*Sedimentology* (2007) **54**, 1417–1446 doi: 10.1111/j.1365-3091.2007.00887.x

# Changing lake dynamics and sequence stratigraphy of synrift lacustrine strata in a half-graben: an example from the Triassic Ischigualasto–Villa Unión Basin, Argentina

RICARDO NÉSTOR MELCHOR
*Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) & Universidad Nacional de La Pampa, Av. Uruguay 151, L6300CLB Santa Rosa, La Pampa, Argentina*
*(E-mail: rmelchor@exactas.unlpam.edu.ar)*

**ABSTRACT**

Well-exposed Triassic rift strata from the Ischigualasto–Villa Unión Basin (NW Argentina) include a 80 to *ca* 515 m thick lacustrine-dominated package that can be correlated across a half-graben using key stratigraphic surfaces (sequence boundaries, lacustrine flooding surfaces and forced regressive surfaces). The characteristics of the synrift lacustrine fill in different parts of the half-graben have been examined and the mechanisms controlling sedimentation inferred. A variety of sedimentary environments are recognized including; volcaniclastic floodplain, mildly saline lake and playa lake, offshore lacustrine, delta front to fluvial-dominated and wave-dominated deltas, distributary and fluvial channel, and interdistributary bay. The succession can be divided into four stratigraphic sequences (SS1 to SS4), the oldest of which (SS1) contains volcaniclastic, fluvial and saline lake deposits; it is thickest close to the western border fault zone, reflecting more rapid subsidence here. Accommodation exceeded sediment and water input during SS1. The second and third sequences (SS2 and SS3) mark the onset of widespread lacustrine sedimentation, reflecting a balance between accommodation creation and water and sediment fluxes. Sequences SS2 and SS3 are represented by offshore meromictic lacustrine and deltaic deposits, the latter mostly sourced from the flexural and southern axial margins of the half-graben. The presence of stacked parasequences bound by lacustrine flooding surfaces is related to climatically induced lake-level fluctuations superimposed on variable rates of subsidence on the controlling rift border fault zone. The youngest sequence (SS4) is represented by the deposits of littoral lacustrine and shallow shelf deltas distinguished by a change in lithofacies, palaeocurrents and sandstone composition, suggesting a switch in sediment supply to the footwall margin to the NW. The change in the sediment source is related to reduced footwall uplift, the possible presence of a relay ramp and/or supply from a captured antecedent drainage network. During SS4, the rate of creation of accommodation was exceeded by the sediment and water discharge. The stratigraphic evolution of lacustrine strata in the half-graben was mainly controlled by tectonic processes, including subsidence rate and the growth and evolution of the border fault zone, but changing climate (inducing changes in water balance and lake level) and autocyclic processes (delta lobe switching) were also important.

**Keywords** Argentina, half-graben, lacustrine delta, stratigraphic architecture, tectonism, Triassic.

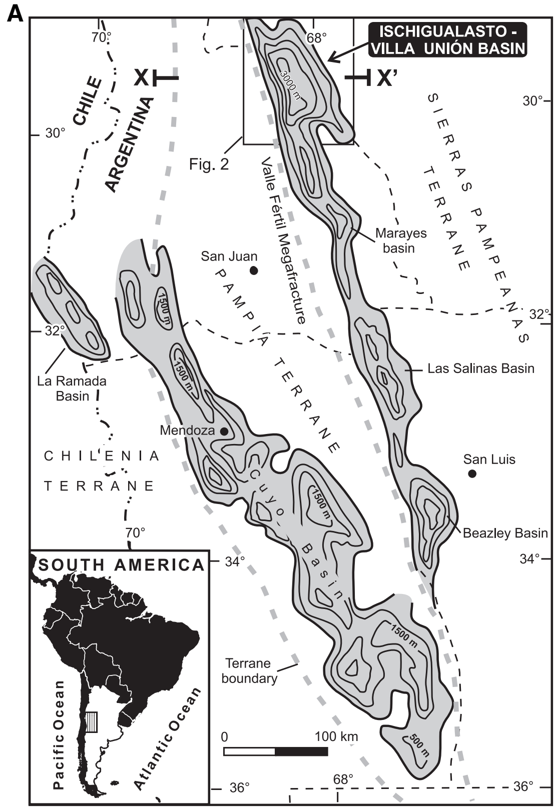
## INTRODUCTION

The evolution of basin-bounding normal fault zones in rift basins exerts a first-order control on the vertical stratigraphic evolution and three-dimensional variability of synrift sequences (e.g. Gawthorpe *et al.*, 1994; Contreras *et al.*, 1997; Gupta *et al.*, 1999; Gawthorpe & Leeder, 2000). However, the factors controlling the stratal geometry and higher frequency cyclicity within synrift successions are often less certain because of the difficulty of discriminating between tectonic controls and variations in sediment supply and/or base level that are determined by climatic change or autocyclic effects (Dart *et al.*, 1994; Hardy *et al.*, 1994; Gawthorpe *et al.*, 2003). In addition, many studies have focussed on coarse-grained alluvial fan and fan delta systems (e.g. Colella, 1988; Dart *et al.*, 1994; Soreghan *et al.*, 1999; Young *et al.*, 2000) in which it is difficult to correlate between successions in different parts of the basins (Gawthorpe *et al.*, 2003).

Triassic lacustrine strata from the Ischigualasto–Villa Unión Basin (NW Argentina) permit comparison of the synrift stratigraphic evolution in different parts of a half-graben, allowing the mechanisms controlling sedimentation to be analysed. Basinwide correlation of lacustrine sequences and parasequences is used to compare time-equivalent successions developed along the footwall and flexural margins of the basin. The aim of the study was to document the vertical and lateral facies variability within a sequence stratigraphic framework in order to examine the significance of tectonic and other controls on synrift deposition in a large lake basin.

## GEOLOGICAL AND TECTONIC SETTING

The Ischigualasto–Villa Unión Basin (Fig. 1A) is one of a number rift basins that developed on the western margin of SW Gondwana during the Early Triassic (e.g. Uliana & Biddle, 1988; Uliana *et al.*, 1989; Tankard *et al.*, 1995; Franzese & Spalletti, 2001). The basin is a NW–SE trending half-graben (Milana & Alcober, 1994) at least 120 km long and 50 km wide (Baraldo *et al.*, 1990; Milana, 1998; Fig. 1A) that received continental sediments mostly from the latest Early Triassic to the Late Triassic (e.g. Spalletti, 1999). The Triassic basins have been modified by Neogene and younger compressional tectonics associated with the Andean foreland (Fig. 1B). The



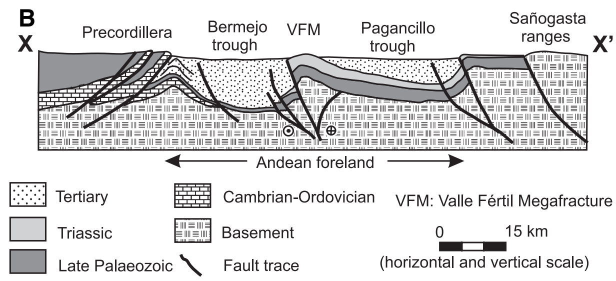




**Fig. 1.** Triassic rift basins in central-western Argentina. (A) Distribution of recognized depocentres and isopach map. Note the presence of two rift branches separated by terrane boundaries (grey dashed lines). The rectangle indicates the position of Fig. 2. X–X′ corresponds with the trace of the section shown in (B). Modified after Ramos (1994), Álvarez & Ramos (1999) and Spalletti (2001). (B) Schematic E–W cross-section (X–X′) of the Andean foreland showing main structures and Cainozoic depositional troughs. Modified from Rossello *et al.* (2005).

Andean foreland basin contains 4 to 7 km of Neogene clastic sediments and is divided by a NNW–SSE trending basement high (the Valle Fértil Megafracture; Figs 1B and 2B) into two troughs: the Bermejo and Pagancillo troughs (Rossello *et al.*, 1996, 2005). The eastern margin of the Valle Fértil Megafracture has been interpreted as a major transpressional left-lateral wrench zone, involving faulting of a crystalline basement and forming a positive flower structure (Rossello *et al.*, 1996; Figs 1B and 2B), which reactivated normal Triassic faults (Fig. 2B). The sediments of the Ischigualasto–Villa Unión Basin are uplifted against the western (Valle Fértil Megafracture) and eastern margin (Sañogasta Ranges) of the Pagancillo trough (Figs 1B and 2A). In cross-section, the Triassic strata display a wedge-shaped geometry (Fig. 2B), although differences in thickness are not obvious in isopach maps because of Neogene to Recent erosion (Fig. 1A). The general NW trend of the flanking Valle Fértil Megafracture (Fig. 1A) and the thickening of Triassic strata towards that structure (Fig. 2B) suggest that the orientation of the half-graben was broadly NW–SE and that the footwall margin lay to the SW (Ramos & Kay, 1991; Georgieff, 1992; Milana & Alcober, 1994; Ruiz & Introcaso, 1999; Rossello *et al.*, 2005). The fill of the Triassic half-graben is represented by a 2500 to >4000 m thick continental succession, which can be subdivided into a number of formations (Fig. 3). Milana & Alcober (1994) and Milana (1998) distinguished two rift episodes on the basis of seismic and tectonostratigraphic analysis. The first phase of rifting is represented in ascending order by the Talampaya, Tarjados, Chañares, Ischichuca, Los Rastros, Lomas Blancas and Río Chiflón formations (Fig. 3). The oldest two formations are composed of red alluvial sandstones and conglomerates, whereas the remaining formations are dominantly fine-grained lacustrine deposits. The deposits of the second rift episode correspond to the Ischigualasto and Los Colorados formations, which are dominantly fluvial units. The lacustrine-dominated succession studied (Chañares, Ischichuca, Los Rastros and Lomas Blancas formations) belongs to the synrift stage of the first rift episode (Fig. 3). The outcrops of the Ischichuca Formation are restricted to locations close to the footwall margin and display a lateral (towards the flexural margin) and vertical transition to the Los Rastros Formation (e.g. Bossi, 1971; Melchor, 2002). In addition, the Lomas Blancas Formation is considered partially equivalent to the Los Rastros Formation (Bossi, 1971; Fig. 3). The lacustrine package has been assigned to the Middle to early Late Triassic (e.g. Stipanicic & Bonaparte, 1979; Stipanicic, 1983; Spalletti *et al.*, 1999; Zavattieri & Melchor, 1999). Four localities spread obliquely across the half-graben over a distance of 95 km were selected for detailed study: (i) Quebrada de Ischichuca close to the footwall margin in the NW; (ii) Río Gualo in the east on the central part of the flexural margin; and (iii) Cerro Morado and (iv) La Torre, both in the southern part of the half-graben on the hanging-wall slope (Figs 2 and 4).

## FACIES ASSOCIATIONS

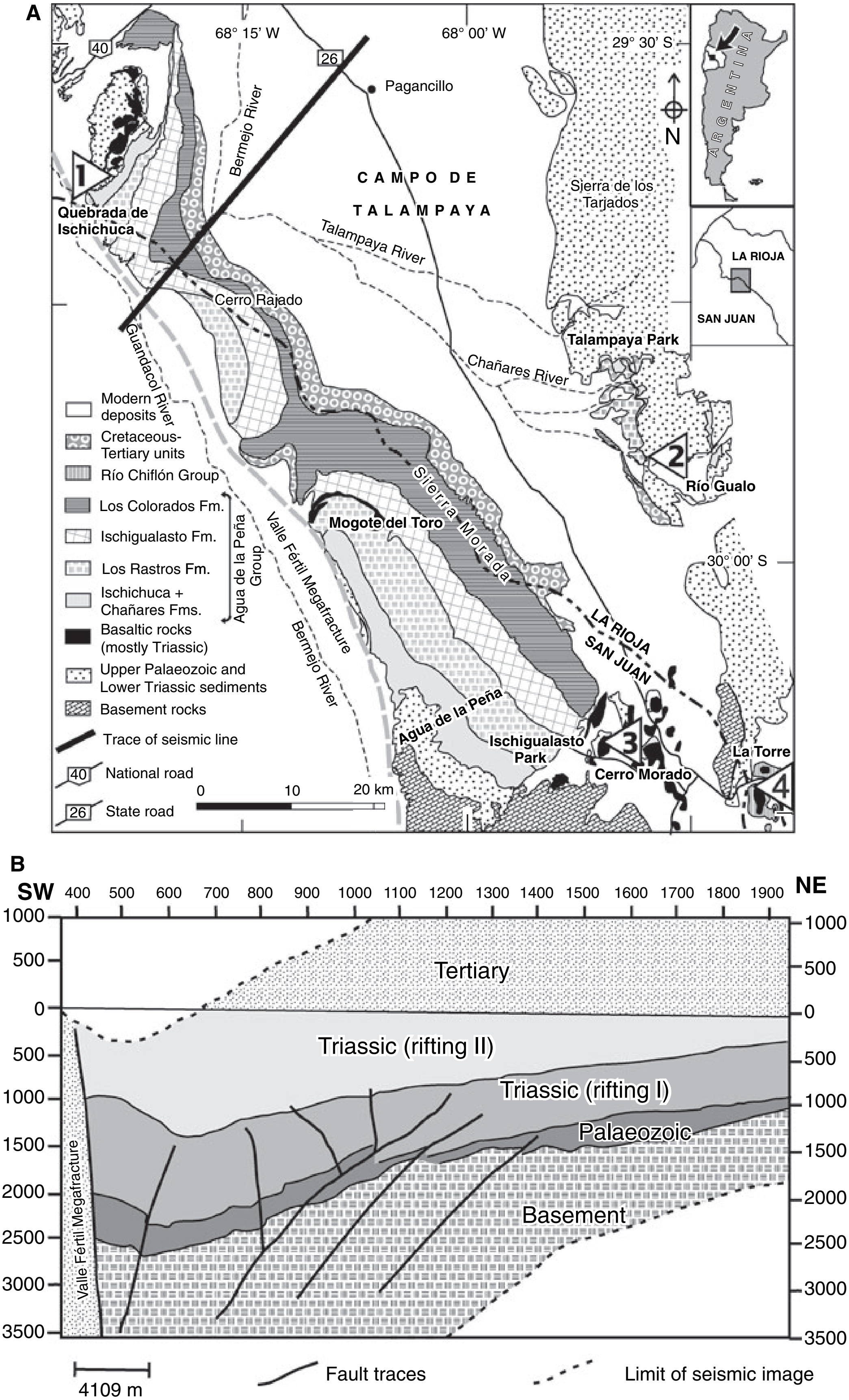
The lacustrine deposits studied lie above a disconformity (Río Gualo, Cero Morado and La Torre) or a correlative conformity (Quebrada de Ischichuca) on the alluvial Tarjados Formation. The top of the lacustrine section is marked by a contact with the overlying fluvial deposits of the Ischigualasto Formation. The lacustrine deposits include the Chañares, Ischichuca, Los Rastros and Lomas Blancas formations (Fig. 3) and display a marked change in thickness from NW to SE. The overall package is *ca* 515 m thick at Quebrada de Ischichuca, 215 m thick at Río Gualo and 82 m thick at La Torre (Fig. 4). The section exposed at the fourth locality, Cerro Morado, is partial and only includes the Chañares Formation.

