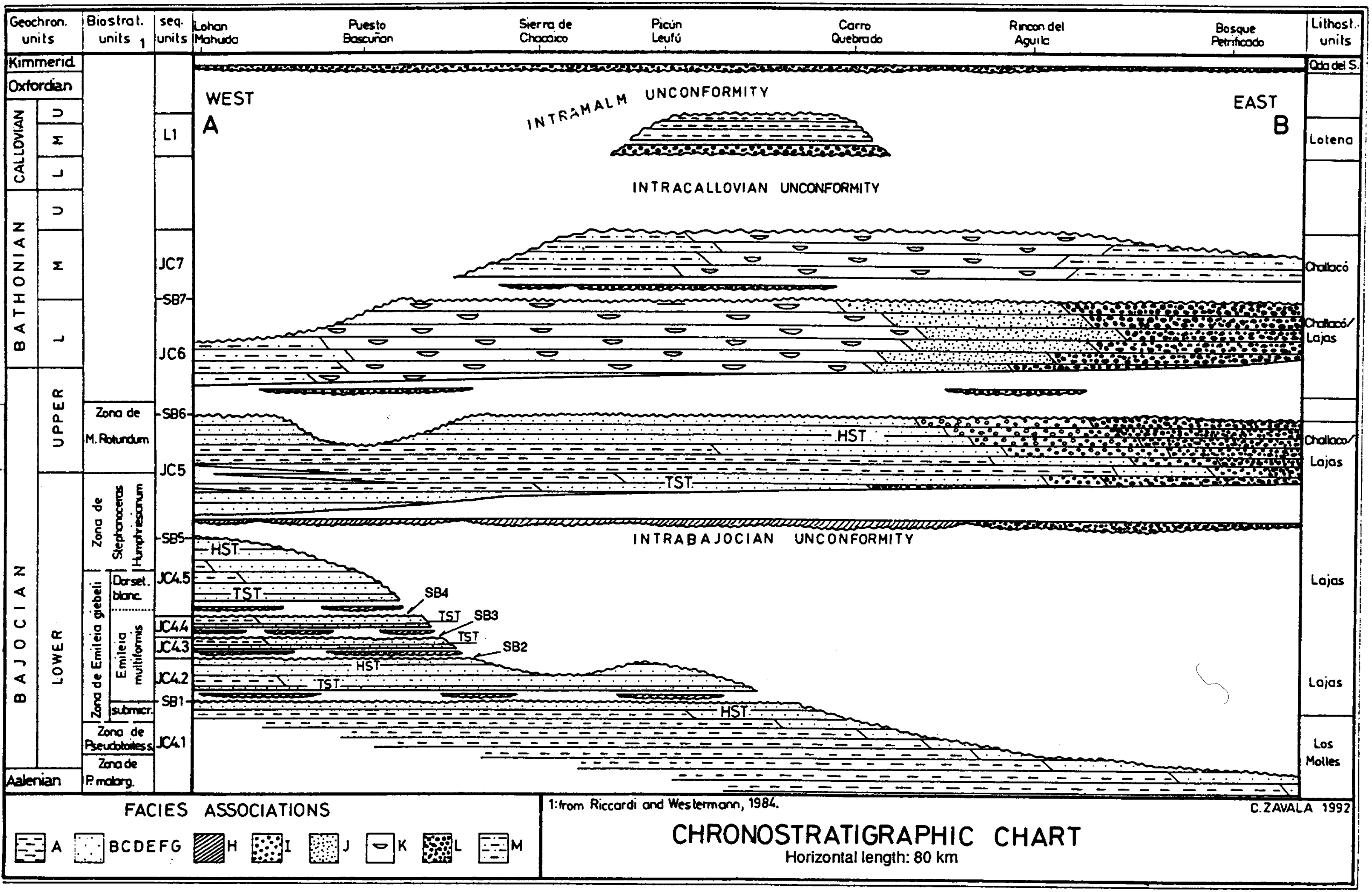

Figure 4: Chronostratigraphic chart for the Middle Jurassic in the study area. Facies associations: A: off-shore marine claystones; B,C,D,E,F and G: shallow-marine sandstones; H: estuarine channel deposits; I: mixed-load meandering rivers deposits; J: sandy-braided fluvial deposits; K: anastomosed fluvial deposits; L: coarse-grained braided river deposits; M: freshwater playa lake deposits. The location of this stratigraphic chart (A-B) is indicated in figure 3. (From Zavala, [17]).

