SEQUENCE STRATIGRAPHIC ANALYSIS OF LACUSTRINE FACIES IN A HALF-GRABEN: EXAMPLE FROM THE TRIASSIC ISCHIGUALASTO - VILLA UNIÓN BASIN (ARGENTINA)

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Resumen. *Análisis estratigráfico secuencial de facies lacustres en hemigrábenes: ejemplo de la cuenca Triásica de Ischigualasto – Villa Unión (Argentina).* Esta contribución presenta un análisis estratigráfico secuencial de la sucesión lacustre de la cuenca triásica de Ischigualasto – Villa Unión, Argentina. Se han estudiado cuatro secciones estratigráficas separadas por aproximadamente 100 kilómetros, que corresponden a la zona de acomodación septentrional (Quebrada de Ischichuca), al margen flexural oriental (Río Gualo) y al margen axial meridional (Cerro Morado y La Torre) del hemigraben. Las asociaciones de facies identificadas, las relaciones estratigráficas del intervalo analizado con la subyacente Formación Tarjados y el trazado de superficies estratigráficas claves permite correlacionar las secciones analizadas. La historia depositacional comprende tres fases que pueden vincularse a diferentes cuencas lacustres. La primera fase está representada por sedimentos volcaniclásticos de planicie de inundación fluvial y depósitos lacustres someros salinos, los que apoyan sobre un límite de secuencia depositacional y se atribuyen a un cortejo de nivel bajo. La siguiente fase está representada por sedimentos de lagos profundos meromícticos (que pasan lateralmente a depósitos más someros) y deltas fluviales e influidos por oleaje; los que componen varias parasecuencias y corresponden a un cortejo transgresivo / de nivel alto. La fase final de sedimentación se vincula con un cambio de paleocorientes y de procedencia, estando representada por deltas someros de plataforma lacustre en una zona de acomodación del hemigraben que constituyen depósitos de cortejo de nivel bajo. La presencia de potentes facies lacustres con moderado a alto contenido orgánico, asociado a la identificación de una zona de acomodación y los potentes depósitos cenozoicos suprayacentes conforman potenciales rocas fuente y reservorio, respectivamente.

INTRODUCTION

Successions of continental closed basins (lacking marine connections or influence) are steadily being analyzed and interpreted using a sequence stratigraphic approach, both based on subsurface data and outcrop examples (e.g. Kokogián *et al.* 1989, Legarreta *et al.* 1993, Liro 1993, Oviatt *et al.* 1994, Scholz *et al.* 1998, Lemons and Chan 1999, Keighley *et al.* 2003). Previous applications of sequence stratigraphic principles to the Ischigualasto – Villa Unión Basin include studies on regional unconformities (Legarreta and Kokogián 1986) and characterization of lacustrine parasequences (Milana 1998). Triassic lacustrine strata from the Ischigualasto – Villa Unión Basin are well-exposed in different localities, thus allowing a comparison of the stratigraphic evolution of the filling in different parts of the half-graben. In particular, this contribution is focused on the lacustrine package that overlies the red beds of the Tarjados Formation, which is analyzed in four localities (about 100 km apart) that belong to the accommodation zone, flexural and axial margin of the half-graben. Detailed logging and stratigraphic analysis (including tracing of lacustrine flooding and ravinement surfaces) permitted basinward correlation of lacustrine parasequences. The vertical and lateral change of depositional systems and the sequence stratigraphy of the lacustrine deposits are analyzed in conjunction with the inferred pattern of subsidence and fault geometry.

GEOLOGICAL SETTING

The Ischigualasto - Villa Unión Basin from northwest Argentina is one of the NW-SE trending half-grabens developed on the margin of southwestern Gondwana during the Early Triassic (Uliana and Biddle 1988,

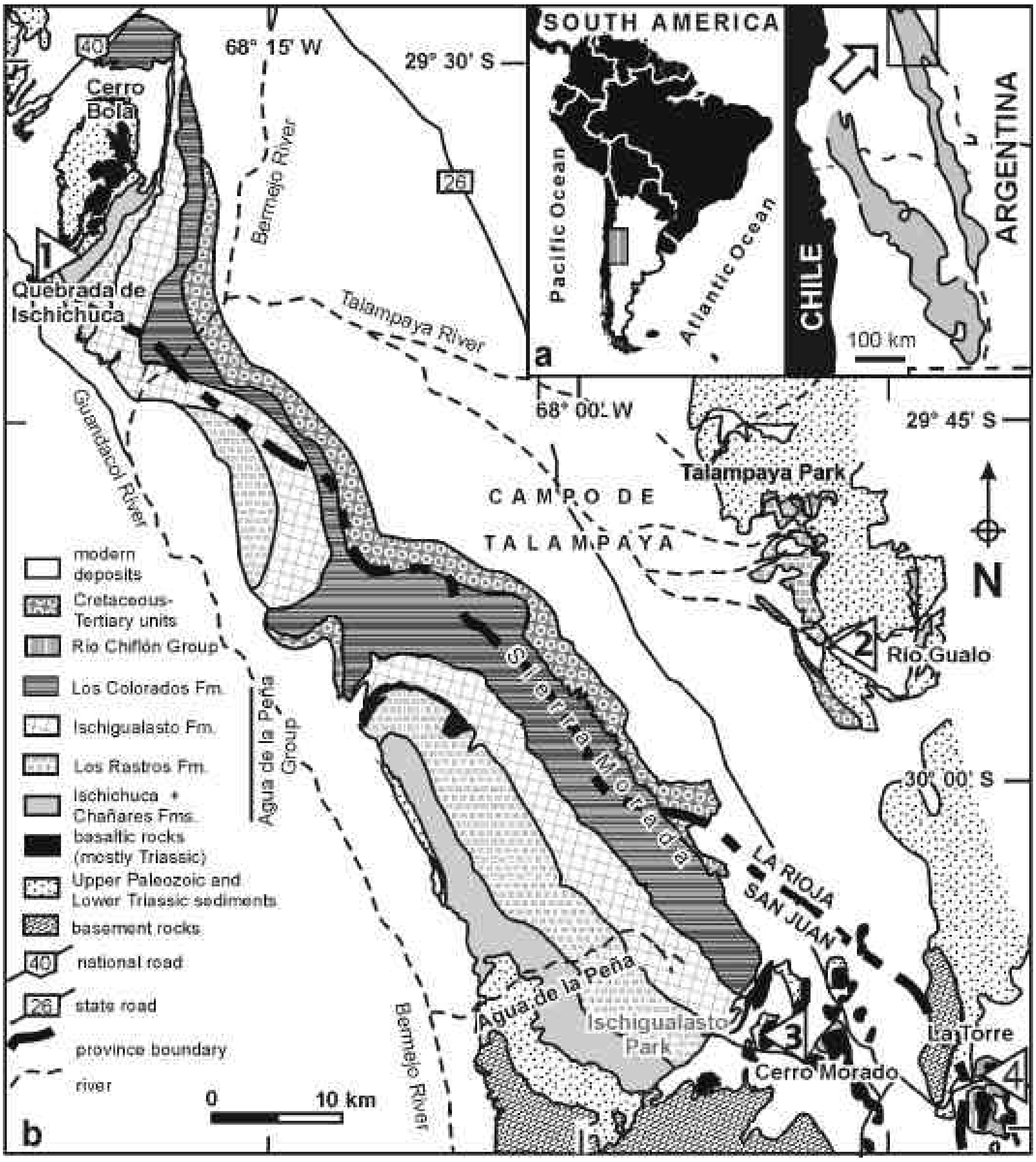

Fig. 1. Location map. (a) Position of the study area in South America (left) and extension of Triassic rift basins in northwest Argentina (right). The rectangle shows position of Fig. 1b. (b) Geologic map of the Ischigualasto – Villa Unión basin showing the localities of study (1-4). Modified from Stipanicic & Bonaparte (1979).