Twelve facies associations are recognized (described in detail in Table 1) and these can be further grouped according to the depositional environment interpreted. The depositional environments include volcaniclastic floodplain (VF facies association), saline lake (SL1 and SL2 facies associations), offshore lacustrine (OL1 and OL2 facies associations), lacustrine delta front and shelf (DF1 and DF2 facies associations), lacustrine delta plain (DP1, DP2 and DP3 facies associations), and lacustrine shelf deltas and littoral settings (SD1 and SD2 facies associations). Figure 5 provides examples of the facies association and Figs 6 and 7 illustrate the component lithofacies.

### VF facies association

The VF facies association is characterized by structureless reworked or primary fine-grained ash-fall tuffs and volcaniclastic sandstones displaying no preferred cyclicity (Fig. 5A). This facies association (corresponding to the Chañares Formation) is recorded at all localities; it overlies the Tarjados Formation and displays lateral changes that can be linked to the inferred geometry of the half-graben. The thickness of the VF facies association is commonly in the range of 44 to 51 m, although at the La Torre locality it is reduced to 2 m (Fig. 4). At Quebrada


A
68° 15' W
68° 00' W
29° 30' S
30° 00' S
40
26
Pagancillo
N
ARGENTINA
LA RIOJA
SAN JUAN
Bermejo River
CAMPO DE
TALAMPAYA
Sierra de los Tarjados
Quebrada de Ischichuca
Talampaya River
Cerro Rajado
Talampaya Park
Guandacol River
Chañares River
Río Gualo
Sierra Morada
Mogote del Toro
Valle Fértil Megafracture
Bermejo River
LA RIOJA
SAN JUAN
Agua de la Peña
Ischigualasto Park
Cerro Morado
La Torre
1
2
3
4
Modern deposits
Cretaceous-Tertiary units
Río Chiflón Group
Los Colorados Fm.
Ischigualasto Fm.
Los Rastros Fm.
Ischichuca + Chañares Fms.
Agua de la Peña Group
Basaltic rocks (mostly Triassic)
Upper Palaeozoic and Lower Triassic sediments
Basement rocks
Trace of seismic line
National road
State road
0
10
20 km
B
SW
NE
400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900
1000
500
0
500
1000
1500
2000
2500
3000
3500
Tertiary
Triassic (rifting II)
Triassic (rifting I)
Palaeozoic
Basement
Valle Fértil Megafracture
4109 m
Fault traces
Limit of seismic image

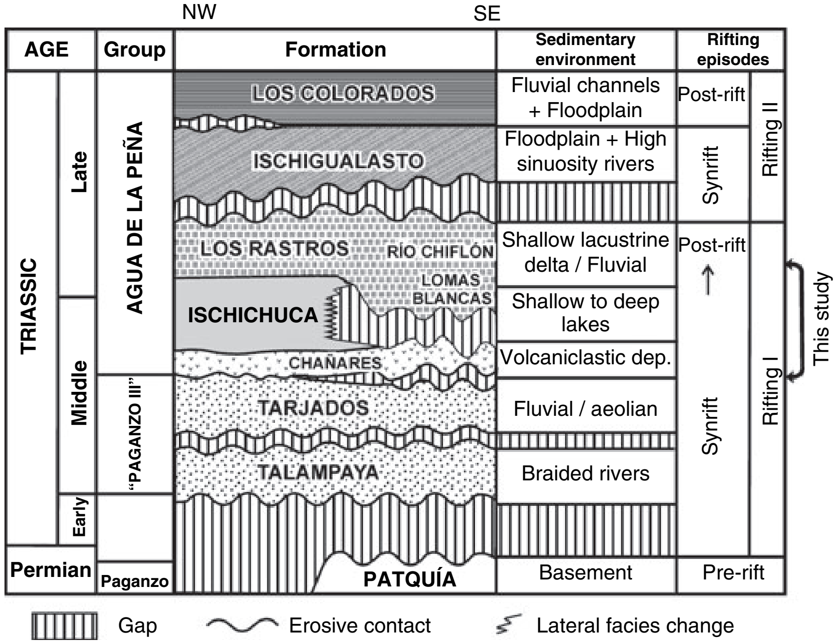



**Fig. 3.** Stratigraphic relationships and summary palaeoenvironmental settings for the lithostratigraphic units of the Ischigualasto–Villa Unión Basin. Also indicated are the two Triassic rifting episodes recognized in the basin (Milana & Alcober, 1994) and the location of studied lacustrine-dominated package. Modified from Stipanicic & Bonaparte (1979), Caselli *et al.* (2001), Melchor (2002, 2004) and Stipanicic & Marsicano (2002).

de Ischichuca, thickly bedded and massive gravely volcaniclastic sandstones (probably deposited by gravity-flow processes) overlie well-bedded, reworked ash-fall deposits with common wave ripples and mudstone interbeds, suggesting a shallow sub-aqueous setting for deposition (Fig. 6B). At Río Gualo the VF facies association is mostly represented by structureless and reworked, silt-sized, ash-fall deposits with poorly developed palaeosols (Figs 5A and 6A), although the upper part of the local succession shows laminated and rippled green siltstones and fine-grained sandstones. Most of the facies association at Rio Gualo represents deposition of distal pyroclastic sediment and epiclastic reworking in a floodplain setting. Pyroclastic deposition was dominantly sub-aerial, although subordinate sedimentation in shallow ponds is recognized towards the top of the succession (laminated and wave-rippled tuffaceous mudstones and siltstones. At Cerro Morado (Fig. 4), the succession is similar to that exposed at Río Gualo, although better developed palaeosols with indurated horizons showing accumulation of silica (silcretes) occur. The reduced thickness of the VF facies association at La Torre (Fig. 4) is attributed to epiclastic reworking of pyroclastic deposits close to the border of the basin.

## SL facies associations

The saline lake (SL) facies associations are restricted to the Quebrada de Ischichuca locality (Fig. 4), which suggests that they have a limited areal extent and probably are related to a rapidly subsiding local depocentre. Stratigraphic relationships indicate that the fluvial facies association (F) at Rio Gualo is partially correlative with the SL facies associations (Fig. 4).

### *Shallow mildly saline lake facies association (SL1)*

Facies association SL1 is represented by thinly bedded variegated mudstones, sandstones, and minor micrite organized in coarsening-upward, metre-scale cycles (Fig. 5B). Deposition of the SL1 facies association took place in a relatively shallow, mildly saline lake, as suggested by faunal remains (mainly conchostracans and ganoid fish scales), scarce evaporite minerals, the dominance of sheet-like beds, and sedimentary structures produced by low-energy currents

**Fig. 2.** Geological map and cross-section of the Ischigualasto–Villa Unión Basin. (A) Geological map showing the location of the main outcrops mentioned in the text and interpreted seismic line shown in (B). Compiled from a range of sources, including Romer & Jensen (1966), Bossi & Herbst (1968), Stipanicic & Bonaparte (1979), and Page *et al.* (1997). (B) Geoseismic line showing the structure of the basins flanking the Valle Fértil Megafracture. The line is flattened on the base of Tertiary strata. Note the change in thickness of Triassic strata, the flower structure related to late Tertiary deformation, and the abrupt western limit of the Triassic sediments. Modified from Rossello *et al.* (2005).

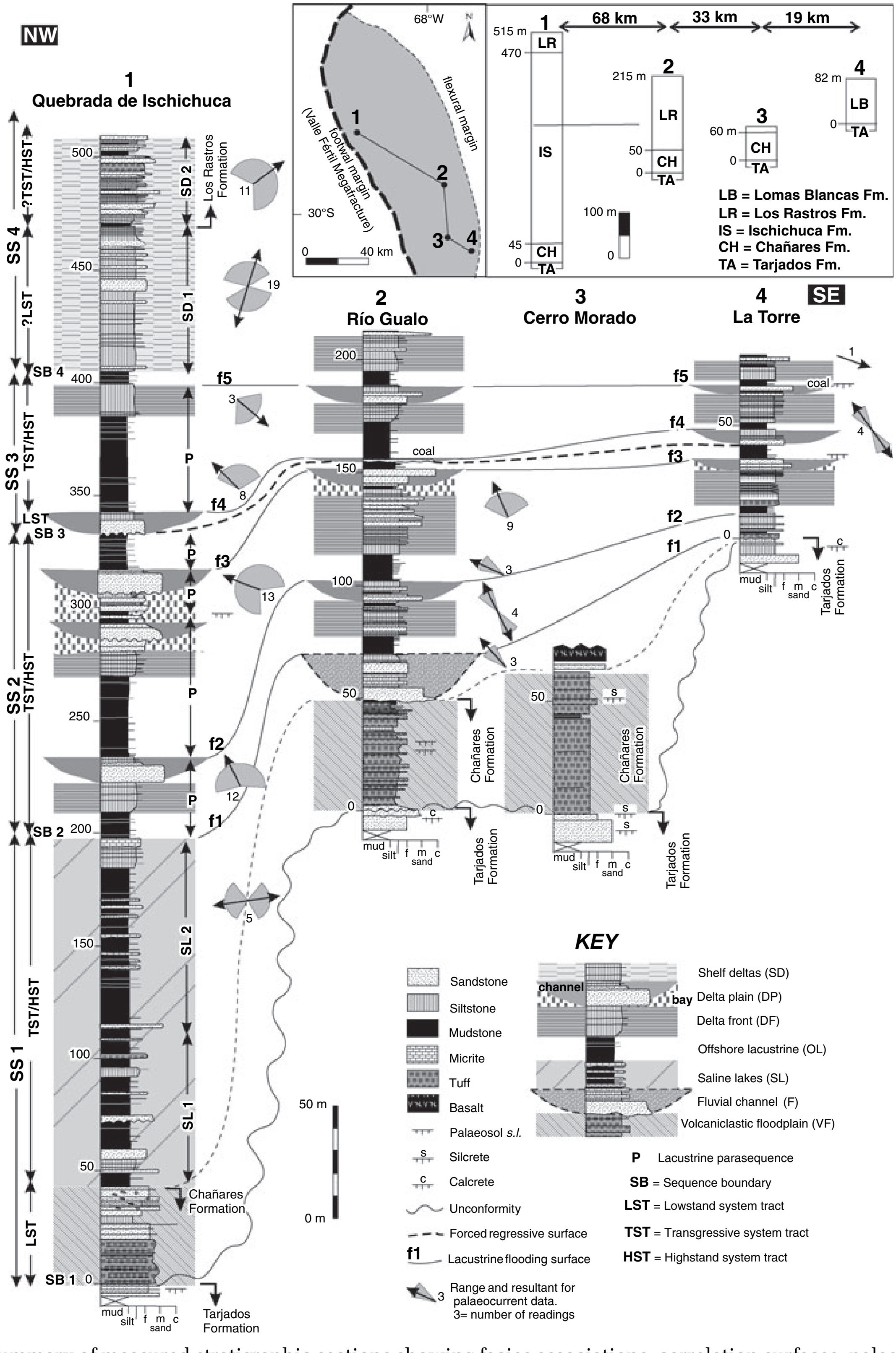



**Fig. 4.** Summary of measured stratigraphic sections showing facies associations, correlation surfaces, palaeocurrents and sequence stratigraphic framework. The sections are plotted using lacustrine flooding surface 5 (f5) as a datum. Palaeocurrent data are from cross-bedding and parting lineation. The inset displays the location of the sections on the reconstructed basin outline and the lithostratigraphy of the sections studied.

**Table 1.** Summary description and interpretation of the facies associations recognized in this study.

| Facies association | Lithology and sedimentary structures | Thickness (m) | Cyclicity | TOC (%) | Interpretation |
|---|---|---|---|---|---|
| VF – volcaniclastic floodplain | Structureless reworked (dominant) and primary ash-fall tuffs and volcaniclastic sandstones. Rare wave and current ripples, palaeosols (silcrete). Common clastic dykes and large carbonate concretions. Massive volcaniclastic gravelly sandstones | 2–51 | | | Sub-aerial and sub-aqueous (shallow ponds) deposition of primary and reworked volcaniclastic sediments in a floodplain setting under semi-arid (?) climate. Common gravity flows |
| SL – saline lakes | *SL1 – shallow, mildly saline lake.* Thinly bedded variegated mudstones and sandstones, silicified micrite, tuffs, gypsum laminae. Dark claystone with organic remains (conchostracans, ostracods, ganoid fish scales, fish bones, plant fragments). Laminated siltstones or sandstones with rare wavy or trough cross-lamination and scattered clay cutans. Occasional mudcraked micrite with fossil footprints and clotted-peloidal or peloidal microtexture. Halite, dolomite, zeolites (identified by X-ray diffractometry) | 76 | Coarsening–shallowing upward cycles | 0·25 | Shallow, mildly saline lake with common and gradual water-level changes |
| | *SL2 – playa lake.* Dark mudstones with papery lamination, mudcracked dolomitic micrite and tetrapod footprints, thin sandstones, and gypsum laminae. Lower part of cycles shale-dominated and upper part micrite-dominated. Dolomitic micrite beds structureless or finely laminated with planar, undulating and lenticular laminae and ptygmatic, contorted crack infillings. Brecciated-nodular or clotted-peloidal microtexture. Unbridged and bridged sandstone crack infillings in mudstone. Calcite, zeolites (identified by X-ray diffractometry) | 63 | 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 deposits | Trough cross-bedded medium-grained to fine-grained sandstones, associated siltstone and mudstone with horizontal and trough cross-lamination. Basal erosive surface | 21 | Fining-upward (9–12 m thick) | | Fluvial non-deltaic channel and associated overbank deposits |