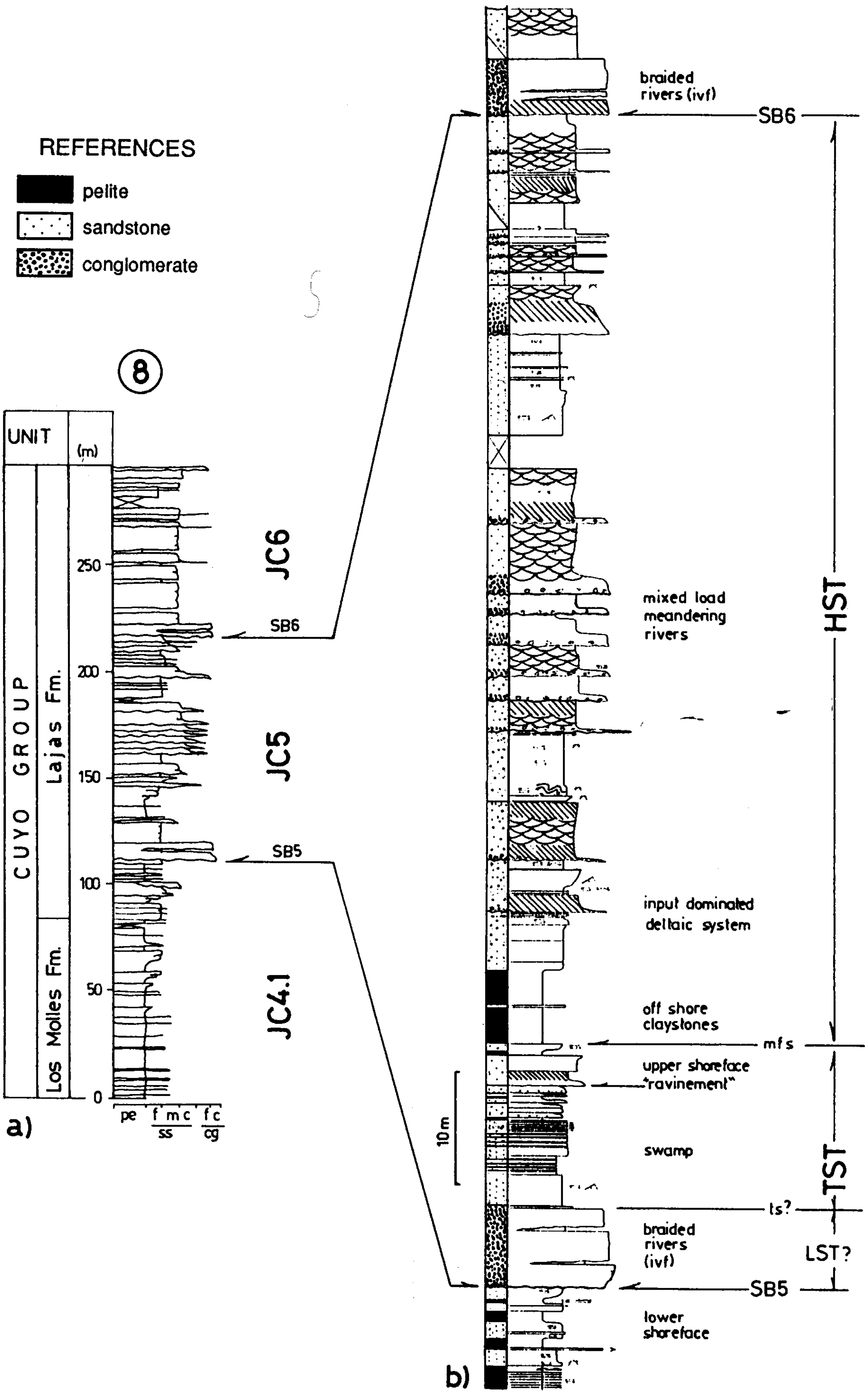

Figure 5: a: section 8 (Rincón del Aguila) with indication of the main lithological and sequence stratigraphic units. **b**: Detail of the JC5 sequence at section 8. ts: transgressive surface; mfs: maximum flooding surface; ivf: incised valley fill.