Uliana *et al.* 1989, Tankard *et al.* 1995, Franzese and Spalletti 2001; Fig. 1a). The basin fill is entirely continental and reaches a maximum thickness of approximately 4000 m (e.g. Milana and Alcober 1994, Kokogián *et al.* 1999). The oldest deposits are red beds of the Talampaya and Tarjados formations, that are succeeded by thin volcaniclastic deposits of the Chañares Formation and widespread lacustrine strata of the Ischichuca, Los Rastros and Lomas Blancas Formations (Fig. 2). Except for the Chañares Formation and the lower part of the Ischichuca Formation, which are shallow lacustrine non-deltaic deposits, the lacustrine succession is typically arranged in coarsening- and shallowing-upward cycles (parasequences) that record delta progradation (López Gamundí *et al.* 1989, Milana 1998, Bellosi *et al.* 2001, Melchor *et al.* 2003). The lacustrine succession of the basin contains sediments of different freshwater to saline paleolakes that varied from shallow and well-oxygenated to moderately deep and thermally stratified.
The general NW trend of the purported border fault of the rift, the Valle Fértil Megafracture, plus the wedge-shaped geometry of the strata indicate that the orientation of the half-graben was roughly NW-SE (e.g.

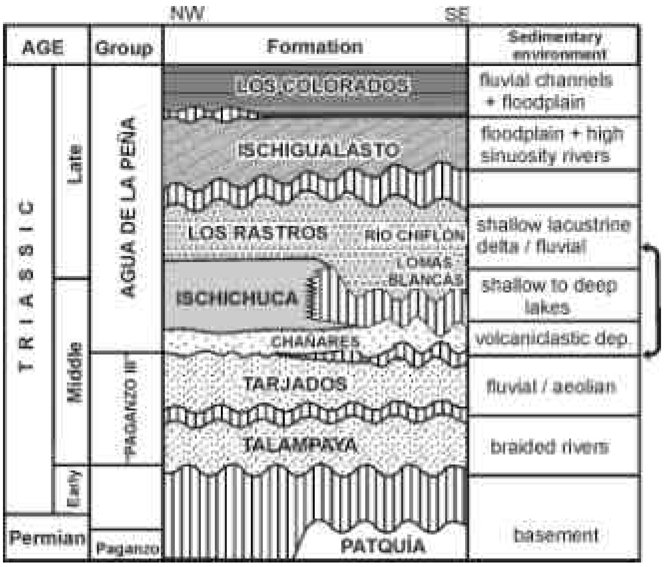

Fig. 2. Stratigraphy of the Ischigualasto-Villa Unión basin showing the relationships of the lacustrine units and different formational names used in the studied localities. The bracket indicates the analyzed package.

Milana and Alcober 1994). The studied localities are located in the northwestern (quebrada or canyon de Ischichuca, locality 1), eastern (Río Gualo, Talampaya Park, locality 2) and southeastern (Cerro Morado and La Torre, localities 3 and 4, respectively) area of the basin (Fig. 1b). Quebrada de Ischichuca locality belong to an accommodation zone margin, Río Gualo was located in the flexural margin and the remaining localities in the southern axial margin of the half-graben.

FACIES ASSOCIATIONS

The studied package lies unconformably on the red beds of the Tarjados Formation. The upper 10-15 m of the Tarjados Formation are pedogenized, although the type and development of paleosol features are different at each studied locality. These features include scattered siliceous rhizoliths (Quebrada de Ischichuca), a well-developed silicified calcrete (Río Gualo), abundant siliceous rhizoliths and a

Table 1. Description and interpretation of facies associations.

Facies association	Lithology	Thickness (m)	Sedimentary structures	Cyclicity	TOC (%)	Interpretation
VF – Volcaniclastic floodplain	Reworked and primary tuffs, massive volcaniclastic sandstones	2 - 51	Generally stuctureless, rare wave and current ripples, paleosols (including silcrete)			Subaerial and subaqueous (pond) deposition of primary and reworked volcaniclastic sediments in a floodplain setting under semiarid climate. Common gravity flows.
SL – saline lakes	***SL1 (shallow, mildly-saline lake).*** Variegated mudstones and sandstones, micrite, tuffs, gypsum laminae.	76	Thin bedding, parallel lamination, wave ripples, trough cross-lamination, mudcracks, footprints, conchostraca and fish remains.	Coarsening-shallowing upward cycles.	0.25	Shallow, mildly saline lake with common water level changes.
	SL2 (playa-lake). Dark mudstones, dolomitic micrite, thin sandstones, and gypsum laminae.	63	Parallel (papery) lamination, mudcracks, and footprints.	Shallowing-upward cycles (0.3-9 m thick).	0.24 – 0.61 (n=2)	Moderately deep, perennial playa-lake and dry mudflats. Marked changes in water level. Possible saline stratification of water column.
F – fluvial channel	Medium to fine grained sandstones, associated siltstone and mudstone.	21	Trough cross-bedding, parallel lamination. Basal erosive surface-	Fining-upward (9-12 m).		Fluvial channel and associated overbank deposits.
OL – Offshore lacustrine	***OL1 (deep freshwater lake)*** Thick fossiliferous black shales with thin sideritic marlstone, mudstone and tuffs.	5 - 42	Monotonous, even, fine to very fine (papery) lamination. Rare rhythmites. Large siderite concretions.		1.0-2.84 (n=3)	Pelagic /hemipelagic sedimentation in deep anoxic waters of a meromictic / oligomictric, freshwater lake.
	OL2 (shallow freshwater lake) Olive green to reddish fossiliferous shales, thin sideritic marlstone, siltstone and tuff.	3 - 17	Fine lamination. Rare concretions.			Offshore deposition in a shallow holomictic lake.

Table 1. Description and interpretation of facies associations (continued).