**Table 1.** (*Continued*)

| Facies association | Lithology and sedimentary structures | Thickness (m) | Cyclicity | TOC (%) | Interpretation |
|---|---|---|---|---|---|
| OL – offshore lacustrine | *OL1 – stratified freshwater lake.* Thick fossiliferous black shales with fine to very fine (papery) lamination interbedded with thin sideritic marlstone (and siderite concretions), green mudstone and tuffs. Shales lack carbonate and bioturbation, and display high C/S ratios (32 and 95, $n = 2$). Organic remains are concentrated in the lower third of each black shale interval and include fish remains (scales, bones and articulated posterior mid-body segments), plants, conchostracans, insects and the chlorophycean freshwater alga *Plaesiodictyon mosellanum* (Brenner & Foster, 1994) | 5–42 | | 1·0–2·84 ($n = 3$) | Pelagic/hemipelagic sedimentation in anoxic waters of the hypolimnion of a meromictic freshwater lake |
| | *OL2 – holomictic freshwater lake.* Thin to thick olive-green or brown fossiliferous shales, thin sideritic marlstone, siltstone and tuff interbeds. Brown shales always overlie or alternate with green shales | 1–17 | | | Offshore deposition in the epilimnion of a freshwater lake |
| DF – delta front + delta shelf | *DF1 – fluvial-dominated delta front.* Thick coarsening-upward and thickening-upward siltstone-dominated successions: laminated mudstones interbedded with thin siltstone laminae, passing upward to thin rhythmically graded laminated siltstone, and scarce wave-rippled fine-grained sandstone beds towards the top. Rare trough cross-lamination, water-escape structures, convolute lamination, and graded sandstone beds. Abundant plant and carbonaceous debris and mica flakes | 4–14 | Coarsening–thickening upward cycles | | Delta front and shelf of a fluvial-dominated delta lobe prograding on a freshwater lake. Dominant pulsatory sedimentation by land-derived, low-density turbidity currents. Low depositional slope |
| | *DF2 – wave-dominated delta front.* Thick coarsening-upward and thickening-upward siltstone-dominated successions with sandstone interbeds showing common wave and storm structures. Parallel-laminated, hummocky cross-stratified or wave ripple cross-laminated sandstones. Common thin sandstone-siltstone packages composed of parallel laminae with internal normal grading. Thick bedsets of hummocky cross-stratification and soft-sediment deformation structures are also recorded | 11–25 | Coarsening–thickening upward cycles | | Delta front and shelf of a wave-dominated delta prograding in an unstratified lake. Background sedimentation as underflow currents, punctuated by overflow currents and storm events |

**Table 1.** (*Continued*)

| Facies association | Lithology and sedimentary structures | Thickness (m) | Cyclicity | TOC (%) | Interpretation |
|---|---|---|---|---|---|
| DP – Delta plain | *DP1 – distributary channel sandstones.* Plano-convex sandbodies composed of thick trough cross-stratified sets of fine to medium-grained sandstone with soft-sediment deformation structures. Overlain by parallel-laminated siltstone and tuff, occasional poorly developed palaeosols with root traces overlain by thin coal horizons (0·03–0·25 m thick). The largest channel sandbody (a single-storey sheet sandstone) shows a central thicker area and two thinner wings, reaching a maximum width of about 1800 m (width/depth ratio < 150). Arkosic arenites with lithic volcanic grains (average composition $Q_{46}$ $F_{29}$ $L_{25}$) | 3–11 | Fining-upward cycles | | Fluvial distributary channels of moderate sinuosity, mixed-load type and low channel slope. Common avulsion |
| | *DP2 – crevasse or secondary channels.* Metre-scale sets of planar and trough cross-bedded medium to fine grained sandstones with soft-sediment deformation structures and reactivation surfaces. Overlain by wave-rippled fine-grained sandstones and parallel-laminated or lenticular-bedded dark mudstones with abundant plant remains. Occasional gently inclined, heterolithic accretion surfaces composed of fine-grained sandstone and siltstone with wavy and flaser bedding and carbonaceous mudstone laminae. Foreset beds dip at a high angle (70–110°) to the mean palaeocurrent direction (from distributary channels, DP1) | 3–20 | 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 and levée.* Crevasse delta: parallel-laminated dark mudstones and fine-grained sandstones with trough cross-lamination, wavy-bedding, climbing ripples, flaser bedding and occasional symmetrical ripples. Rare inclined heterolithic lateral accretion surfaces. Abundant plant remains and mica flakes. Levée: thin beds of ripple-laminated or flat-laminated sandstones interbedded with dark mudstones, logs and *in situ* tree stumps. Convexo-planar sandbodies with internal trough cross-lamination or lamination parallel to bed top | 2–10 | Coarsening-upward cycles (2–8 m thick) | | Crevasse deltas and levée deposits, which represent the infilling of shallow lakes of the delta plain by small deltas and laterally correlative deposits |

**Table 1.** (*Continued*)

| Facies association | Lithology and sedimentary structures | Thickness (m) | Cyclicity | TOC (%) | Interpretation |
|---|---|---|---|---|---|
| SD – shelf deltas and littoral lacustrine | *SD1 – wave-dominated littoral lacustrine.* Thick laminated and wave-rippled siltstone successions with sandstone interbeds and occasional graded heterolithic beds capped by parallel-laminated and wave-rippled sandstones and isolated hummocky lenses (convexo-planar, symmetrical sandstone bodies with a low aspect ratio; 2–30 m long and 0·07–0·4 m high). Laminated siltstone is arranged in tabular, inversely graded laminasets. Lithic volcanic arenites (average composition $Q_{29}$ $F_{14}$ $L_{57}$) | 50 | Occasional coarsening-upward 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 sub-aqueous, nearshore lacustrine setting. Background sedimentation from river-fed underflows |
| | *SD2 – shallow-shelf deltas.* Cycles composed of thin dark laminated claystone, thick succession of parallel-laminated, wave-rippled and current-rippled siltstone with interbedded fine-grained parallel-laminated sandstone and laminated or cross-laminated tuff; capping cross-bedded medium-grained sandstone. Occasional hummocky cross-stratification, soft-sediment deformation structures, and interference ripples. Lithic volcanic arenites (average composition $Q_{29}$ $F_{14}$ $L_{57}$) | 40 | Coarsening-upward (6–15 m thick) | | Progradation of small mouth bars in a shallow, low-energy lacustrine shelf. Sub-aqueous ash-fall deposits |

TOC = total inorganic carbon.

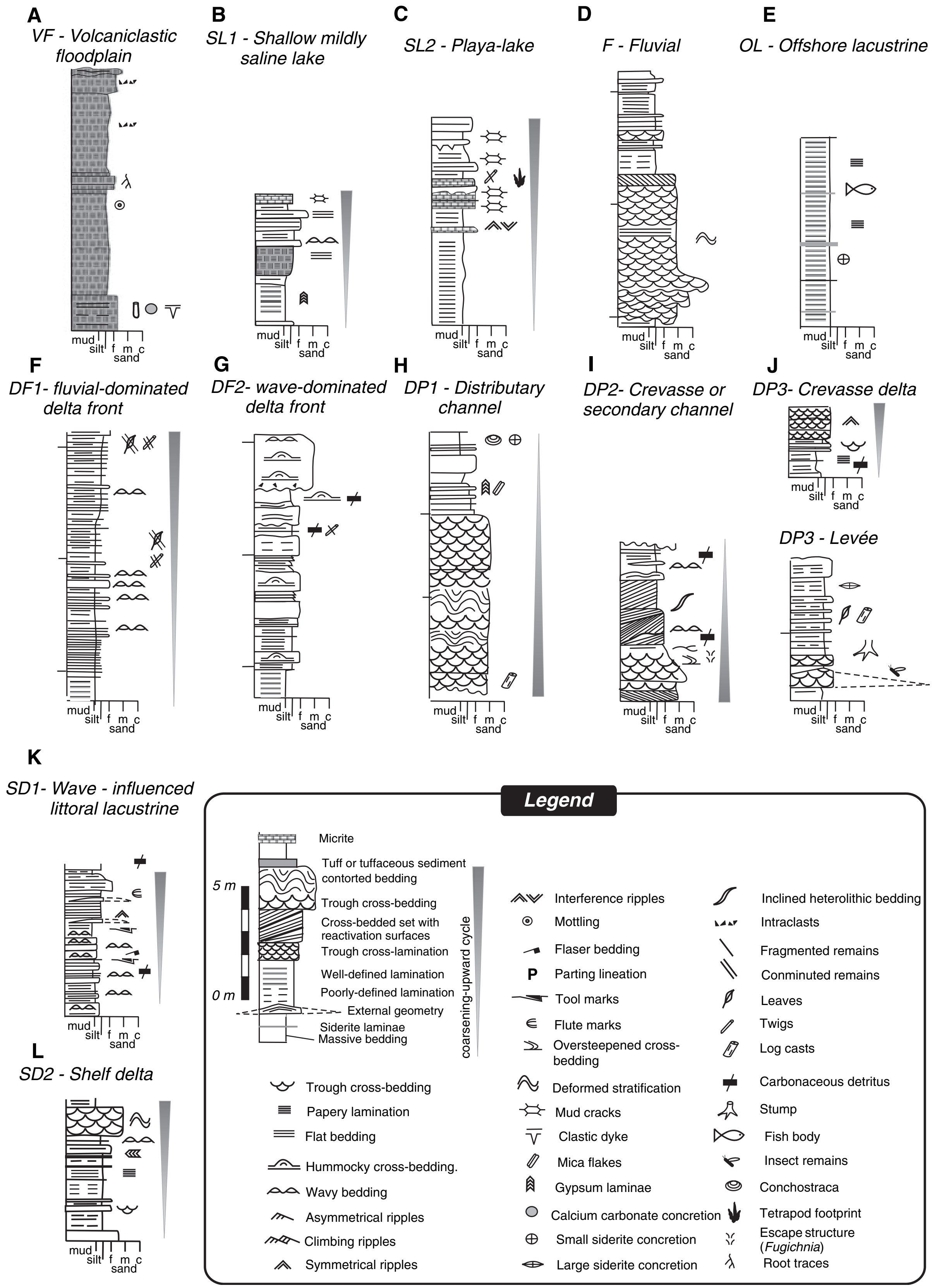



**Fig. 5.** Detailed graphic logs illustrating the characteristic features of each of the facies associations (see also Table 1 and text for discussion).

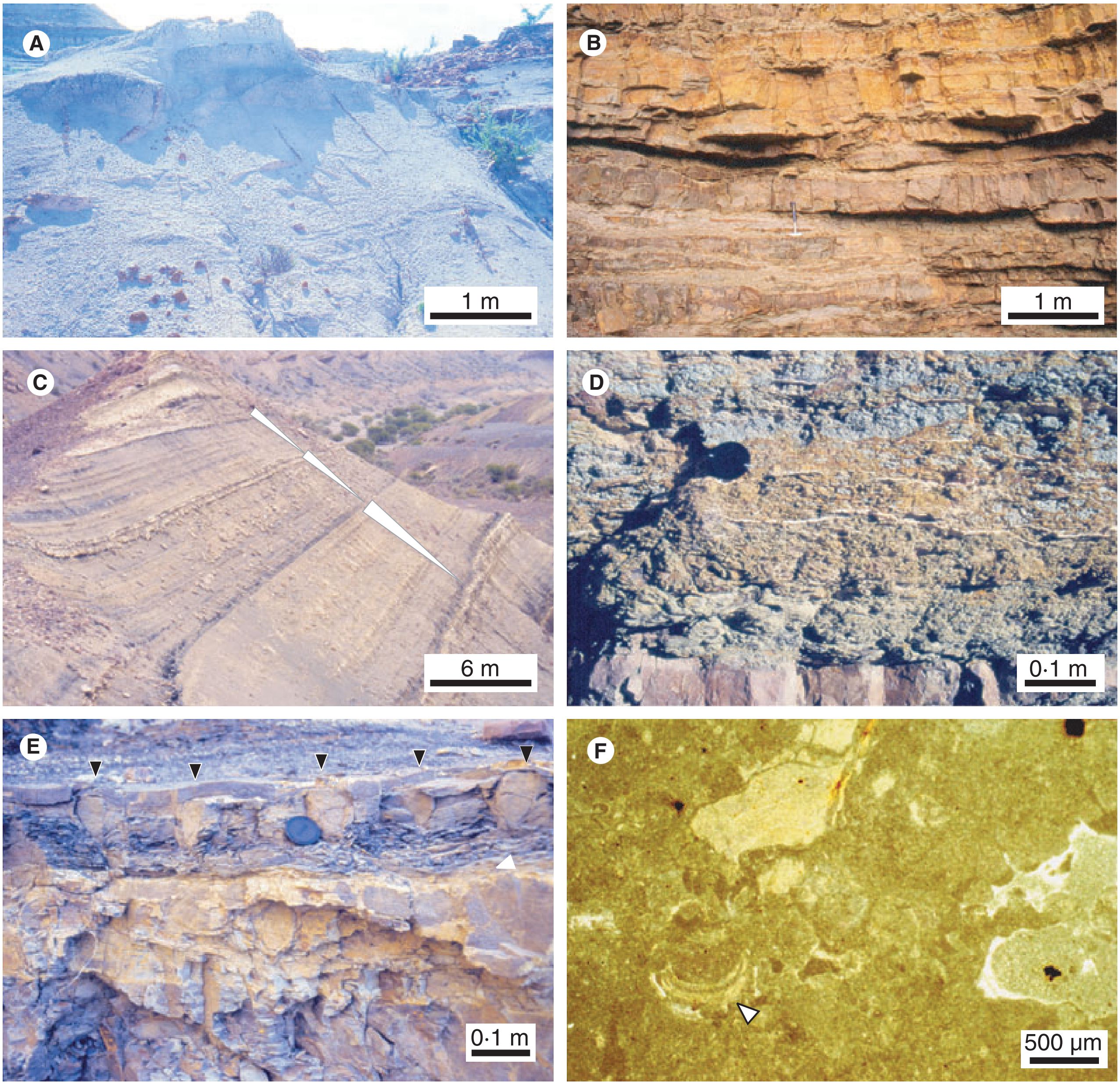



**Fig. 6.** Examples of the main facies associations. (A, B) Volcaniclastic floodplain (VF). (C, D) Shallow, mildly saline lake (SL1). (E, F) Playa lake (SL2). (A) Poorly bedded to massive tuffs and tuffaceous siltstones at Río Gualo (Fig. 3). (B) Well-bedded tuffs and tuffaceous sandstones with interbedded mudstones at Quebrada de Ischichuca. (C) General view of three complete shallowing-upward lacustrine cycles (triangles). (D) Close-up of variegated mudstones with poorly defined lamination and irregular gypsum laminae. (E) Close-up showing the gradual vertical passage from dark shales to dolomitic micrite (bed top indicated by a white arrow) and overlying dark shales with sand-filled wedges connected by a thin sandstone bed (bridged crack infillings), which are indicated by black arrows. (F) Photomicrograph of dolomitic micrite showing brecciated to clotted texture. Note crescentic laminated clay cement (arrowed).