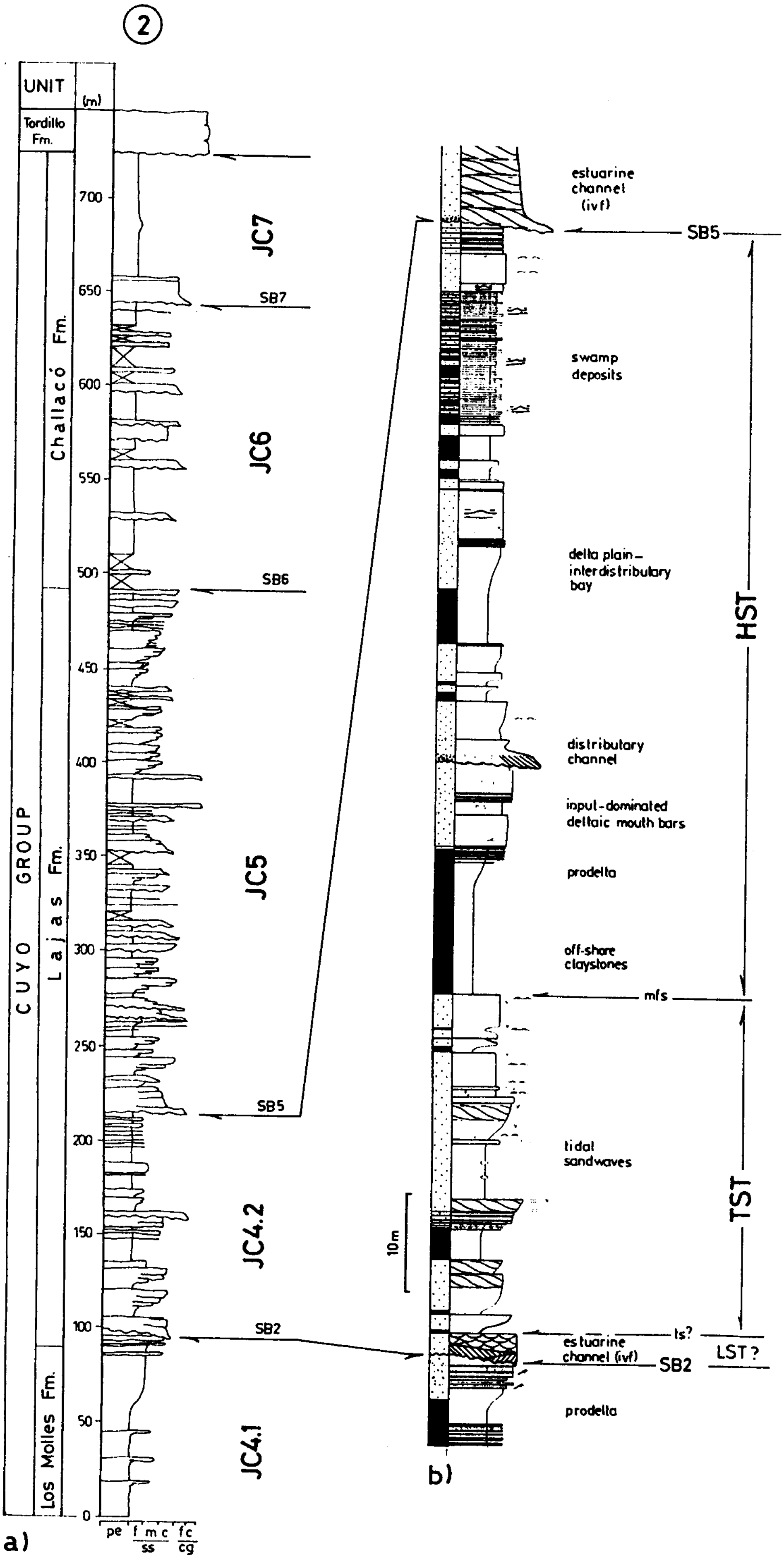

Figure 6: **a**: section 2 (Estancia Charahuilla) with indication of the main lithological and sequence stratigraphic units. **b**: Detail of the JC4.2 depositional sequence at section 2. ts: transgressive surface; mfs: maximum flooding surface; ivf: incised valley fill. References in figure 5.