Facies association	Lithology	Thickness (m)	Sedimentary structures	Cyclicity	TOC (%)	Interpretation
DF - Delta front + delta shelf	Gray, thick siltstone successions, subordinate claystone, and sandstone. Plant debris.	4 - 14	Horizontal lamination, common graded (rhythmitic) lamination, wavy bedding, hummocky cross-stratification, flaser and climbing ripples. Rare soft-sediment deformation structures.	Coarsening-thickening upward cycles		Pulsatory sedimentation in a deep lake by land-derived low-density turbidity currents. At some location, wave processes dominate. Low depositional slope.
DP - Delta plain	***DP1 (distributary channel sandstones).*** Fine to medium-grained sandstone and minor siltstone and tuff. Quartz-feldspathic sandstones with metamorphic clasts.	3 - 11	Thick trough cross-stratified sets with soft-sediment deformation structures. Parallel lamination in finer-grained term. Channel sandbodies with width/depth ratio < 150.	Fining-upward cycles.		Fluvial distributary channels of moderate sinuosity of mixed-load type and low channel slope. Common avulsion.
	DP2 (crevasse or secondary channels). Medium to fine grained sandstones and mudstones (occasionally carbonaceous). Abundant plant debris.	3 - 20	Planar cross-stratified sandstones with soft-sediment deformation structures and reactivation surfaces. Mudstones with wavy, flaser and horizontal lamination. Rare lateral accretion surfaces.	Fining upward cycles (3-8 m thick).	2.28	Secondary or crevasse channels of the delta plain, dominated by lateral accretion onto point bars. Common avulsion, high sedimentation rates.
	DP3 (crevasse deltas + levee). Micaceous, fine-grained gray sandstones, siltstones, and mudstones. Abundant plant detritus. Rare evaporite crystals.	2 - 10	Trough cross-lamination, wavy bedding, climbing ripples, flaser bedding, lateral accretion surfaces and poorly laminated mudstones. Siderite concretions.	Coarsening -upward cycles (2-8 m thick).		Crevasse deltas and levee deposits, which represent the infilling of shallow lakes of the delta plain by small deltas and laterally correlative deposits.
SD – shelf deltas and littoral lacustrine	***SD1 (wave-dominated littoral setting).*** Thick olive- or brown-gray siltstone successions with thin sandstone interbeds. Heterolithic intervals. Abundant plant detritus. Lithic volcanic sandstones.	50	Parallel lamination, wave ripples, common sole marks. Isolated hummocky lenses (anisotropic hummocky cross-stratification). Rhythmitic graded heterolithic beds.	Occasional coarsening- and thickening – upward trend (< 4 m thick).	0.91–1.43 (n=2)	Sedimentation influenced by oscillatory and combined flows (including storm events) in a subaqueous, nearshore lacustrine setting. Background sedimentation from river-fed underflows.
	SD2 (shallow shelf deltas). Olive green siltstone, medium-grained sandstones, dark claystones, and fine-grained tuffs. Lithic volcanic sandstones.	40	Wave rippled and parallel laminated siltstone, trough and planar cross-stratified sandstone. Rare hummocky cross-stratification and soft-sediment deformation structures.	Coarsening-upward (6-15 m thick)		Progradation of small mouth bars in a shallow, low-energy lacustrine shelf. Subaqueous ash-fall deposits.

moderately developed silcrete (Cerro Morado), and a well-developed calcrete (La Torre). Table 1 contains a generalized description and interpretation of the different facies association (see also Fig. 3), including

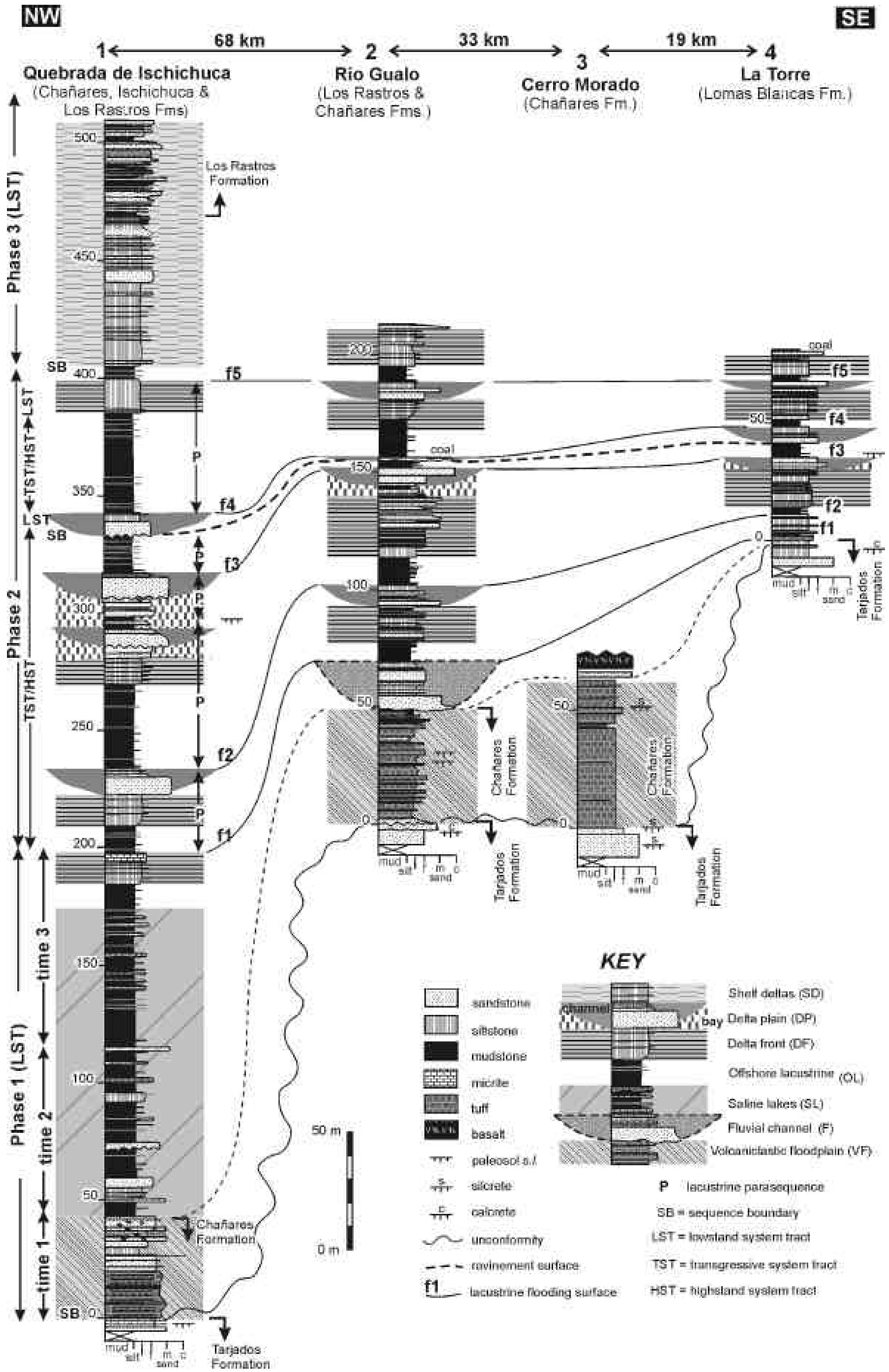

Fig. 3. Schematic stratigraphic sections at the studied localities showing facies associations, correlation surfaces and sequence stratigraphic framework. The sections were leveled using lacustrine flooding surface # 5 (f5).