(Fig. 6C and D). Coarsening-upward cycles reflect water-level changes, probably accompanied by marked variations in the surface area of the lake (Fig. 5B). Fine-grained sediments and tuffs were deposited mostly underwater in a low-energy environment and deposition of coarser sediments took place in shallower waters probably linked to unconfined sheetflooding and shoreline processes. Micrites were deposited in lake mudflats and display palustrine features (Armenteros & Daley, 1998) that suggest repeated wetting and drying of lacustrine carbonate mud.

*Perennial playa-lake facies association (SL2)*
Facies association SL2 is characterized by shallowing-upward cycles composed of dark mudstones with paper lamination overlain by mud-cracked dolomitic micrite (Fig. 5C). This facies association is interpreted as the product of sedimentation in a moderately deep, perennial playa lake surrounded by extensive dry mudflats (e.g. Hardie *et al.*, 1978; Roberts *et al.*, 1994), which suffered marked changes in lake level. The succession contains lithologic (dolomitic micrite, gypsum laminae, zeolites), stratigraphic (shallowing-upward cycles; Fig. 5C) and biologic (conchostracan and notostracan remains) features that point to arid/semi-arid climatic conditions. However, the occurrence of dolomite-calcite mixtures and scarce evaporites suggests that marked evaporative conditions were rarely achieved during deposition. Finely laminated dark mudstones indicate accumulation by settling from suspension on an oxygen-deficient lake bottom, pointing to probable water stratification due to salinity contrasts either as result of increased influx of fresh surface water (ectogenic meromixis) or saline groundwater input (e.g. Anderson *et al.*, 1985; Renaut & Tiercelin, 1994). Vertical sandstone crack infillings (Fig. 6E) are interpreted as desiccation cracks produced by exposure of water-saturated, lacustrine muds following lake-level draw down with later infilling by wind-blown or sheetflood sand (Hardie *et al.*, 1978; Allen, 1984: p. 545; Astin & Rogers, 1991; Rogers & Astin, 1991; Gierlowski-Kordesch & Rust, 1994). Additional evidence for repeated water-level changes are the palustrine dolomitic micrite (Fig. 6F), including brecciated-nodular and clotted-peloidal microtextures, which are considered to reflect repeated flooding and drying of lime mud (e.g. Smoot & Olsen, 1988, 1994; Armenteros & Daley, 1998; Freytet & Verrecchia, 2002).

The cycles recognized within this facies association (Fig. 5C) are comparable in lithologic composition, thickness and transgressive–regressive character to the Van Houten cycles recognized in the Newark Supergroup of eastern North America, which represent precession cycles of 21 kyr duration (Olsen, 1986, 1990).

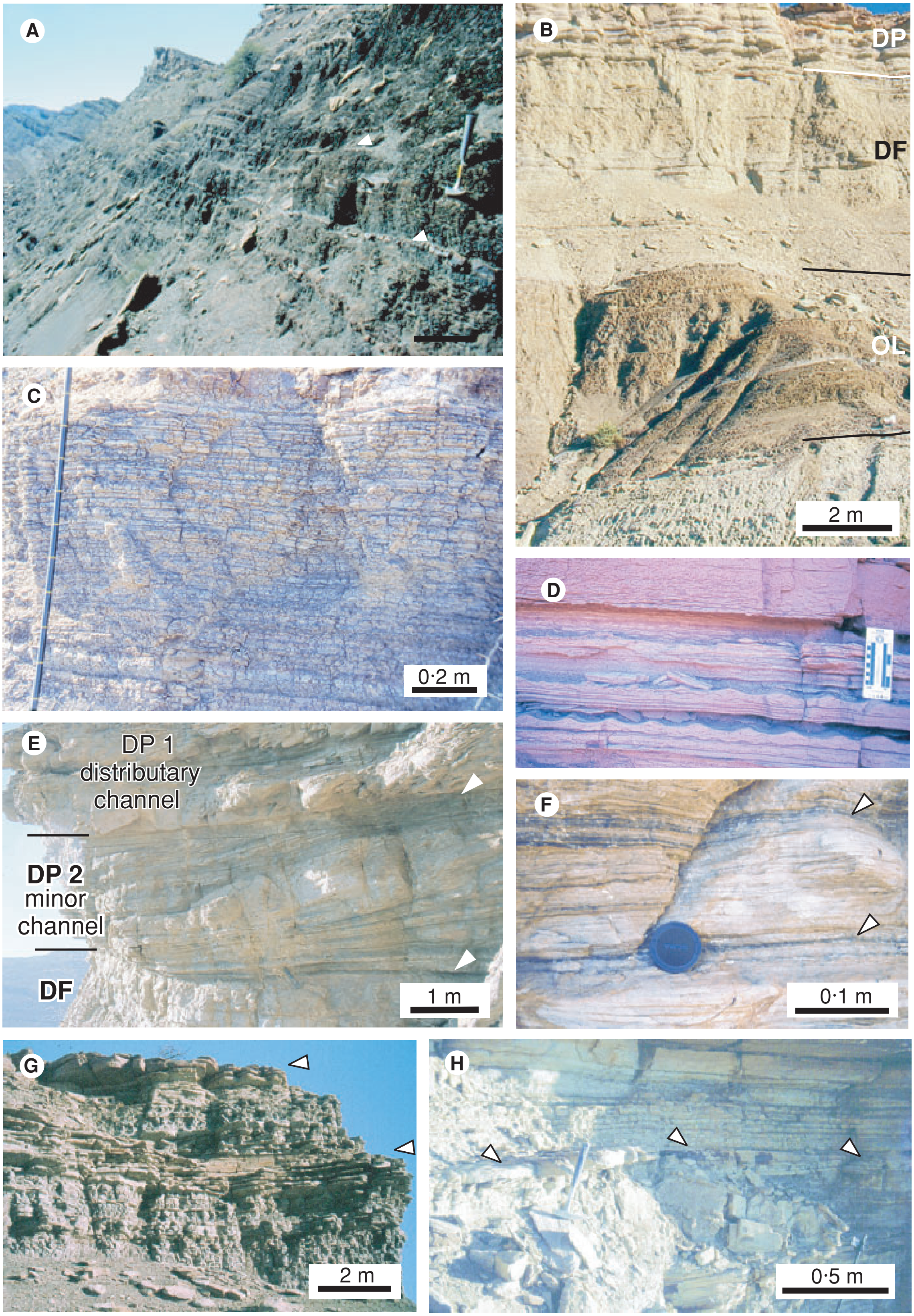
## Fluvial channel facies association (F)

The fluvial channel facies association was only recorded at the Río Gualo locality and is represented by a 21 m thick, fining-upward succession that overlies an erosive unconformity resting on the VF facies association (Fig. 5D). This facies association represents deposition in fluvial channels and adjacent floodplain ponds, as suggested by the general fining-upward tendency, bounding erosive surface and sedimentary structures. The channel-fill deposits are composed of quartzolithic sandstones with a significant amount of sand-sized ovolcanic clasts. The latter are basic to intermediate volcanics and might represent reworking of the deposits of the underlying VF facies association.

## OL facies associations

Offshore lacustrine (OL) facies associations are well represented in three of the localities studied (Fig. 4) and include stratified freshwater lake (OL1) and holomictic freshwater lake (OL2) facies associations. A lacustrine setting for these facies associations is inferred from the ubiquitous occurrence of Conchostraca (e.g. Tasch, 1969; Frank, 1988; Gray, 1988) and is in agreement with the abundance of plant remains, presence of insects, sedimentary structures and lithology (Table 1). A freshwater setting is indicated by the presence of the alga *Plaesiodictyon mosellanum* (Brenner & Foster, 1994; Zavattieri & Melchor, 1999) and by relatively high C/S ratios (cf. Berner & Raiswell, 1984). The main differences between the two facies associations are the thickness, colour and organic carbon content of the shales: OL1 is composed of thick, black paper shales with moderate to high organic carbon content, whereas OL2 comprises thinner intercalations of green or brown laminated shales with a lower organic content. Both facies associations are laterally correlative in the localities studied. This correlation and the common features between both facies associations suggest probable deposition in a single lake basin, both below (OL1) and above (OL2) the thermocline.

*Stratified freshwater lake facies association (OL1)*
The OL1 facies association is characterized by thick (up to 40 m thick) fossiliferous, monotonous black shale successions with fine to very fine (millimetre to sub-millimetre) lamination interbedded with thin sideritic marlstone laminae (Fig. 5E). This facies association only crops out at Quebrada de Ischichuca, where six stacked and laterally continuous dark shale intervals of uniform thickness were identified. These microlaminated black lacustrine shales (Fig. 7A) are pelagic/hemipelagic deposits that accumulated mostly by settling from suspension, below fair-


A
B
DP
DF
OL
2 m
C
0·2 m
D
E
DP 1
distributary
channel
DP 2
minor
channel
DF
1 m
F
0·1 m
G
2 m
H
0·5 m

weather wavebase in the absence of bottom-living burrowing invertebrates (e.g. Olsen, 1985; Talbot & Allen, 1996). The above-mentioned features indicate the prevalence of oxygen-deficient or anoxic bottom waters, which is common in permanently stratified (and probably deep) lakes (e.g. Demaison & Moore, 1980; Katz, 1995). This kind of lake usually sustains high surface productivity and occurs in warm, humid climate regimes with minimal seasonal contrasts (e.g. Talbot, 1988; Parrish, 1998). These features are in agreement with the palaeolatitude estimated from palaeomagnetic data (Prezzi *et al.*, 2001) and palaeoclimate information from vertebrate and plant remains (e.g. Bonaparte, 1969; Volkheimer, 1969; Artabe *et al.*, 1998) for the Ischigualasto–Villa Unión Basin. The absence of carbonate in the pelagic sediments suggests carbonate undersaturation in the lake waters or perhaps just in the hypolimnion during highstands, as is the case with Lake Malawi (e.g. Finney & Johnson, 1991; Pilskaln, 2004). The formation of sideritic marlstone laminae (Fig. 7A) and siderite concretions probably occurred in a thin zone of methane oxidation located close to the sediment surface during early diagenesis (Raiswell, 1988), which is favoured by low sulphate concentrations, high sedimentation rates and high organic carbon concentration (Curtis & Coleman, 1986; Mozley, 1989).

### *Holomictic freshwater lake facies association (OL2)*

The OL2 facies association is represented by olive-green or brown fossiliferous shale successions (up to 17 m thick), interbedded with sideritic marlstone, siltstone and tuff laminae (Fig. 5E). This facies association was deposited by settling from suspension of fine-grained detritus from well-mixed lake waters, in offshore settings. As mentioned above, it is considered probable that this facies association was deposited in the epilimnion of the same, large lake where the OL1 facies association was deposited, the latter representing deposition in the hypolimnion.

## Delta front and delta shelf facies associations (DF)

The delta front and delta shelf facies associations comprise coarsening-upward and thickening-upward siltstone-dominated successions. A distinction can be made between fluvial-dominated and wave-dominated deltas based mainly on the abundance of wave-generated structures in the delta front facies (Fig. 5F and G). In addition, distributary channel sandstones (DP1 facies association) are considerably thinner than the associated delta front facies (DF) in the case of the wave-dominated delta deposits (Table 2). The ratio between the thickness of distributary channel sandstones and DF facies in each delta lobe of wave-dominated, flexural-margin deltas (Río Gualo) is always lower than 0·2, whereas it is in the range of 0·35 to 0·95 for fluvial-dominated deltas emplaced in footwall or flexural margins (Quebrada de Ischichuca and La Torre).

### *Delta front and delta shelf in fluvial-dominated deltas (DF1)*

The DF1 facies association is composed of 4 to 14 m thick, coarsening-upward and thickening-upward siltstone-dominated successions with interbedded sandstone beds lacking a significant amount of wave-generated or storm-generated structures (Fig. 5F). This facies association displays a basal transition to OL (offshore lacustrine shales, both OL1 and OL2) and is truncated at the

**Fig. 7.** Outcrop examples of main facies associations. (A, B) Offshore lacustrine (OL). (C, D) Delta front (DF). (E, F) Delta plain (DP). (G, H) Shelf deltas and littoral lacustrine (SD). (A) Monotonous succession of finely laminated black shales with marlstone intercalations (indicated by arrows) from SS3 at Quebrada de Ischichuca locality. Hammer for scale is 0.35 m long. (B) Succession of offshore lacustrine (OL), delta front (DF) and delta plain (DP) facies associations from a wave-dominated delta of SS3 at Río Gualo. (C) Thinly bedded, siltstone-dominated deposits (land-derived density flows) from the delta front of a river-dominated delta deposit (SS2) at Quebrada de Ischichuca. (D) Wave-rippled siltstones and sandstones from upper delta front deposits at La Torre belonging to SS3. The scale is 0.1 m. (E) Deposits of crevasse or secondary channels (DP2) showing lateral accretion surfaces (bracketed by arrows) overlain by coarse-grained distributary channel sandstones (DP1). Example from SS2 at Quebrada de Ischichuca. (F) Detail of the previous figure showing bedding in the interval with lateral accretion surfaces (bracketed by arrows) showing bed composed of fine-grained sandstone and siltstone with wavy-bedding and carbonaceous mudstone interbeds. (G) Two shallowing-upward and coarsening-upward cycles composed of laminated siltstone and wave-rippled or parallel laminated sandstones (SD2 facies association) from SS4 at Quebrada de Ischichuca. White arrows indicate the top of each cycle. (H) Convexo-planar, isolated hummocky lens (SD1 facies association) from SS4 at Quebrada de Ischichuca. Top of lens indicated by arrows.