generated sedimentary structures, like sigmoidal tidal bundles, "herring bone" cross-stratification, and trough cross-beds. These accumulations are interpreted as an estuarine channel-fill.

A 34 meters thick of coarsening-upward facies associations stack up on top of the channel fill. Due to the presence of sigmoidal tidal-bundles, they are interpreted as tidal sand-waves (Fig. 6b). These deposits show a retrogradational stacking pattern, and are sharply overlaid by 15 meters of off-shore marine claystones. Over these off-shore deposits, a forestepping set of delta-front deposits related to input-dominated deltaic systems is registered. Stream mouth-bar deposits show gently deepening foreset beds and no tidal influence. The sequence ends up with 50 meters of sandstones and claystones of delta-plain origin. Distributary channels, interdistributary bay, and swamp deposits are common (Fig. 6b).

The estuarine channel at the base of the JC4.2 sequence is interpreted as an incised valley fill, deposited during late lowstand to early transgressive systems tracts. Tidal sand waves with a landward stepping stacking pattern are interpreted as deposited during the transgressive systems tract. Off-shore marine claystones, delta front sandstones and delta plain deposits, arranged with a progradational trend, are interpreted to represent the highstand systems tract (Fig. 6b).

DISCUSSION AND CONCLUSIONS

Recognition of depositional sequences and systems tracts in different marine to continental transitions of the Middle Jurassic Cuyo Group, can be used to erect models for understanding how the succession of changes in sedimentary architecture might be related to relative sea-level.changes.

The proposed conceptual evolutionary models in both proximal and shelfal settings are shown in the figures 7 and 8. Same of the conclusions that can be drawn from these observations are as follows.

1) In proximal settings (Fig. 7), two kinds of fluvial deposits have been recognized. One of them consist of coarse-grained multistory braided-river deposits that appear linked to the fill of incised valleys cutted in the platform during stages of relative sea level falls (Fig. 5b). The other type consist of sandy high-sinuosity fluvial deposits that represent widespread fluvial deposition developed during the highstand systems tract (Fig. 5b).