associations were observed and are noted below. The VF facies association is recorded in three of the four localities and display lateral changes that can be linked to the inferred geometry of the half graben. At Quebrada de Ischichuca, subaqueous pyroclastic fall deposits are overlain by volcaniclastic sandstones deposited by gravity flows. At Río Gualo the VF facies association is mostly represented by subaerial pyroclastic floodplain deposits with poorly developed paleosols, although the upper part of the local succession was deposited in shallow ponds. At Cerro Morado, deposition and reworking of primary pyroclastic material was mostly subaerial and better developed paleosols with indured horizons showuing accumulation of silica (silcretes) were identified. The absence of the VF facies association at La Torre (Fig. 3) is considered as indicative of proximity to the margin of the half-graben.
The SL facies association is restricted to the Quebrada de Ischichuca locality, which suggest that they have a limited areal extent and probably is related to deeply subsided depocenters. Stratigraphic relationships indicate that the fluvial facies (F facies association) from Rio Gualo are laterally correlative with the saline lakes facies association (SL). This lateral relationship suggest that rivers drained the flexural margin highlands (Río Gualo) and shallow lakes were developed on lowland, distal areas close to the border fault (Quebrada de Ischichuca). The correlative intervals of the overlying deltaic lacustrine sections (OL, DF and DP facies associations) have markedly different thickness; the thickest succession is located at the northernmost locality and the thinnest succession is found at the southernmost locality (cf. Bossi 1971). For this interval, it is not certain if deposition took place in a single lake or different interconnected lakes, although the first alternative is more likely as suggested by the marked correlation between localities that is apparent using key stratigraphic surfaces (Fig. 3). The main differences are related to the nature of the lake and the features of the associated subaqueous deltaic facies. The thick black shales of OL1 facies subassociation were deposited in a meromictic lake (Quebrada de Ischichuca), whereas the thinner olive-gray shales from OL2 facies subassociation reflect greater mixing and oxygenation of the lake waters, which probably was an holomictic lake (Río Gualo and La Torre). In contrast, the associated DF facies association suggest river-dominated deltas at Quebrada de Ischichuca and wave-(and storm) dominated deltas in shallower parts of the lake (Río Gualo and La Torre). Thin impure coal horizons are found at definite horizons in wave-dominated deltas (Fig. 3).
Finally, the SD facies association represents the transition from the typical river-dominated deltaic and deep lacustrine facies of the Ischichuca Formation to the shallow shelf deltas of the Los Rastros Formation (similar to those described at the type area).

DEPOSITIONAL DYNAMICS AND SEQUENCE STRATIGRAPHIC EVOLUTION

The analysis of the available sedimentologic, mineralogic, geochemical, and stratigraphic information permitted the recognition of three major depositional phases and the paleogeographic evolution of the lacustrine filling of the basin, which are summarized in Table 2.

Phase 1: Pyroclastic eruptions and low-energy lowstand shallow lakes (VF, SL, F facies associations)

This phase includes the deposition of abundant pyroclastic material (VF facies association) and the successive development of two kind of low-energy shallow lakes (shallow mildly-saline lake and perennial playa lake of SL facies association). The lacustrine deposits of this phase are only recorded at Quebrada de Ischichuca and are correlated with fluvial channel facies from Río Gualo. This interval correspond to lowstand deposits, essentially because of its lithofacial features and areal restriction to more subsided parts of the half-graben (Legarreta *et al.* 1993). The lower sequence boundary is located at the base of the volcaniclastic deposits of the Chañares Formation or VF facies association (Milana and Alcober 1994). The upper sequence boundary is located in the upper part of the interval corresponding to phase 2 sediments (Fig. 3). Sedimentation was governed by a low to moderate accommodation rate and limited clastic supply. Phase 1 can be divided into three successive sedimentation events (times 1 to 3).
Time 1. The pyroclastic deposits display similar thickness in three of the studied localities (Fig. 3), although are missing in the southern axial margin. This distribution was influenced by secondary epiclastic and erosive processes. A progression can be identified in the VF facies association, from NW to SE (Fig. 3, Table 2): from predominantly subaqueous deposition (accommodation zone margin), mixed subaqueous and subaerial deposition with poorly developed paleosols (flexural margin), and dominantly subaerial deposition

Table 2. Summary of depositional events and sequence stratigraphy for the lacustrine package of the Ischigualasto – Villa Unión Basin. QI= Quebrada de Ischichuca, RG= Río Gualo, LT= La Torre, CM= Cerro Morado.

Phase	**Depositional systems**			**Hydrology**	**Accommodation & supply**	**Sequence stratigraphy**	**Source area**	**Paleoclimate**	**Tectonism**
	Accommodation zone (QI)	**Flexural margin (RG)**	**Axial margin (LT, CM)**						
Phase 1	Time 1 – Subaqueous pyroclastic fall + volcaniclastic gravity flow deposits	Subaerial pyroclastic floodplain (paleosols) and ponds	Mostly subaerial pyroclastic floodplain (silcrete)	Closed basin, probably segmented in a number of depocenters.	Underfilled. Low accommodation. Low clastic supply.	Lower part of lowstand wedge	Unknown	Semiarid	Early synrift.
	Time 2 - Shallow mildly saline lake	Thin fluvial deposits lying unconformably on volcaniclastic deposits.	Missing	Basin closure. Gradual water-level changes. Temporary water stratification	Underfilled. Low accommodation. Low clastic supply.	Upper part of lowstand wedge.	Unknown	Semiarid	Early synrift. Subsidence.
	Time 3 - Perennial playa-lake and dry mudflats		Missing	Temporary basin closure or groundwater-fed through-flow basin. Abrupt water-level changes. Saline water stratification.	Underfilled. Low accommodation. Low clastic supply.	Upper part of lowstand wedge.	From flexural margin (SE). Quartz-feldspathic sandstones.	Warm and semiarid.	Early synrift. Subsidence.
Phase 2	Deep freshwater oligomictic or meromictic lake and fluvial-dominated deltas.	Shallow freshwater holomictic lake and wave-dominated deltas	Shallow freshwater holomictic lake and river-dominated deltas.	Basin closure or recurrent mixing of epilimnion and hypolimnion waters.	Balanced fill. High accommodation. Low to moderate clastic supply	Transgressive and highstand system tracts. Contains a sequence boundary.	From flexural margin (E or SE). Quartz-feldspathic sandstones.	Warm and humid. Low wind strength.	Early synrift. Increased subsidence.
Phase 3	Shallow shelf deltas and wave dominated littoral deposits	Missing	Missing	Open basin. No water stratification.	Overfilled. Low accommodation. High clastic supply.	Lowstand system tract.	Accommodation zone margin (NW). Lithic volcanic sandstones.	Climate deterioration (less humid). Moderate to high wind strength.	Late synrift. Flexural margin faulting. Provenance and paleocurrent change.

with better developed paleosols (axial margin). These differences are linked to the inferred palaeogeographic location of the different sections.