**Table 2.** Thickness of distributary channel sandstones in comparison with associated delta front facies association for fluvial-dominated and wave-dominated deltas for the different studied sections.

| Delta type | DP1 (m) | DF (m) | DP1/DF |
|---|---|---|---|
| *Fluvial dominated deltas* | | | |
| Quebrada de Ischichuca | | | |
| | 7·6 | 11·4 | 0·67 |
| | 5·2 | 7·0 | 0·74 |
| | 8·4 | 8·8 | 0·95 |
| La Torre | | | |
| | 5·5 | 16·2 | 0·34 |
| | 4·4 | 12 | 0·37 |
| *Wave-dominated delta* | | | |
| Río Gualo | | | |
| | 3·0 | 17·4 | 0·17 |
| | 4·0 | 24·6 | 0·16 |
| | 1·5 | 11·3 | 0·13 |

DP1, distributary channel sandstones; DF, delta front and shelf.

top by DP1 (distributary channel sandstones) or has a gradual passage to DP2 or DP3 (interdistributary bay deposits; Fig. 7B). The presence of thinly bedded, well-sorted siltstones, showing graded laminae with abundant mica flakes and plant debris (Fig. 7C) attest to land-derived density flows with low sediment concentrations, probably surge-like turbidity currents (Mulder & Alexander, 2001). Related facies suggest deposition in a distal deltaic lobe setting as hyperpycnal flows of fluvial origin (e.g. Bates, 1953; Mulder & Alexander, 2001). Graded sandstone beds either represent turbidity-flow deposits resulting from catastrophic floods or are linked to suspension clouds generated by storms. The depositional slope on the delta front was probably low, by analogy with sandy foresets prograding into standing freshwater elsewhere (e.g. Kostic *et al.*, 2002) and the shelf deltas of Lake Malawi (Johnson *et al.*, 1995). In the case of the Ischigualasto-Villa Unión Basin, this inference is supported by: (i) the parallelism and considerable lateral extent of bedding and lamination; (ii) the transitional passage to underlying black shales; (iii) the scarcity of soft sediment deformation structures; and (iv) the lack of significant scouring by coarse-grained sediments. Comparison with possible modern analogues (the flexural margin shelf deltas of Lake Malawi; Johnson *et al.*, 1995) suggests that the DF facies association would include the toe of slope of the deltaic shelf (thick siltstone succession) and intermediate and upper part of the delta front (coarser-grained interval).

*Delta front and delta shelf of wave-dominated deltas (DF2)*
The DF2 facies association includes coarsening-upward and thickening-upward siltstone-dominated successions with sandstone interbeds that are considerably thicker (11 to 25 m thick) and displays greater influence of oscillatory flows than those of the DF1 facies association (Fig. 5D). Facies association DF2 was only identified at Río Gualo. DF2 represents a delta front and its basinward extension as a wave-dominated delta lobe that prograded into well-mixed lake waters, as suggested by the accompanying OL2 facies association. Finely laminated graded beds, which are interpreted as underflow deposits, represent the background sedimentation in a well-oxygenated setting. Between underflow events, finer-grained overflow sediments settled and were reworked by oscillatory flows. Deposition of coarse-grained sediments during occasional high-energy storm events (hummocky cross-stratified beds) punctuated background sedimentation.

## Delta plain facies associations (DP)

The delta plain facies associations include distributary channel sandstones (DP1), crevasse or secondary channels (DP2) and crevasse deltas and levées (DP3). DP facies associations generally overlie DF (delta front and shelf) and are covered by the OL (offshore lacustrine shales) facies associations. As illustrated in Fig. 8, distributary channel sandbodies (DP1) are scoured into and display lateral transitions to interdistributary bay deposits (DP2 and DP3). DP facies associations are composed of a tabular intercalation between finer-grained sediments of offshore lacustrine and coarser-grained delta front facies associations (Fig. 9A and B). At some horizons, distributary channel deposits (DP1) sharply overlie laminated shales (OL) and contain scattered slump and mass-flow deposits.

*Distributary channel sandstones (DP1)*
The DP1 facies association is typically composed of plano-convex sandbodies showing thick sets of fine-grained to medium-grained trough cross-stratified sandstone (Fig. 5H). This facies association displays sedimentary structures, sandbody geometries and stratigraphic relationships that characterize distributary channels in a delta-plain setting (e.g. Elliot, 1986; Figs 5H, 8 and 9B); it is more thickly developed in association with the deposits of fluvial-dominated deltas at Quebrada

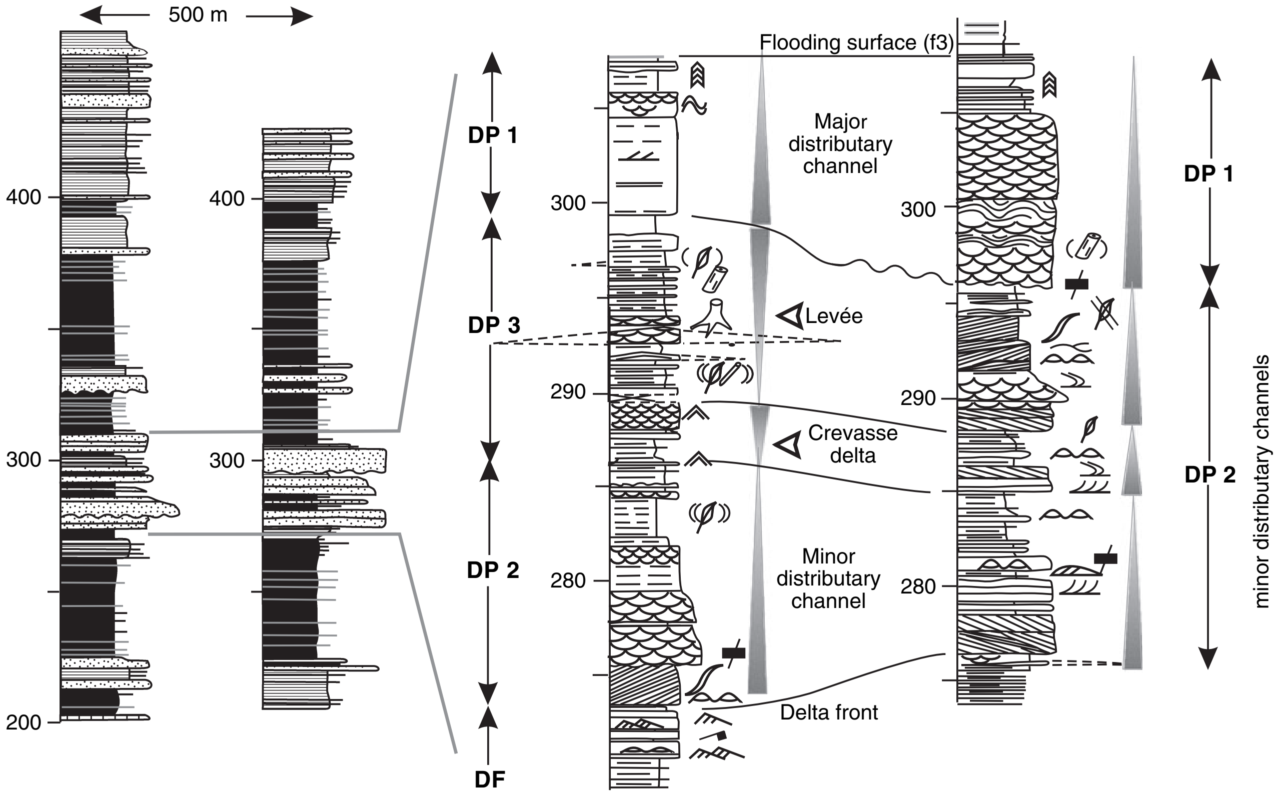



**Fig. 8.** Detail of lateral correlation and interpretation of relationships between distributary channel sandstones (DP1), crevasse or secondary channels (DP2), and crevasse deltas plus levée deposits (DP3) for two laterally equivalent sections measured at Quebrada de Ischichuca in SS2. Legend as for Fig. 5.

de Ischichuca. Here, the relatively high apparent channel width/depth ratio, the large variability of palaeoflow indicators, the sandbody geometry, and the dominant grain-size are indicative of laterally unstable channels of moderate sinuosity, probably of the mixed-load type (Hirst, 1991; Orton & Reading, 1993). The largest channel observed at Quebrada de Ischichuca (Fig. 9A and B) is encased in finer-grained delta plain sediments, which is suggestive of repeated shifting by avulsion (Orton & Reading, 1993), probably as a consequence of lobe progradation (Jones & Schumm, 1999). Large channel width/depth ratio indicates a reduced channel slope. The fine-grained deposits that cap the channel fills are interpreted as abandonment deposits (including poorly developed palaeosols and thin coal beds), which are sharply overlain by black shales, reflecting lobe inundation. Channel sandstones are arkosic arenites with abundant plagioclase grains ($Q_{41-52}$ $F_{24-26}$ $L_{23-28}$, $n = 5$).

*Crevasse or secondary channels (DP2)*

The DP2 facies association contains fining-upward, metre-scale cycles composed of cross-bedded sandstones overlain by fine-grained rocks which are suggestive of fluvial sedimentation (Fig. 5I). Vertical and lateral facies relationships indicate deposition in minor delta plain channels (Fig. 8). Each fining-upward cycle represents sedimentation in a crevasse channel (cf. Elliot, 1986) as suggested by the presence of common reactivation surfaces and lateral correlation with crevasse deltas and levée deposits (DP3 facies association; Fig. 8). These minor channels were dominated by lateral accretion on point bars (Fig. 7E). Relatively thin fining-upward cycles also point to frequent avulsions, as is common in many deltaic distributary channels (e.g. Elliot, 1986; Wells *et al.*, 1994). Upon abandonment, the channel was infilled by interdistributary bay muds with abundant plant debris and reworked by low-energy oscillatory flows (Fig. 7F).

*Crevasse deltas and levées (DP3)*

The DP3 facies association comprises thinly bedded heterolithic and cross-laminated facies arranged in metre-scale coarsening-upward cycles (Fig. 5J). Related facies associations and sedimentary features (e.g. abundant wave and

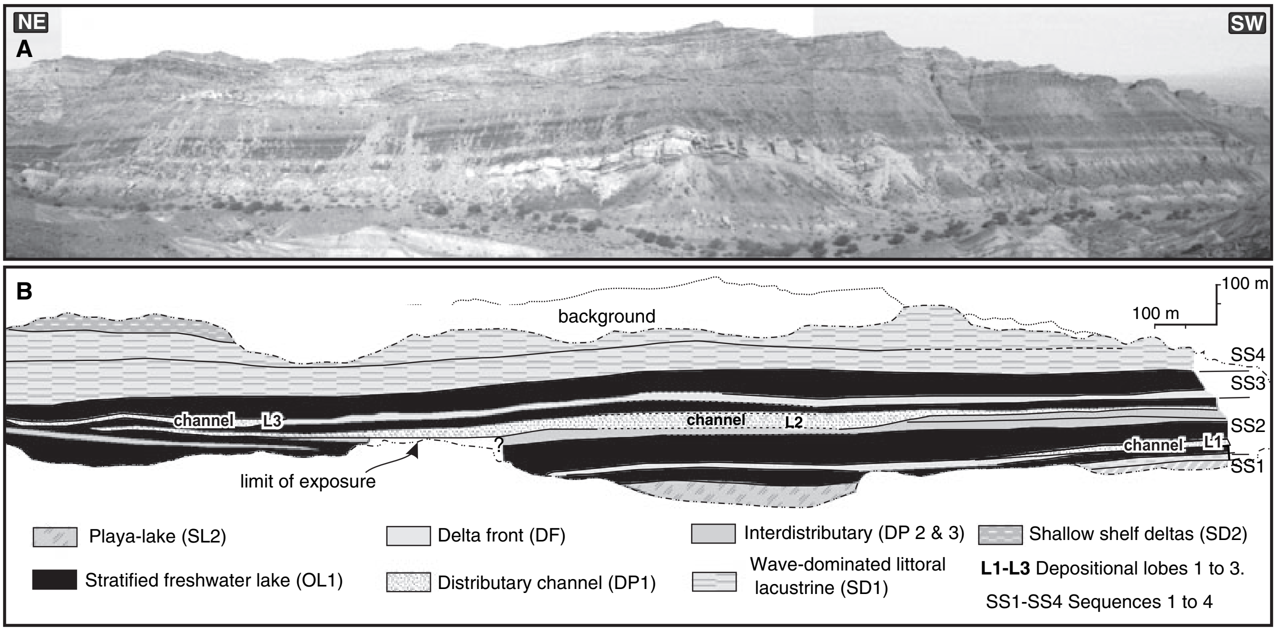



**Fig. 9.** Geometry, facies associations and stratigraphic relationships of part of the lacustrine package at Quebrada de Ischichuca. (A) Photomosaic of the SE flank of the Quebrada de Ischichuca. Note resistant whitish beds in the centre of the mosaic (second delta lobe of SS2) and tabular geometry of darker intervals (black shales of OL1 facies association). Orientation of the outcrop is N25°E, which is roughly perpendicular to the mean palaeocurrent direction (compare Fig. 4). (B) Interpretative drawing of mosaic distinguishing between the different facies associations. Note apparent change of channel position in successive delta lobes (L1–L3) and the interval corresponding to each sequence (SS1–SS4).

climbing ripples, heterolithic lithology, *in situ* tree stumps) of the DP3 facies association suggest deposition in interdistributary bays in a delta plain environment (Figs 5J and 8). The crevasse delta deposits might represent the infilling of shallow lakes by small deltas. Levée deposits correspond to fine-grained sediments marginal to crevasse channels that were sub-aerially exposed and colonized by plants. Small associated convexo-planar sandbodies (Fig. 5J) are distinctive and probably represent small crevasse lobes, which are an important component of deltaic levée successions (Elliot, 1986). Levée deposits are laterally correlated with crevasse channel sediments (Fig. 8).

## Shelf delta and littoral lacustrine facies associations (SD)

The SD facies associations are typified by thick (up to 50 m) siltstone-dominated successions with current and wave structures interbedded with parallel-laminated and wave-rippled sandstones (Fig. 5K and L). These facies associations were mostly encountered in the uppermost part of the section measured at Quebrada de Ischichuca (Fig. 4). A comparison with the underlying facies associations (DF–DP; Fig. 4) suggests a change of mean palaeotransport direction and provenance. The coarser-grained sandstones from the SD facies association are lithic volcanic arenites ($Q_{24-36}$ $F_{8-22}$ $L_{50-64}$, $n = 5$). These changes are interpreted as reflecting a major modification in basin configuration, as discussed below.

### *Wave-dominated littoral lacustrine facies association (SD1)*

The wave-dominated littoral lacustrine facies association (SD1) is distinguished from the similar siltstone-dominated delta front and delta shelf facies associations (DF) by: (i) a greater proportion of sandstone (40% against 13%) and a reduced amount of claystone; (ii) the presence of hummocky lenses, parallel-laminated sandstone beds and heterolithic beds; and (iii) the absence of an upward transition to DP2 and DP3 facies associations (interdistributary bay deposits). The sandstones are volcanic-derived lithic arenites with abundant plagioclase grains, contrasting with the composition of the underlying delta plain facies associations (DP), which are arkosic arenites.