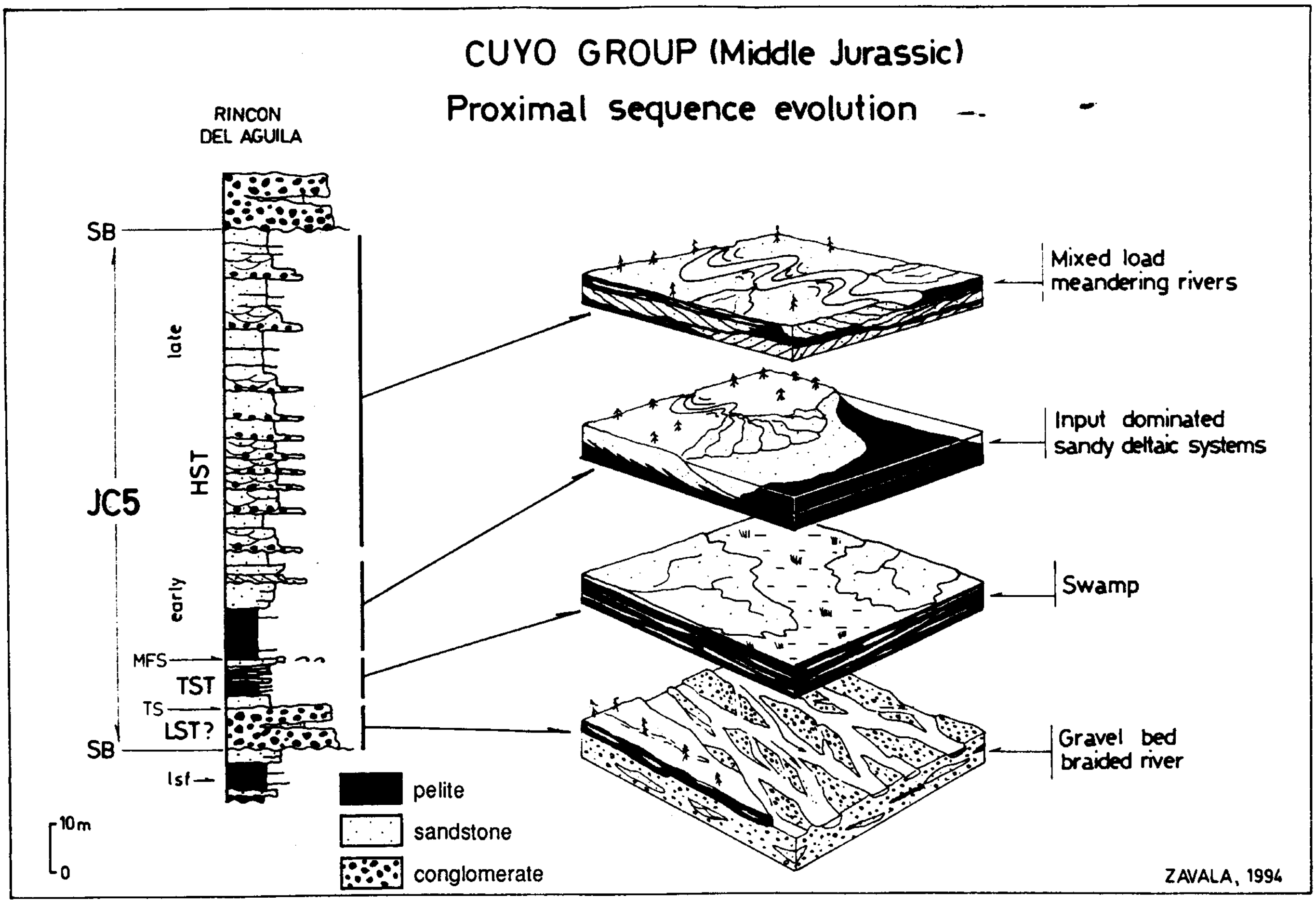

Figure 7: Depositional model for a sequence evolution in a proximal setting. lsf: lower shoreface; ts: transgressive surface; mfs: maximumflooding surface; SB: sequence boundary.