Time 2. The first type of lake can be characterized as shallow, mildly saline, and dominated by fine-grained clastic sedimentation (Table 2, Fig. 3). The lake was hydrologically closed and might have developed temporary stratification. Lake-level changes were common but gradual and less marked that in the next sedimentation event. Water-level changes were probably accompanied by variations in lake salinity / alkalinity.

Time 3. A gradual increase in the participation of dark shales and dolomitic carbonate beds, plus repeated evidence for subaerial exposure and desiccation mark the transition to the second lake type. This can be depicted as a playa-lake surrounded by dry mudflats. Basin-centre deposits records gradational stacking of moderately organic-rich mudstone during lake flooding and dolomitic muds plus reduced evaporite minerals during lake desiccation. The fringing mudflats were repeatedly flooded and desiccated, which resulted in the formation of common vadose and palustrine features and preservation of tetrapod tracks. The potential of preservation of organic matter was slightly higher that in the previous lacustrine phase but was severely affected by frequent lake-level changes that exposed to oxidation and erosion vast areas of the lake floor. The playa-lake probably suffered only temporary hydrological closure or was a groundwater-fed through-flow playa basin (Rosen 1994). The fluvial facies association lies unconformably on VF facies association and the former is considered roughly correlative with shallow saline lake deposits (times 2 and 3). The channel filling is composed by quartzo-lithic sandstones with a significant amount of paleovolcanic clasts. The latter represent intermediate to basic volcanic textures and might be sourced from a volcanic highland related with the profuse pyroclastic deposits of VF facies association.

Phase 2: Deep freshwater lakes and highstand deltas (OL, DF, DP facies associations)

Phase 2 deposits display a gradual transition with the underlying shallow lacustrine facies of the phase 1 and reflect sedimentation in a deep freshwater lake (OL) associated with the development of fluvial- and wave-dominated deltas. A total of three progradational deltaic lobes are recorded. The stratigraphic record of delta progradation is represented by 12-80 m thick coarsening and shallowing-upward parasequences (Fig. 3), which include prodelta, delta front and delta plain facies. This thickness range is accepted as an approximation to the maximum depth of the lake. In the Quebrada de Ischichuca area the lake waters were permanently or frequently stratified with anoxic bottom waters, which favored the preservation of organic matter. The common presence of siderite also points to strongly reducing conditions, at least below the sediment-water interface, and water stratification. The low carbonate content of hemipelagic-pelagic black shales suggest high lake levels related to a wetter climate and/or source areas with scarce limestones. Pelagic / hemipelagic prodelta muds were replaced landward by silty surge-like turbidity flow deposits that conformed a very gently sloping delta front and shelf. The slope of delta front and shelf were probably less than 3 ° by comparison with modern tropical rift-lake deltas (Johnson *et al.* 1995). The fluvial channels of the delta displayed high to moderate sinuosity, mixed load and low channel slope. Major distributaries were separated by ample interdistributary bays or shallow lakes in the delta plain, where prograded small crevasse deltas. Most of the preserved delta plain facies are subaqueous deposits, which is probably a consequence of the location of the studied sections at a considerable distance from the shoreline.

At Quebrada de Ischichuca, where large outcrops are available, delta front and delta plain facies associations form 10-42 m thick depositional lobes with a lens-shaped cross-section separated by 13-40 m thick tabular black shale intervals. Each of these lobes contain one plane-convex channel sandbody showing prominent wings encased in delta plain and delta front facies, resembling the cross-section geometry commonly envisaged for fluvial-influenced delta lobes (e.g. Galloway and Hobday 1996:404). Three deltaic lobes can be recognized in the analyzed sections, which seem to migrate upsection toward the northeast. This apparent translation of the locus of channel deposition may indicate incipient faulting in the flexural margin of the half-graben, although an autocyclic control cannot be excluded. The mean orientation of paleocurrent indicators for the channels of these delta lobes was N317° (n=30). This means that they were sourced from the flexural margin of the half-graben. The largest depositional lobe is up to 42 m thick and at least 3 km wide. These measurements compare favorably with the lowstand lobes of the Dwangwa delta, which is the largest of the flexural margin deltas of the Lake Malawi (Scholz 1995a).

Phase 2 deposits are mostly interpreted as lake highstands due to the dominance of offshore shales and marked progadational parasequence stack (Legarreta *et al.* 1993). The three first parasequences show a

marked progradational stacking pattern indicated by an increase in the thickness of the black shale interval (Fig. 3). They are interpreted as transgressive and highstand lacustrine deposits.
The third delta lobe cover erosively laminated black shales (OL1) without intervening delta front sediments (DF). This abrupt facies superposition can be traced in correlative sections from the flexural and axial margins of the basin (Fig. 3) and it is interpreted as product of a marked decrease in water level that resulted in a basinward translation of facies belts. The basinward translation of the facies belts is recognized as a forced regression in the sequence stratigraphic terminology (e.g. Posamentier *et al.* 1992; Dam and Surlyk 1992; Lemons and Chan 1999). The third lobe probably rests on or contains a sequence boundary. Its coarse-grained deposits represents a lowstand delta and are covered by black shales considered as transgressive + highstand deposits (Dam and Surlyk 1992).
Lacustrine deltaic parasequences are not easily related to lake – level changes, except when independent evidence is available. However, this study demonstrate that it is possible to correlate lacustrine flooding and ravinement surfaces between sections located about 100 km apart. In consequence, most of the parasequences of phase 2 deposits correspond to lake level changes.

Phase 3: Shallow wave-dominated lake and shelf delta (SD facies association)
This stage documents the existence of a lake influenced by fair-weather and storm waves of moderate energy, probably under a windy climate and is only recorded at Quebrada de Ischichuca. Moderate wind stress is commonly related to a large lake fetch, which could be linked with the mentioned locality at the northwest end of the rift-lake. This tract displays sedimentologic and stratigraphic attributes in common with the lower section of the Los Rastros Formation at Ischigualasto Park (cf. Melchor *et al.* 2003).
This phase is represented by two adjacent (sub)environments that display poor to moderately developed cyclicity. Progradation of small sandy delta lobes (SD2, Table 1) associated with shoreline sediments is recorded as coarsening-upward deltaic cycles. The thickness of these cycles suggest that basinal depth range was approximately 6-15 m. Delta lobes probably have developed on the lake shelf and displayed very gentle slopes.
Shallowing-upward packages of facies subassociation SD1 (wave-dominated littoral lacustrine sediments) were deposited by processes of shoreline progradation. They are envisaged as fringing the deltaic deposits (SD2) in the area of maximum wave attack. Offshore sediments accumulated below wave-base in a shallow lake have preserved a moderate amount of organic matter. They are mostly interpreted as the product of quasi-steady hyperpycnial turbidity currents (Mulder and Alexander 2001).
The deposits of phase 3 display a change in paleocurrent indicators and in modal sandstone composition in relation with the previous phase. Paleocurrent data indicate transport from the southeast in the previous phases that changed to northwest in phase 3. Accordingly, sandstone composition changed from quartzo-feldsphatic to lithic volcanic sandstones These changes suggest that the transition between both facies associations would contain a sequence boundary (e.g. Miall and Arush 2001) and reflect a major reorganization in basin configuration. Phase 3 sediments are considered as lowstand deposits due to their lithofacies attributes and location above a sequence boundary.