Deposition of SD1 was influenced by oscillatory and combined flows in a permanently sub-aqueous, nearshore lacustrine setting. Coarsening-upward cycles of SD1 are interpreted as shallowing-upward successions representing progradation of high-energy nearshore sediments over lower-energy offshore lacustrine sediments (Figs 5K and 7G). The background sedimentation corresponds to siltstone-dominated intervals. Inversely graded and wave-influenced siltstone lamina sets are interpreted as quasi-steady or waxing hyperpycnal turbidity current deposits (Mulder & Alexander, 2001). The interbedded sandstone beds represent density flows of higher sediment concentration and claystone partings correspond to deposition from interflow/overflow currents. Parallel-laminated sandstone beds were deposited by high-energy combined flows, as suggested by the common association with hummocky lenses (Fig. 7H). The latter structures are comparable with anisotropic hummocky cross-stratification (Midtgaard, 1996), which is linked to deposition from oscillatory-dominant combined flow with a slightly stronger unidirectional flow component. Eyles & Clark (1986) and Martel & Gibling (1991) reported the presence of hummocky lenses in lacustrine deposits – similar to those reported herein – and interpreted them as reflecting sediment starvation.

*Shallow shelf delta facies association (SD2)*

The SD2 facies association comprises coarsening-upward cycles composed of thin dark claystone, thick laminated siltstone and cross-bedded, medium-grained sandstone (Fig. 5L). Each cycle is interpreted as the record of progradation of small deltas into a shallow lake. Finely laminated claystones represent sedimentation from settling in an open lake; these were succeeded by silty deposits of sub-aqueous mouth bars, and occasional thinly laminated siltstone intervals related to dilute river plumes. Sandstone beds dominated by planar lamination were produced by friction-dominated river flows in moderately shallow water. Partial modification or complete reworking of sandstone beds by waves and occasional storm events indicates deposition above wavebase and moderate to strong lake basin energy. The accumulation of fine-grained tuffs or tuffaceous sediments with cross-lamination is interpreted as sub-aqueous ash-fall deposits, partially reworked by currents and mixed with epiclastic sediment. SD2 cycles are similar to those described by Melchor *et al.* (2003) for the Los Rastros Formation at Ischigualasto Park.

## CORRELATION OF SECTIONS

The sections were correlated using three types of stratigraphic surface: (i) the unconformity between the Tarjados and Chañares formations; (ii) lacustrine flooding surfaces; and (iii) a forced regressive surface (Fig. 4). Aside from lacustrine flooding surfaces f2 to f5 (Fig. 4), the correlated horizons are considered to be sequence boundaries because they mark a sharp change in lithofacies that can be correlated regionally and attributed to the end of periods of base-level fall or an increase in the rate of lake deepening (Van Wagoner *et al.*, 1988, 1990; Christie-Blick, 1991). Four tectonostratigraphic sequences are recognized, SS1 to SS4 from base to top. The expression of sequence boundaries in fault-controlled rift basins is complicated because subsidence may outstrip the rate of base-level fall in parts of the basin. The sequence boundary will be expressed here as an increase in the rate of deepening rather than a basinward shift in facies (e.g. Emery & Myers, 1996). Thus the base of SS1 is marked by the presence of incised fluvial channels only in the hangingwall (Río Gualo), and the base of SS2 coincides with a flooding surface (f1) which places deep lacustrine facies (OL2) on top of fluvial channel facies (F) at Río Gualo, and offshore lacustrine (OL1) on saline lacustrine (SL2) at Quebrada de Ischichuca.

The lowermost stratigraphic surface is the unconformity between the Tarjados and Chañares formations (Fig. 4), marked by the contact between red, coarse-grained sandstones with pedogenic features (top of the Tarjados Formation) and grey, massive pyroclastic deposits (base of the Chañares Formation). The upper 10 to 15 m of the Tarjados Formation shows pedogenic features throughout the basin, although the type and development of the palaeosols change laterally. The topmost palaeosol varies between a well-developed silicified calcrete (Río Gualo), a moderately developed silcrete with abundant siliceous rhizoliths (Cerro Morado), a well-developed calcrete (La Torre), and scattered siliceous rhizoliths (Quebrada de Ischichuca). The greater degree of development of palaeosols on the eastern flexural margin localities (Río Gualo, Cerro Morado and La Torre) compared with the the footwall margin (Quebrada de Ischichuca) suggest that a disconformity on the flexural margin can be traced with a correlative conformity near the border fault margin.

Lacustrine flooding surfaces (f1–f5; Fig. 4) are distinguished by the sharp superposition of lacustrine shales (OL facies association) over coarser-grained sediments and are traceable between the footwall and flexural margin of the half-graben (Fig. 4). Most flooding surfaces represent the contact between lacustrine shales and underlying fluvial cross-bedded sandstone or palaeosols (DP1 facies association). Thin impure coals may underlie the contact and the first few metres of the lacustrine shale above the flooding surface commonly contain a greater amount of organic remains (including plant, insect and fish remains, and conchostracans). In particular, the first flooding surface (f1) is represented by the inferred basinward onlap of offshore lacustrine black shales (OL) onto saline lake, fluvial or volcaniclastic floodplain facies associations (SL, F and VF), depending on the section considered. This surface coincides with a sequence boundary (SB2) and is considered to be more significant than the other lacustrine flooding surfaces as it marks a major expansion of the lake basin.

A single forced regressive surface at the base of SS3 is marked by the erosive superposition of distributary channel sandstones (DP1 facies association) on offshore lacustrine shales (OL) in all localities studied. The coarser-grained DP1 facies association lying above the forced regressive surface displays deformational features and mass-flow deposits.

## BASIN FILL HISTORY

### Depositional dynamics and sequence stratigraphic evolution

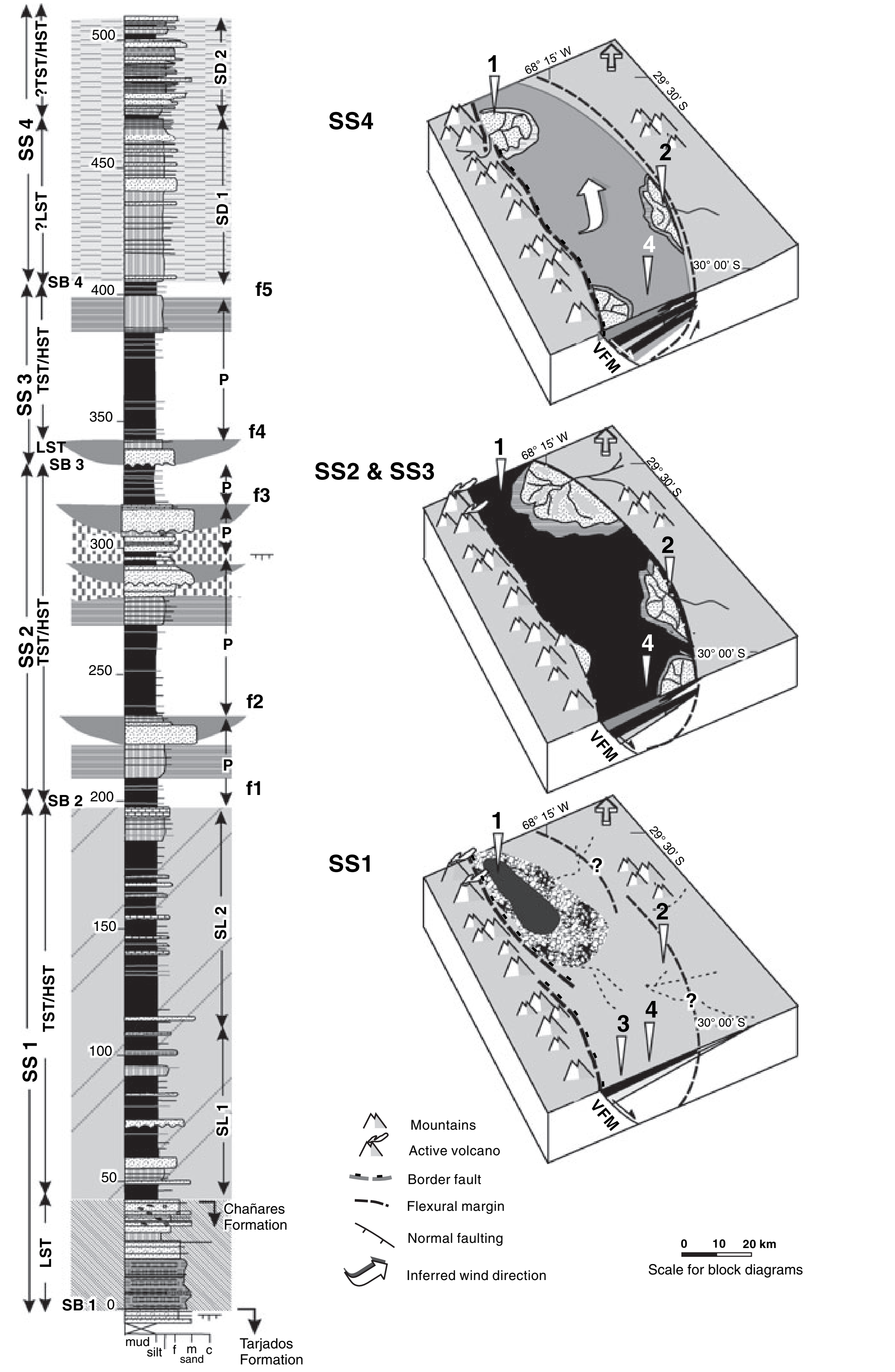
The analysis of the available sedimentologic and stratigraphic information on the lacustrine-dominated fill of the Ischigualasto–Villa Unión Basin permits the recognition of four tectonostratigraphic sequences which correspond to four major episodes of synrift sedimentation. The palaeogeographic evolution for the package studied along with inferred lake-level changes and the sequence stratigraphic framework are illustrated in Fig. 10 and summarized in Table 3.

#### *SS1: Pyroclastic eruptions, low-energy shallow lakes, and flexural margin rivers (VF, SL and F facies associations)*

The first sequence boundary (SB1) separates the red beds of the Tarjados Formation from the overlying VF facies association (Chañares Formation). The lower sequence (SS1) includes the deposition of abundant pyroclastic deposits that were reworked in alluvial settings (VF facies association). Fluvial sedimentation (F facies association) became more localized and occurred lateral to two kinds of low-energy shallow lakes (shallow mildly saline lake and perennial playa lake of SL facies associations). This sequence is thicker (197 m) along the northern footwall margin and thins out (to 2 m) on the southern part of the flexural margin (Fig. 4). The VF and F facies associations represent the lowstand deposits of the first sequence. The inclusion of the fluvial deposits (F facies association) in the lowstand wedge is tentative and based on sedimentary features and on the correlation of the upper and lower bounding surfaces (Fig. 4). The VF facies association displays similar thickness in three of the localities studied, although it is poorly developed along the southern part of the flexural margin. This difference is related to a combination of erosion and a low rate of accommodation creation. Similarly, the character of the VF facies association changes from NW to SE (Fig. 4; Table 3). Predominantly sub-aqueous deposits were found in the northern footwall margin (Quebrada de Ischichuca), mixed sub-aqueous and sub-aerial deposition with poorly developed palaeosols on the flexural margin to the east (Río Gualo) and dominantly sub-aerial deposition with better-developed palaeosols on the flexural margin to the south (Cerro Morado). The upper part of the lowstand wedge (VF facies association) contains shallow lacustrine deposits (Río Gualo and Quebrada de Ischichuca) and gravity-flow deposits (Quebrada de Ischichuca), suggesting the transition to transgressive/highstand deposits. The latter are represented by two types of saline lake deposits (SL facies associations). The first type of lake was shallow, mildly saline, and dominated by fine-grained clastic sedimentation (SL1 facies association). The lake was hydrologically

**Fig. 10.** Sequence stratigraphy superimposed on summary lithologic succession from Quebrada de Ischichuca, and block diagrams illustrating the palaeoenvironmental and palaeogeographic evolution of the studied lacustrine basin fill. 1, Quebrada de Ischichuca; 2, Río Gualo; 3, Cerro Morado; 4, La Torre; VFM, Valle Fértil Megafracture (border fault zone); LST, lowstand system tract; TST, transgressive system tract; HST, highstand system tract; SB, sequence boundary; f, lacustrine flooding surface; P, parasequence. Key as for Fig. 5.



SS 4
?TST/HST
?LST
SB 4
SS 3
TST/HST
LST
SB 3
SS 2
TST/HST
SB 2
SS 1
TST/HST
LST
SB 1
500
450
400
350
300
250
200
150
100
50
0
SD 2
SD 1
P
SL 2
SL 1
f5
f4
f3
f2
f1
Chañares Formation
Tarjados Formation
mud
silt
f
m
c
sand
SS4
SS2 & SS3
SS1
1
2
3
4
68° 15' W
29° 30' S
30° 00' S
VFM
?
Mountains
Active volcano
Border fault
Flexural margin
Normal faulting
Inferred wind direction
0
10
20 km
Scale for block diagrams

**Table 3.** Summary of stratigraphic, palaeoenvironmental, palaeoclimatic and tectonic evolution of the studied lacustrine-dominated interval in the Ischigualasto-Villa Unión Basin (see also Fig. 10).

| Sequence stratigraphy | | Depositional systems: North-western footwall (1) | Eastern flexural (2) | Southern flexural (3, 4) | Hydrology | Accommodation and supply | Source area | Palaeoclimatic conditions | Tectonism |
|---|---|---|---|---|---|---|---|---|---|
| SS1 | LST | Sub-aqueous pyroclastic fall & volcaniclastic gravity flow deposits | Sub-aerial pyroclastic floodplain (palaeosols) and ponds, unconformably overlain by fluvial deposits | Mostly sub-aerial pyroclastic floodplain (silcrete) | Closed basin, increased sedimentation close to footwall | Underfilled. Low accommodation. Low clastic supply | Unknown | Semi-arid? | Early synrift |
| | TST/HST | Shallow mildly saline lake | Missing? | Missing | Basin closure. Gradual water-level changes. Temporary water stratification | | Unknown | Semi-arid? | Early synrift. Incipient subsidence |
| | | Perennial playa-lake and dry mudflats | Missing? | Missing | Temporary basin closure or groundwater-fed through-flow basin. Abrupt water-level changes. Saline water stratification | | From flexural margin (?) | Semi-arid? | Early synrift. Incipient subsidence |
| SS2 | TST/HST | Hypolimnion of meromictic lake and fluvial-dominated deltas | Epilimnion of meromictic lake and wave-dominated deltas | Epilimnion of meromictic lake and river-dominated deltas | Basin closure. Water stratification | Balanced fill. High accommodation. Low to moderate clastic supply | From flexural or axial margin (E or SE). Arkosic sandstones | Warm and humid. Low wind strength | Early synrift. Increased subsidence |
| SS3 | LST<br>TST/HST | | | | | | | | |

**Table 3.** (*Continued*)

| Sequence stratigraphy | | Depositional systems: North-western footwall (1) | Eastern flexural (2) | Southern flexural (3, 4) | Hydrology | Accommodation and supply | Source area | Palaeoclimatic conditions | Tectonism |
|---|---|---|---|---|---|---|---|---|---|
| SS4 | LST (TST/HST?) | Shallow shelf deltas and wave-dominated littoral deposits | Shallow deltas | Shallow deltas | Open basin. No water stratification | Overfilled. Low accommodation. Moderate clastic supply | From footwall margin (SW). Relay ramps or antecedent drainage as sediment routes. Lithic volcanic arenites | Moderate to high wind strength | Late synrift to post-rift. Reduced footwall margin uplift. Provenance and palaeo current change |

SS, stratigraphic sequences; LST, lowstand system tract; TST/HST, transgressive & highstand system tracks; 1, Quebrada de Ischichuca; 2, Río Gualo; 3, Cerro Morado; 4, La Torre.

closed and might have developed temporary stratification. Lake-level changes were gradual and probably accompanied by variations in lake salinity/alkalinity. The passage to the second type of saline lake (SL2 facies association) is marked by a gradual increase in the proportion of dark shales and dolomitic carbonate beds, and repeated evidence for sub-aerial exposure and desiccation. The setting where the SL2 facies association was deposited is envisaged as a playa lake surrounded by dry mudflats. Basin-centre deposits record the aggradational stacking of moderately organic-rich dark muds during lake flooding and dolomitic mud plus scarce evaporite minerals during lake desiccation. The changes in water level were frequent and marked, as inferred from the abundance of sandstone-filled cracks encased in laminated black shales. 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 minor preservation of evaporites suggests that the playa lake suffered only temporary hydrological closure or was a groundwater-fed, through-flow playa basin (Rosen, 1994).