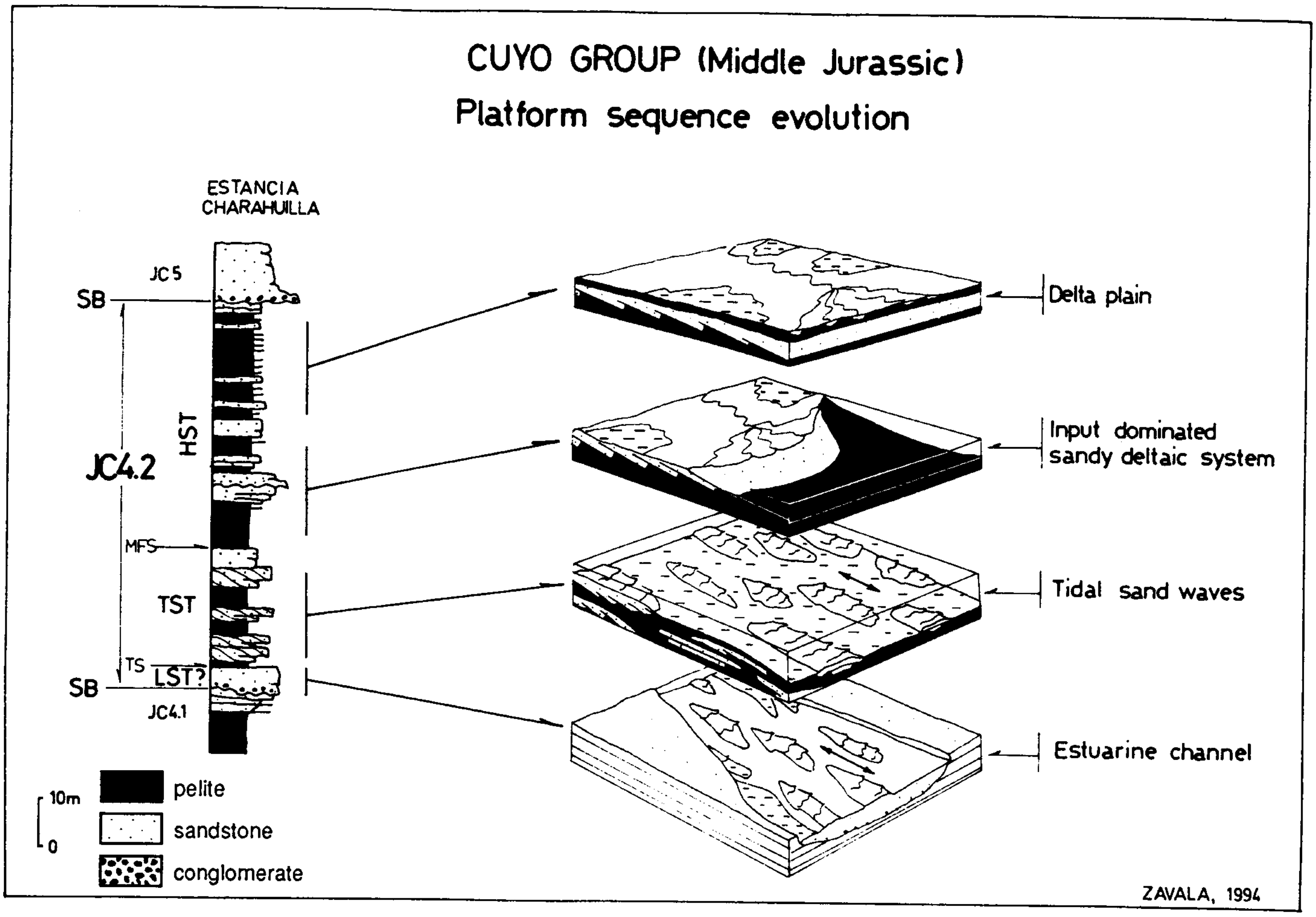

Figure 8: Depositional model for a sequence evolution in a platform setting. ts: transgessive surface; mfs: maximum flooding surface; SB: sequence boundary.

2) Swamp deposits recognized above the incised valley fill accumulations and below the maximum flooding surface (section 8) (Fig. 5b) are interpreted as the result of poor drainage conditions, related to rising groundwater tables linked to a base level rise, during the transgressive systems tract stage [18].
3) Over the shelfal areas, incised valley fills often begin with sandy-braided fluvial deposits, that show an evolution to estuarine-channel deposits (Fig. 6b). These sandy channel-fills are laterally related with coarse-grained braided river deposits in more proximal areas. This kind of lateral relationships have also been suggested by Van Wagoner et al. [3].
4) Tidal environments, related to meso- or macrotidal conditions, are more common during transgressive systems tracts (Fig. 8). Deposits related to highstand systems tract often show no tidal influence, or record a rather microtidal range. Deltaic successions, record mostly wave and input dominated styles (Figs. 7 and 8). These relationships between shallow marine environments and systems tracts are similar to those described by Van Wagoner [19] for the Upper Cretaceous Sego Sandstone of the western USA.
5) The proposed models are in general in agreement with the conceptual models developed by Jervey [20], Posamentier and Vail [21] and Posamentier et al. [8], and with the ideas advanced by Shanley and McCabe [10,18]. Nevertheless, the examples and models drawn from the Middle Jurassic Cuyo Group (Fig 7 & 8) differ from the previous conceptual models in the fact that they show no widespread fluvial deposition linked to the bayline position. Our observations are in closer agreement with views by Miall [22], regarding the inexistence of the "bayline" and the manner that fluvial profiles are adjusted. Widespread Middle Jurassic fluvial deposition across the Southern fringe of the Neuquén basin occurred all along the highstand systems tract, and not only in the late highstand systems tract, as has been suggested by previous conceptual models.

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