CONTROLS ON SEDIMENTATION AND BASIN DEVELOPMENT

The general NW trend of the purported border fault of the rift, the Valle Fértil Megafracture, plus the wedge-shaped geometry of the strata for the analyzed interval indicates that the orientation of the half-graben was roughly NW-SE (e.g. Milana and Alcober 1994). Strata show the greatest thickness at Quebrada de Ischichuca and thin-out towards the E-SE, which suggest that the footwall margin was located toward the southwest (Georgieff 1992, Milana and Alcober 1994, Ruiz and Introcaso 1999). The stratigraphic evolution of the studied interval of the Ischigualasto - Villa Unión Basin is comparable with that of low-latitude lacustrine rift basins (Scholz *et al.* 1998). The main features in common with low-latitude lacustrine rift basins are the presence of flexural margin unconformities accompanied by a basinward translation of facies belts and evidence for repeated lake - level changes (Scholz *et al.* 1998). Milana and Alcober (1994) and Milana (1998) recognized two rifting episodes within the filling of the Ischigualasto Villa – Unión Basin. In that model, both the Chañares and Ischichuca formations would correspond to the first synrift stage and the analyzed package would include early synrift (phase 1 + phase 2) to late synrift sediments (phase 3).

The interplay between water and sediment fill rate (mostly climatically driven) and potential accommodation rate (tectonically driven) define three distinct basin lake states: underfilled, balanced-fill and overfilled (Carroll and Bohacs 1999). These three stages correspond with three idealized facies associations (Carroll and Bohacs 2001): evaporative, fluctuating profundal and fluvial-lacustrine, respectively. The idealized facies associations and basin states of Carroll and Bohacs (1999, 2001) can be identified in the Ischigualasto – Villa Unión Basin (Table 2). Phase 1 sediments (volcaniclastic deposits, shallow lakes and playa lake) correspond to an underfilled basin state given that the rate of potential accommodation always exceeded water and sediment fill. These shallow lakes were restricted to elongated topographic depressions close to the border fault and suggest that the half-graben had an interior drainage during this phase (Gawthorpe and Leeder 1987).

Phase 2 sediments (deep lacustrine shales and delta lobes) represent balanced-fill basin conditions. This state is commonly evidenced by fluctuating profundal facies. Water and sediment inflows regularly filled the lake to sill level and could even have created surface outflows (Carroll and Bohacs 1999). Paleocurrent data suggest that these deltas were sourced from the flexural margin. In addition, the marked progradational character of the delta lobes is typical of flexural margin deltas (Scholz 1995a). A similar size range between delta lobes of flexural deltas of the Ischichuca Los Rastros lake and Lake Malawi (Dwangwa delta) suggest that the highstand deltas of phase 2 may have had a surface area of several tens of square kilometres (i.e. in the range ~40-100 km^2, after Scholz 1995a). Furthermore, the existence of a large drainage on the flexural margin of the half-graben, as suggested by the presence of large channel sandbodies, indicates reduced relief and limited faulting on that margin, which is typical of the early stages of rifting (Scholz 1995a).

Phase 3 sediments (lake nearshore and shelf delta) are interpreted as representing an overfilled basin state, where the influx rate of sediments and water exceeds potential accommodation, and fluvial-lacustrine facies dominate (Carroll and Bohacs 1999). The change to overfilled state is related to important tectonic events that modified the basin configuration, as evidenced by paleocurrent and provenance changes between phases 2 and 3. A possible explanation for these changes is that footwall uplift and flexural margin faulting inhibited the lateral input of sediment and favored the development of deltas at the axial margin or at accommodation zones, as documented in many modern rift basins (e.g. Scholz *et al.* 1998). This inference is in agreement with the available mean paleocurrent data and the known half-graben physiography. The absence of stratigraphic evidence for sublacustrine fans or channels and lack of any other evidence for increased depositional slope, which are typical of axial margin deltas (Scholz 1995a; Johnson *et al.* 1995), suggest that the most probable alternative is location of the area within an accommodation (transfer) zone of the rift system. Studies on modern rifts demonstrated that accommodation zone margin rivers typically generate the largest sediment influx into lacustrine rift basins (e.g. Morley *et al.* 1990; Scholz 1995a,b; Scholz and Hutchinson 2000). Thus, the overfilled basin state inferred for phase 3 can be linked to the large sediment influx typical of accommodation zones. A possible consequence of this inference is the possible existence of a linked half-graben to the north of the known outcrops of the Ischigualasto – Villa Unión Basin, whose deposits are poorly known. The location of phase 3 sediment at the northernmost tip of the half-graben may imply that the moderate to high wave energy recorded within SD facies association is related to increased wind energy as a result of greater lake fetch in the direction of maximum elongation of the basin.

SOURCE-ROCK AND RESERVOIR POTENTIAL

The published information on source-rock characteristics of the lacustrine organic-rich facies of the Ischigualasto - Villa Unión Basin is scarce (Uliana *et al.* 1999). Chebli *et al.* (2001) stated that the lacustrine black shales of the Ischigualasto-Villa Unión Basin are immature with respect to petroleum generation on the basis of a theoretical analysis (Lopatin diagram). The black shales of the Ischichuca Formation (OL1, Table 1) from the analysed succession contain organic matter of terrestrial origin and display maximum TOC values close to 3%. Assuming a wedge-shaped geometry and a conservative areal extent (750 km^2) for the black shale intercalations, it is estimated that the total volume of organic rich shales can reachs ~40 km^3. Spore colour index range (2-4) suggests that the organic matter can have reached a thermal maturation state that permitted oil generation (Batten 1996); although the influence of spore oxidation remains to be assessed (A. M. Zavattieri, written comm. 1999). Vitrinite reflectance data is not available for the studied succession. Recent models of lacustrine petroleum source rocks (Carroll and Bohacs 2001), point out that terrestrial kerogen commonly generates hydrocarbons over a greater temperature range than do most algal-dominated kerogens. Besides the existence of a moderate volume of potential source rocks, the coarser-grained fluvio-deltaic deposits of phase 2 or phase 3 of the Ischichuca Formation and the overlying Cenozoic deposits (Goergieff 1992) are potential reservoir facies. The sediments of the phase 3 sediments (SD facies association) correspond to deltaic and nearshore deposits probably located in an accommodation zone, which are areas of a rift system that display structural and sedimentary properties that make them optimum locations for structural hydrocarbon traps (Morley *et al.* 1990, Scholz 1995a,b). Accommodation zone deposits are particularly prospective for hydrocarbon exploration in rift basins because of the high probability of structural closure, the high sediment discharge, and probable juxtaposition of reservoir and organic rich facies (Scholz 1995b). The potentially favorable features mentioned above plus the apparent discrepancy between the different maturity inferences would warrant further detailed studies on the thermal maturation of the organic-rich facies of the basin.