### *SS2: Stratified freshwater lakes and highstand deltas (OL, DF, DP)*

A second sequence boundary (SB2) coincides with the onset of widespread freshwater lacustrine sedimentation in the basin and is distinguished by offshore lacustrine shales (OL) that onlap onto saline lake, fluvial or volcaniclastic floodplain facies associations (SL, F and VF), depending on the position within the basin (Fig. 4). SS2 also displays thickness changes (40 to 135 m) and is divided by lacustrine flooding surfaces (f2–f3; Fig. 4) into a series of 12 to 80 m thick, shallowing-upward parasequences. Each parasequence is composed of OL, DF and DP facies associations, in ascending order. The second sequence is mostly interpreted as transgressive/highstand deposits because of the dominance of lacustrine shales and the progadational stacking of parasequences (Legarreta *et al.*, 1993). The greater amount of organic remains above the lacustrine flooding surface probably reflects stratigraphic condensation during transgression.

The architecture of this sequence can be observed at Quebrada de Ischichuca, where large outcrops are available with a strike roughly perpendicular to the mean palaeocurrent direction, which is towards the NW (Fig. 9). At this location, delta front and delta plain facies associations (DF, DP) form 10 to 42 m thick depositional lobes with a lens-shaped cross-section separated by 13 to 40 m thick tabular black shale intervals (Fig. 9A and B). Each of the lobes contains a single plano-convex channel sandbody showing prominent wings encased in delta plain and delta front facies (Fig. 9B). Three deltaic lobes can be recognized in the sections analysed. These lobes change position upsection towards the NE (Fig. 9B). The largest depositional lobe (L2 in Fig. 9B) is up to 42 m thick and at least 3 km wide. These dimensions compare favourably with the lowstand lobes of the Dwangwa delta, which is the largest of the flexural margin deltas of Lake Malawi (Scholz, 1995).

The second sequence reflects sedimentation in a meromictic and freshwater lake (OL) associated with the development of fluvial-dominated and wave-dominated deltas (DF, DP; Fig. 10). Lake processes varied across the basin. In the area close to the footwall (Quebrada de Ischichuca), laminated black shale was deposited in anoxic bottom waters, which favoured the preservation of organic matter (OL1 facies association). The common presence of early diagenetic siderite also points to strongly reducing conditions, at least below the sediment–water interface. Along the flexural margin of the half-graben to the east and south, offshore lacustrine shales are olive green and have a lower organic carbon content (OL2 facies association). The implied lateral correlation between OL1 and OL2 facies associations and the location of the latter on the flexural margin of the basin suggests OL2 was deposited in well-mixed, oxygenated waters of the epilimnion of the same lake where OL1 was deposited.

The deltas associated with the deep lacustrine shales can be classified as either fluvial-dominated (Quebrada de Ischichuca and La Torre) or wave-dominated (Río Gualo). In the fluvial-dominated deltas, pelagic/hemipelagic prodelta muds were replaced landward by silty surge-like turbidity-flow deposits that constructed a very gently sloping delta front and shelf, as suggested by the lack of steep clinoforms or stratigraphic evidence for sub-lacustrine fans. The delta-top fluvial channels had high to moderate sinuosity, mixed sediment load and low channel slopes. On the delta plain, the major distributaries were separated by wide interdistributary bays or shallow lakes into which small crevasse deltas prograded (Fig. 8). The mean orientation of palaeocurrent indicators for the channels associated with fluvial-dominated delta lobes of the second sequence is N317° ($n = 30$; Fig. 4), which suggests that they were sourced from the flexural margin of the half-graben (Fig. 10). In contrast, the wave-dominated deltas of SS2 (Río Gualo) contain coarser-grained and thicker delta front successions, which display a dominance of wave and storm structures superimposed on silty surge-like turbidity-flow deposits. The palaeocurrent data for the wave-dominated delta lobes is towards N326° ($n = 12$, Fig. 4), which also suggests a flexural to southern axial source for these sediments.

### *SS3: Stratified freshwater lakes and highstand deltas (OL, DF, DP)*

The third sequence boundary (SB3) is marked by a forced regressive surface that juxtaposes distributary channel sandstones (DP1 facies association) above offshore lacustrine shales (OL) in all localities studied. In addition, the sandstones overlying the surface contain deformational features (slumps, convolute bedding) and are laterally equivalent to mass-flow deposits at Quebrada de Ischichuca. This abrupt facies superposition and the associated deformational features are interpreted as a product of a marked and/or rapid decrease in base level, which resulted in a basinward translation of facies belts, suggestive of a forced regression (e.g. Dam & Surlyk, 1992; Posamentier *et al.*, 1992; Lemons & Chan, 1999). The third stratigraphic sequence (SS3) is the thinnest and varies less in thickness (70 to 30 m). This sequence is also subdivided by lacustrine flooding surfaces (f4 and f5; Fig. 4) into parasequences, which are up to 60 m thick.

The third sequence (SS3) involves the same facies associations as SS2, and is composed of a stacked pair of delta lobes at each of the localities studied (Figs 4 and 10). The earlier delta lobes are thin (2 to 7 m) and rest erosively on laminated black shales (OL). The coarse-grained deposits of this delta lobe represent a lowstand delta and are covered by black shales considered as transgressive and highstand deposits (cf. Dam & Surlyk, 1992).The upper SS3 delta lobes exhibit features similar to those of the underlying lobes at Río Gualo and La Torre, although they are considerably thinner (4·5 to 6·5 m thick). At Río Gualo, the second delta lobe is capped by 0·15 m thick impure coal. The second SS3 lobe is only represented by a 15 m thick succession of delta-front silty deposits (DF facies association) at Quebrada de Ischichuca.

### *SS4: Shallow wave-dominated lake and shelf delta (SD facies associations)*

The fourth sequence boundary (SB4) is recognized by the superposition of a thick siltstone-dominated succession (SD facies associations) on offshore lacustrine shales (OL) and by a change in sandstone provenance (cf. Miall & Arush, 2001). SS4 is well represented only at Quebrada de Ischichuca, where it is at least 105 m thick. This sequence documents the existence of a lake influenced by fair-weather and storm waves, probably under a windy climate. SS4 contains sub-aqueous wave-dominated shoreline lacustrine sediments (SD1 facies association) considered as lowstand deposits, which are overlain by small sandy delta lobes (SD2 facies association) that would represent transgressive/highstand deposits. The latter are arranged in coarsening-upward and shallowing-upward, 6 to 15 m thick parasequences. Similar parasequences were recognized at Ischigualasto Park (Milana, 1998; Melchor *et al.*, 2003), although it is unclear whether these footwall parasequences can be correlated. The wave-dominated littoral lacustrine sediments (SD1 facies association) are envisaged as peripheral to deltaic deposits (SD2) and reflect shoreline progradation. The abundance of wave and storm structures suggests location in an area of wave attack (Fig. 10).

SS4 exhibits a marked palaeocurrent and sandstone provenance change, in comparison with the previous sequences. Palaeocurrent data indicate transport from the SE in the previous sequences and this changed to the SW for SS4 (Figs 4 and 10). Sandstone composition changed from arkosic (average composition $Q_{46}\,F_{29}\,L_{25}$ for SS2 and SS3) to volcanic lithic arenites (average composition $Q_{29}\,F_{14}\,L_{57}$ for SS4). These changes reflect a major modification in basin configuration and are tentatively assigned to the end of the synrift phase.

## DISCUSSION

The character and evolution of the studied Ischigualasto–Villa Unión basin fill is comparable with that of other low-latitude lacustrine rift basins (e.g. Scholz *et al.*, 1998). The main features in common are the presence of flexural margin unconformities that are replaced by a correlative conformity at the footwall (i.e. SB1 and SB3; Fig. 4) accompanied by a basinward translation of facies belts and evidence for repeated lake-level changes (Scholz *et al.*, 1998).

### Controls on sedimentation and basin development

SS1 (volcaniclastic deposits, saline lakes and fluvial deposits; VF, SL, F) corresponds to an underfilled basin state, when the rate of potential accommodation exceeded water and sediment fill (Carroll & Bohacs, 1999, 2001; Withjack *et al.*, 2002). The distribution of shallow lacustrine (SL) and fluvial (F) deposits (mainly at Quebrada de Ischichuca and Río Gualo, respectively) suggests that saline lacustrine facies were restricted to deeply subsided, internally drained depressions located close to the master fault during early stages of basin development. It is not possible to ascertain whether deposition took place in more than one depocentre during this sequence.

The second and third sequences (SS2 and SS3; offshore lacustrine shales and delta lobes, OL, DF, DP) represent balanced-fill basin conditions, when water and sediment inflows regularly filled the lake to sill level and may have created surface outflows (Carroll & Bohacs, 1999). Elsewhere, this basin state is commonly evidenced by fluctuating deep facies (Olsen, 1990; Carroll & Bohacs, 1999, 2001; Withjack *et al.*, 2002). In the sections studied, a number of changes in lake level can be inferred from the stacking of lacustrine parasequences and by the stratigraphic evidence for a forced regression at the base of SS3 (Fig. 4). Given the current understanding of fault evolution in rift basins (e.g. Gawthorpe & Leeder, 2000), the similar stratigraphic development of SS2 and SS3 in different parts of the half-graben is consistent with an advanced stage of fault linkage leading to the development of a single larger depocentre. The development of stratified lakes with thick pelagic-hemipelagic sediments was facilitated by an increase in subsidence rate, accompanied by a favourable hydrologic balance. Palaeocurrent data and the position of the studied sections within the half-graben suggest that the deltas were mainly sourced from the flexural margin. This inference is in agreement with the marked progradational character of the delta lobes, which is typical of flexural and axial margin deltas (Scholz, 1995). A similar thickness and width of the largest recorded delta lobe of SS2 and those of the modern Dwangwa delta (Lake Malawi) suggest that some of the highstand delta lobes could have reached a surface area of several tens of square kilometres (i.e. in the range *ca* 40 to 100 $km^2$ after Scholz, 1995). Furthermore, the existence of large drainage basins on the flexural margin of the half-graben, as suggested by the presence of moderate to large channel sandbodies in the delta plain, indicates reduced relief and limited faulting on that margin, as is typical of half-graben development (Scholz, 1995). The location of wave-dominated deltas on the eastern flexural margin and the large thickness of delta front facies compared with the associated distributary channel sandstones (DP1/DF ratio; Table 2) can be linked with their tectonic and palaeogeographic setting. The thick wave-dominated delta-front succession may have resulted from reduced subsidence in a ramp-like flexural margin setting that created a large and shallow shelf frequently affected by wave and storm processes. Lacustrine deltaic parasequences are not easily related to lake-level changes, except when independent evidence is available (e.g. Lemons & Chan, 1999). The correlation of lacustrine flooding and forced regressive surfaces between three sections separated by about 95 km, and parasequences showing similar lithofacies in different parts of the half-graben (Fig. 4), suggest that the stacking pattern of the parasequences in SS2 and SS3 corresponds to lake-level changes that affected the entire basin. The silty delta front facies representing the upper delta lobe at Quebrada de Ischichuca (Fig. 4) suggests more limited progradation of the flexural margin deltas into the footwall area at this time.

The main controlling factor during SS2 and SS3 deposition was fault-induced subsidence accompanied by a favourable hydrologic balance, whereas lake-level variations that produced the lacustrine parasequences were probably driven by short-term climatic fluctuations because of the similarity between footwall and flexural margin sequences. The apparent translation of the locus of distributary channel position at Quebrada de Ischichuca (Fig. 9B) may correspond to autocyclic delta-lobe switching.

The deposits of SS4 (lake nearshore and shelf delta, SD) are interpreted as representing an overfilled basin state. In other lacustrine basins, this state is typified by sediment and water fluxes exceeding the rate of accommodation creation and dominance of fluvial-lacustrine facies (Carroll & Bohacs, 1999; Withjack *et al.*, 2002). The achievement of an overfilled state is related to change in basin configuration, as evidenced by the lithofacies, palaeocurrent and provenance data. The mean palaeocurrent data and the known half-graben physiography suggest that the sediments were mainly sourced from the footwall margin during deposition of SS4, as opposed to a flexural/axial source for SS2 and SS3 (Figs 4 and 10). Footwall margin uplifts typically deliver low sediment volumes to rift basins except for streams entering the basin at relay ramps between stepping border faults or transverse antecedent drainage (e.g. Leeder & Gawthorpe, 1987; Gawthorpe & Leeder, 2000; Withjack *et al.*, 2002). Both alternatives could apply here. The changes in sandstone provenance can be understood by comparison with the studies on the influence of rift basin asymmetry on modern sand composition in Lake Tanganyika by Soreghan & Cohen (1993). These authors noted a marked increase in the amount of lithic grains in footwall sands in relation to flexural margin, axial and accommodation (rift transfer zone) sands. Although it is not clear if this pattern is common to continental rifts or a local effect because comparable studies are scarce (Garzanti *et al.*, 2001), similar sand compositional variation is inferred here for the hangingwall (SS2 and SS3) and footwall (SS4) margins of the basin. The location of the deposits of SS4 at the northern part of the half-graben implies that the moderate wave energy inferred for the SD facies associations could relate to increased wind energy as a result of greater lake fetch in the direction of maximum elongation of the basin (Fig. 10).