CONCLUSIONS

The Chañares, Ischichuca, Los Rastros and Lomas Blancas formations corresponds to different stages of dominantly lacustrine sedimentation during the synrift phase of the Triassic Ischigualasto – Villa Unión Basin. Variations in the characteristics of the successive lake basins are controlled by the tectonic evolution of the half-graben and changing climatic conditions. Most of the sediments were sourced from the flexural margin of the half-graben, although the upper part of the succession records the input of detritus from an accommodation zone margin.

Four distinct lake types are recognized, which are arranged in three depositional phases. The two first lacustrine deposits (phase 1) correspond to low-energy shallow water sedimentation under a semiarid climate deposited on a landscape formed by volcaniclastic sediments. A mildly saline lake and a playa-lake have been recorded. The lakes were emplaced in a low gradient basin and experienced frequent climatically-driven water-level changes. The two remaining lake types are freshwater lakes associated with deltaic sedimentation. The third lake type is a deep freshwater lake with a meromictic regime (phase 2). Detrital sedimentation was concentrated in fluvial- and wave-dominated deltas that display delta front, shelf, interdistributary bay and distributary channel facies. Lake level was dominantly high although at least three lobe progradation and flooding events are recognized. Water level changes include a sharp fall that produced an unconformity on the flexural margin of the half-graben. The identified lacustrine flooding and ravinement surfaces can be traced between three localities located 100 km apart on the flexural and axial margin of the half graben. In consequence, it is inferred that lake level changes affected the whole basin during the phase 2 and that lacustrine flooding surfaces can be used for correlation purposes in the Ischigualasto – Villa Unión Basin. The last lake type corresponds to shallow-water and wave-dominated littoral deposits associated with shallow shelf deltas (phase 3). The latter deltaic sedimentation marks the transition to the overlying Los Rastros Formation. Deposition was strongly influenced by a high clastic supply from the accommodation zone of the half-graben and marked wind strength, which was favoured by the location of the Quebrada de Ischichuca at the northwestern end of the half-graben.

Phase 1 and most of phase 2 sediments compose lowstand and transgressive/highstand deposits, respectively. The lower sequence boundary is located at the base of the underlying Chañares Formation (VF facies association). The upper part of phase 2 sediments and phase 3 sediments correspond to another sequence that is not fully exposed.

The Ischichuca Formation contains a large volume of lacustrine black shales with moderate to high organic carbon content associated with prospective reservoir rocks (deltaic and littoral deposits of phase 3 and overlying Cenozoic deposits) and probably belongs to an accommodation zone margin (optimum sites for structural hydrocarbon traps in half grabens). These features warrant further detailed studies to evaluate the source rock and reservoir potential of the basin.

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REFERENCES

Batten, D.J. (1996) Palynofacies and petroleum potential. In: Palynology: Principles and Applications, (Eds J. Jansonius, and D.C. McGregor), American Association of Stratigraphic Palynologists Foundation, 3 (26B), 1065-1084.

Bellosi, E., Jalfin, G., Bossi, G., Muruaga, C., Boggetti, D. and Chebli, P. (2001) Ambientes sedimentarios en cuencas triásicas de Argentina. *Boletín de Informaciones Petroleras*, 68, 54-83.

Bossi, G.E. (1971) Análisis de la Cuenca Ischigualasto - Ischichuca. *1st Congreso Hispano-Luso-Americano de Geología Económica*, Madrid, 2, 1, 611-626.

Carroll, A.R. and Bohacs, K.M. (1999) Stratigraphic classification of ancient lakes: Balancing tectonic and climatic controls. *Geology*, 27, 99-102.

Carroll, A.R. and Bohacs, K.M. (2001) Lake-type controls on petroleum source rock potential in nonmarine basins. *AAPG Bull.*, 85, 1033-1053.

Chebli, G.A., Ploszkiewicz, J.V. and Azpiroz, G.M. (2001) El Sistema Triásico y los hidrocarburos. In: El Sistema Triásico en la Argentina (Eds. A.E. Artabe, E.M. Morel and A.B. Zamuner), pp. 283-315, Fundación Museo de La Plata, La Plata, Argentina.

Dam, G. and Surlyk, F. (1992) Forced regressions in a large wave- and storm-dominated anoxic lake, Rhaetian-Sinemurian Kap Stewart Formation, East Greenland. *Geology*, 20, 749-752.

Franzese, J.R. and Spalletti, L.A. (2001) Late Triassic-early Jurassic continental extension in southwestern Gondwana: tectonic segmentation and pre-break-up rifting. *J. S. Am. Earth Sci.*, 14, 257-270.

Galloway, W.E. and Hobday, D.K. (1996) *Terrigenous Clastic Depositional Systems*, 2nd ed., Springer, Berlin, 489 pp.

Georgieff, S. (1992) Análisis estratigráfico del subsuelo del Campo de Talampaya (Cuenca de Ischigualasto - Ischichuca, La Rioja, Argentina). *4th Reunión Argentina de Sedimentología*, La Plata, Actas, 3, 9-16.

Johnson, T.C., Wells, J.D., and Scholz, C.A. (1995) Deltaic sedimentation in a modern rift lake. *GSA Bull.*, 107, 812-829.

Keighley, D., Flint, S., Howell, J. and Moscariello, A. (2003) Sequence stratigraphy in lacustrine basins: A model for part of the Green River Formation (Eocene), southwest Uinta Basin, Utah, U.S.A. *Journal of Sedimentary Research*, 73, 987-1006.

Kokogián, D.A., Boggetti, D.A. and Rebay, G.A. (1989) Cuenca Cuyana – El análisis estratigráfico secuencial en la identificación de entrampamientos estratigráficos sutiles. *1st Congreso Nacional de Exploración de Hidrocarburos*, Mar del Plata, pp. 649-674.

Kokogián, D.A., Spalletti, L.A., Morel, E., Artabe, A., Martínez, R.N., Alcober, O.A., Milana, J.P., Zavattieri, A.M. and Papú, O.H. (1999) Los depósitos continentales triásicos. *Anales del Instituto de Geología y Recursos Minerales*, 29, 377-398.

Leeder, M.R. and Gawthorpe, R.L. (1987) Sedimentary models for extensional tilt-block/half-graben basins. In: *Continental Extensional Tectonics* (Eds M.P. Coward, J.F. Dewey and P.L. Hancock), *Geol. Soc. London Spec. Publ.*, 28, 139-152.

Legarreta, L. and Kokogián, D.A. (1986) Carácter regional e interregional de las discontinuidades intratriásicas. Cuencas de Ischigualasto – Villa Unión, Las Salinas y Cuyana. Secuencias deposicionales. YPF, informe inédito, 40 pp.

Legarreta, L., Uliana, M.A., Larotonda, C.A. and Meconi, G.R. (1993) Approaches to nonmarine sequence stratigraphy: theoretical models and examples from Argentine basins. In: *Subsurface Reservoir Characterization from Outcrop Observations* (Eds R. Eschard and B. Doligez). *Collection Colloques et Seminaires*, Institut Francais du Petrole, 51, 125-143.

Lemons, D.R. and Chan, M.A. (1999) Facies architecture and sequence stratigraphy of fine-grained lacustrine deltas along the eastern margin of Late Pleistocene Lake Bonneville, northern Utah and southern Idaho. *AAPG Bull.*, 83, 635-665.

Liro, L.M. (1993) Sequence stratigraphy of a lacustrine system: Upper Fort Union Formation (Paleocene), Wind River Basin, Wyoming, U.S.A. In: *Siliciclastic Sequence Stratigraphy: Recent Developments and Applications* (Eds P. Weimer and H.W. Posamentier), American Association of Petroleum Geologists, Memoir 58, 317-333.

López Gamundí, O., Álvarez, L., Andreis, R., Bossi, G.E., Espejo, I., Fernández Seveso, F.F., Legarreta, L., Kokogián, D., Limarino, C.O. and Sessarego, H. (1989) Cuencas Intermontanas. In: *Cuencas Sedimentarias Argentinas* (Eds G. Chebli, and L.A. Spalletti), *Serie Correlación Geológica*, 6, 123-167.

Melchor, R.N., Bellosi, E. and Genise, J.F. (2003) Invertebrate and vertebrate trace fossils from a Triassic lacustrine delta: The Los Rastros Formation, Ischigualasto Provincial Park, San Juan, Argentina. In:*Icnología: Hacia una convergencia entre geología y biología* (Eds L.A. Buatois and M.G. Mángano), Asociación Paleontológica Argentina, Publicación Especial, 9, 17-33.

Miall, A.D. and Arush, M. (2001) The Castlegate Sandstone of the Books Cliffs, Utah: Sequence stratigraphy, paleogeography, and tectonic controls. *J. Sed. Res.*, 71, 537-548.

Milana, J.P. (1998) Anatomía de parasecuencias en un lago de rift y su relación con la generación de hidrocarburos, cuenca triásica de Ischigualasto, San Juan. *Rev. Asoc. Geol. Argentina*, 53, 365-387.

Milana, J.P. and Alcober, O. (1994) Modelo tectosedimentario de la cuenca triásica de Ischigualasto (San Juan, Argentina). *Rev. Asoc. Geol. Argentina*, 49, 217-235.

Morley, C.K., Nelson, R.A., Patton, T.L. and Munn, S.G. (1990) Transfer zones in the East African Rift System and their relevance to hydrocarbon exploration in rifts. *AAPG Bull.*, 74, 1234-1253.

Mulder, T. and Alexander, J. (2001) The physical character of subaqueous sedimentary density flows and their deposits. *Sedimentology*, 48, 269-299.

Oviatt, C.G., McCoy, W.D. and Nash, W.P. (1994) Sequence stratigraphy of lacustrine deposits: a Quaternary example from the Bonneville basin, Utah. *GSA, Bull.*, 106, 133–144.

Posamentier, H.W., Allen, G.P., James, D.P., and Tesson, M. (1992) Forced regressions in a sequence stratigraphic framework: Concepts, examples, and exploration significance. *AAPG Bull.*, 76, 1687-1709.

Rosen, M.R. (1994) The importance of groundwater in playas: a review of playa classifications and sedimentology and hydrology of playas. In: *Paleoclimate and Basin Evolution of Playa Systems* (Ed M.R. Rosen), Geol. Soc. Am. Spec. Pap., 289, 1-18.

Ruiz, F. and Introcaso, A. (1999) Un modelo gravimétrico 3D de la profunda cuenca sedimentaria de Ischigualasto – Villa Unión (San Juan y La Rioja)-Argentina. *Rev. Brasil. Geofísica*, 17, 3-11.

Scholz, C.A. (1995a) Deltas of the Lake Malawi Rift, East Africa: seismic expression and exploration implications. *AAPG Bull.*, 79, 1679-1697.

Scholz, C.A. (1995b) Seismic stratigraphy of an accommodation-zone margin rift-lake delta, Lake Malawi, Africa. In: *Hydrocarbon Habitat in Rift Basins* (Ed J.J. Lambiase), *Geol. Soc. London Spec. Publ.*, 80, 183-195.

Scholz, C.A. and Hutchinson, D.R. (2000) Stratigraphic and structural evolution of the Selenga Delta Accommodation Zone, Lake Baikal Rift, Siberia. *Int. J. Earth Sci.*, 89, 212-228.

Scholz, C.A., Moore, T.C. Jr., Hutchinson, D.R., Golmshtok, A.J., Klitgord, K.D. and Kurotchkin, A.G. (1998) Comparative sequence stratigraphy of low-latitude versus high-latitude lacustrine rift basins: seismic data examples from the East African and Baikal Rifts. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 140, 401-420.

Stipanicic, P.N. and Bonaparte, J.F. (1979) Cuenca triásica de Ischigualasto - Villa Unión (provincias de San Juan y La Rioja). In: *Segundo Simposio de Geología Regional Argentina* (Ed J.C.M. Turner), Academia Nacional de Ciencias, Córdoba, 1, 523-575.

Tankard, A.J., Uliana, M.A., Welsink, H.J., Ramos, V.A., Turic, M., França, A.B., Milani, E.J., Brito Neves, B.B. de, Eyles, N., Skarmeta, J., Santa Ana, H., Wiens, F., Cirbián, M., López Paulsen, O., Germs, G.J.B., De Witt, M.J., Machacha, T. and Miller, R.McG. (1995) Tectonic controls of basin evolution in Southwestern Gondwana during the Phanerozoic. In: *Petroleum basins of South America* (Eds A.J. Tankard, R. Suárez Soruco and H.J. Welsink), *AAPG Mem.*, 62, 5-52.

Uliana, M.A. and Biddle, K.T. (1988) Mesozoic-Cenozoic paleogeographic and geodynamic evolution of southern South America. *Rev. Brasil. Geocienc.*, 18, 172-190.

Uliana, M.A., Biddle, K.T. and Cerdan, J. (1989) Mesozoic extension and the formation of Argentine sedimentary basins. In: *Extensional Tectonics and Stratigraphy of North Atlantic Margins* (Eds A.J. Tankard and H.R. Balkwill), *AAPG Mem.*, 46, 599-614.

Uliana, M.A., Legarreta, L., Laffitte G. and Villar H. (1999) Estratigrafía y geoquímica de las facies generadoras de hidrocarburos en las cuencas petrolíferas de Argentina. *4th Congreso Exploración y Desarrollo de Hidrocarburos*, Buenos Aires, Actas, 1, 1-61.