## CONCLUSIONS

The studied synrift lacustrine-dominated succession of the Triassic Ischigualasto–Villa Unión Basin (Chañares, Ischichuca, Los Rastros and Lomas Blancas formations) can be divided into four sequences in which there are lacustrine parasequences and surfaces that can be correlated across and along the basin. The fine-grained to medium-grained lacustrine deltaic successions can be correlated between the flexural and footwall margins of the half-graben. These deltas display gentle foreset slopes and the development of shallow shelfs. Variations in the character of successive sequences were primarily controlled by the tectonic evolution of the half-graben and, secondarily, by changing climatic conditions. Most of the sediments were sourced from the flexural or southern axial margin of the half-graben, although the upper part of the succession records the input of sediment from the footwall margin.

The oldest stratigraphic sequence (SS1) is composed of volcaniclastic and fluvial deposits composing a lowstand wedge (VF and F facies associations) succeeded by transgressive/highstand deposits restricted to more deeply subsiding areas close to the main border fault, represented by saline lake deposits (SL facies associations). The activity of the border fault system and the poor development of fluvial drainage on the flexural margin of the half-graben (reduced clastic supply) controlled the location and character of this sequence. The palaeoclimate was probably semi-arid, although strong evaporative conditions were not achieved. The playa-lake cycles are comparable with Van Houten cycles.

Increased subsidence and the development of a large fluvial drainage network on the flexural margin of the half-graben (favoured by a positive hydrologic balance) dictated the deposition of the sequences SS2 and SS3. A large, thermally stratified lake received sediment mostly from the flexural margin via fluvial-dominated and wave-dominated deltas. Both types of deltas display differences in the thickness of delta front and distributary channel thickness, as well as in the amount of wave-generated structures, which can be related to position within the half-graben. Lacustrine flooding surfaces bound parasequences that reflect lake-level changes assigned to climatic oscillations. Delta-lobe switching of autocyclic origin also operated during SS2.

Sequence SS4 reveals a change in lithofacies, palaeocurrents and sandstone composition. The sediments were now sourced from the footwall margin reflecting access to new routes of sediment input from the west, probably related to the presence of relay ramps or captured antecedent drainage.

## ACKNOWLEDGEMENTS

Luis Spalletti introduced the author to the study of the Ischigualasto–Villa Unión Basin. This project was funded partially by project PEI 138/99 from CONICET, project PICT 6156 of the Agencia Nacional de Promoción Científica y Tecnológica, and project 136/CN from the Universidad Nacional de La Pampa. Sedimentology reviewers, Michael Talbot and Alastair Ruffell, and editor Peter Haughton made significant comments and suggestions that improved the paper considerably.

## REFERENCES

**Allen, J.R.L.** (1984) *Sedimentary Structures – Their Character and Physical Basis. Dev. Sedimentol.*, **30,** Elsevier, Amsterdam, 1256 pp.

**Álvarez, P.P.** and **Ramos, V.A.** (1999) The Mercedario rift system in the principal Cordillera of Argentina and Chile (32° SL). *J. S. Am. Earth Sci.*, **12,** 17–31.

**Anderson, R.Y., Dean, W.E., Bradbury, J.P.** and **Love, D.** (1985) Meromictic lakes and varved lake sediments in North America. *Bull. US Geol. Surv.*, **1607,** 1–19.

**Armenteros, I.** and **Daley, B.** (1998) Pedogenic modification and structure evolution in palustrine facies as exemplified by the Bembridge Limestone (Late Eocene) of the Isle of Wight, southern England. *Sed. Geol.*, **119,** 275–295.

**Artabe, A.E., Morel, E.M., Spalletti, L.A.** and **Brea, M.** (1998) Paleoambientes sedimentarios y paleoflora asociada en el Triásico tardío de Malargüe, Mendoza. *Rev. Asoc. Geol. Argentina*, **53,** 526–548.

**Astin, T.R.** and **Rogers, D.A.** (1991) 'Subaqueous shrinkage cracks' in the Devonian of Scotland reinterpreted. *J. Sed. Petrol.*, **61,** 850–859.

**Baraldo, J., Monetta, A.** and **Soechting, W.** (1990) Triásico de San Juan. Relatorio de Geología y Recursos Naturales de la Provincia de San Juan, 11th Congreso Geológico Argentino, San Juan, Argentina, pp. 124–139.

**Bates, C.C.** (1953) Rational theory of delta formation. *AAPG Bull.*, **37,** 2119–2162.

**Berner, R.A.** and **Raiswell, R.A.** (1984) C/S method for distinguishing freshwater from marine sedimentary rocks. *Geology*, **12,** 365–368.

**Bonaparte, J.F.** (1969) Datos sobre la evolución paleoecológica en las formaciones Triásicas de Ischigualasto–Villa Unión (San Juan – La Rioja). *Acta Geológica Lilloana*, **10,** 189–206.

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

**Bossi, G.E.** and **Herbst, R.** (1968) Noticias sobre la geología de La Torre, provincia de La Rioja, República Argentina. *Rev. Asoc. Geol. Argentina*, **23,** 45–54.

**Brenner, W.** and **Foster, C.B.** (1994) Chlorophycean algae from the Triassic of Australia. *Rev. Palaeobot. Palynol.*, **80,** 209–234.

**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.

**Caselli, A.T., Marsicano, C.M.** and **Arcucci, A.B.** (2001) Sedimentología y paleontología de la Formación Los Colorados, Triásico superior (provincias de La Rioja y San Juan, Argentina). *Rev. Asoc. Geol. Argentina*, **56,** 173–188.

**Christie-Blick, N.** (1991) Onlap, offlap, and the origin of unconformity-bounded depositional sequences. *Mar. Geol.*, **97,** 35–56.

**Colella, A.** (1988) Pliocene-Holocene fan deltas of the Messina Strait. In: *Fan deltas – Excursion Guidebook* (Ed. A. Colella), pp. 139–152. Universita della Calabria, Cosenza, Italy.

**Contreras, J.C., Scholz, C.H.** and **King, G.C.P.** (1997) A model of rift basin evolution constrained by first-order stratigraphic observations. *J. Geophys. Res.*, **102,** 7673–7690.

**Curtis, C.D.** and **Coleman, M.L.** (1986) Controls on the precipitation of early diagenetic calcite, dolomite and siderite concretions in complex depositional sequences. In: *Roles of Organic Matter in Sediment Diagenesis* (Ed. D.L. Gautier), *SEPM Spec. Publ.*, **38,** 23–33.

**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.

**Dart, C.J., Collier, R.E.L., Gawthorpe, R.L., Keller, J.V.** and **Nichols, G.** (1994) Sequence stratigraphy of (?)Pliocene-Quaternary synrift, Gilbert-type deltas, northern Peloponesos, Greece. *Mar. Petrol. Geol.*, **11,** 545–560.

**Demaison, G.J.** and **Moore, G.T.** (1980) Anoxic environments and source bed genesis. *AAPG Bull.*, **64,** 1179–1209.

**Elliot, T.** (1986) Deltas. In: *Sedimentary Environments and Facies* (Ed. H.G. Reading), 2nd edn, pp. 113–154. Blackwell, Oxford.

**Emery, D.** and **Myers, K.** (1996) *Sequence Stratigraphy*. Blackwell Science Ltd., Oxford, 297 pp.

**Eyles, N.** and **Clark, B.M.** (1986) Significance of hummocky and swaley cross-stratification in late Pleistocene lacustrine sediments of the Ontario basin, Canada. *Geology*, **14,** 679–682.

**Finney, B.P.** and **Johnson, T.C.** (1991) Sedimentation in Lake Malawi (East Africa) during the past 10,000 years: a continuous paleoclimate record from the southern tropics. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **85,** 351–366.

**Frank, P.W.** (1988) Conchostraca. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **62,** 399–403.

**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.

**Freytet, P.** and **Verrecchia, E.P.** (2002) Lacustrine and palustrine carbonate petrography: an overview. *J. Paleolimnol.*, **27,** 221–237.

**Garzanti, E., Vezzoli, G., Andò, S.** and **Castiglioni, G.** (2001) Petrology of rifted-margin sand (Red Sea and Gulf of Aden, Yemen). *J. Geol.*, **109,** 277–297.

**Gawthorpe, R.L.** and **Leeder, M.R.** (2000) Tectono-sedimentary evolution of active extensional basins. *Basin Res.*, **12,** 195–218.

**Gawthorpe, R.L., Fraser, A.J.** and **Collier, R.E.L.** (1994) Sequence stratigraphy in active extensional basins: Implications for the interpretation of ancient basin fills. *Mar. Petrol. Geol.*, **11,** 642–658.

**Gawthorpe, R.L., Hardy, S.** and **Ritchie, B.** (2003) Numerical modelling of depositional sequences in half-graben rift basins. *Sedimentology*, **50,** 169–185.

**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.

**Gierlowski-Kordesch, E.H.** and **Rust, B.R.** (1994) The Jurassic East Berlin Formation, Hartford Basin, Newark Supergroup (Connecticut and Massachusetts): A saline lake-playa-alluvial plain system. In: *Sedimentology and Geochemistry of Modern and Ancient Saline Lakes* (Eds R.W. Renaut and W.M. Last), *SEPM Spec. Publ.*, **50,** 249–265.

**Gray, J.** (1988) Evolution of the freshwater ecosystem: the fossil record. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **62,** 1–214.

**Gupta, S., Underhill, J.R., Sharp, I.** and **Gawthorpe, R.L.** (1999) Role of fault interactions in controlling synrift sediment dispersal patterns: Miocene, Abu Alaqa Group, Suez Rift, Sinai, Egypt. *Basin Res.*, **11,** 167–189.

**Hardie, L.A., Smoot, J.P.** and **Eugster, H.P.** (1978) Saline lakes and their deposits: a sedimentological approach. *Int. Assoc. Sedimentol. Spec. Publ.*, **2,** 7–41.

**Hardy, S. Dart., C.** and **Waltham, D.** (1994) Computer modelling of the influence of tectonics upon sequence architecture of coarse-grained fan deltas. *Mar. Petrol. Geol.*, **11,** 561–574.

**Hirst, J.P.P.** (1991) Variations in alluvial architecture across the Oligo-Miocene Huesca fluvial system, Ebro Basin, Spain. In: *The Three-dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery* (Eds A.D. Miall and N. Tyler), *SEPM Concepts Sedimentol. Paleontol.*, **3,** 111–121.

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

**Jones, L.S.** and **Schumm, S.A.** (1999) Causes of avulsion: an overview. *Int. Assoc. Sedimentol. Spec. Publ.*, **28,** 171–178.

**Katz, B.J.** (1995) Factors controlling the development of lacustrine petroleum source rocks – an update. In: *Paleogeography, Paleoclimate, and Source Rocks* (Ed. A.Y. Huc), *AAPG Stud. Geol.*, **40,** 61–79.

**Kostic, S., Parker, G.** and **Marr, J.G.** (2002) Role of turbidity currents in setting the foreset slope of clinoforms prograding into standing fresh water. *J. Sed. Res.*, **72,** 353–362.

**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., 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.

**Martel, A.T.** and **Gibling, M.R.** (1991) Wave-dominated lacustrine facies and tectonically controlled cyclicity in the Lower Carboniferous Horton Bluff Formation, Nova Scotia, Canada. In: *Lacustrine Facies Analysis* (Eds P. Anadón, L.l. Cabrera and K. Kelts), *Int. Assoc. Sedimentol. Spec. Publ.*, **13,** 223–243.

**Melchor, R.N.** (2002) Formación Ischichuca: su distinción de las Formaciones Chañares y Los Rastros (Triásico, Norte de la cuenca Ischigualasto-Villa Unión), Argentina. In: *15th Congreso Geológico Argentino* (Eds N. Cabaleri, C.A. Cingolani, E. Linares, M.G. López de Luchi, H.A. Ostera and H.O. Panarello), pp. 690–693, Actas, Buenos Aires.

**Melchor, R.N.** (2004) Trace fossil distribution in lacustrine deltas: Examples from the Triassic rift lakes of the Ischigualasto - Villa Unión basin, Argentina. In: *Application of Trace Fossils to Stratigraphic Analysis* (Ed. D. McIlroy), *Geol. Soc. London Spec. Publ.*, **228,** 333–352.

**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.

**Midtgaard, H.H.** (1996) Inner-shelf to lower-shoreface hummocky sandstone bodies with evidence for geostrophic influenced combined flow, Lower Cretaceous, West Greenland. *J. Sed. Res.*, **66,** 343–353.

**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.

**Mozley, P.S.** (1989) Relation between depositional environment and the elemental composition of early diagenetic siderite. *Geology*, **17,** 704–706.

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

**Olsen, P.E.** (1985) Constraints in the formation of lacustrine microlaminated sediments. *US Geol. Surv. Circular*, **946,** 34–35.

**Olsen, P.E.** (1986) A 40-million year lake record of early Mesozoic orbital climatic forcing. *Science*, **234,** 842–848.

**Olsen, P.E.** (1990) Tectonic, climatic, and biotic modulation of lacustrine ecosystems – examples from Newark Supergroup of Eastern North America. In: *Lacustrine Exploration: Case Studies and Modern Analogues* (Ed. B.J. Katz), *AAPG Mem.*, **50,** 209–224.

**Orton, G.J.** and **Reading, H.G.** (1993) Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size. *Sedimentology*, **40,** 475–512.

**Page, S., Limarino, C.O.** and **Caselli, A.** (1997) Basaltos alcalinos en el Triásico de la cuenca de Ischigualasto – Villa Unión, provincias de la Rioja y San Juan. *Rev. Asoc. Geol. Argentina*, **52,** 202–208.

**Parrish, J.T.** (1998) *Interpreting Pre-Quaternary Climate from the Geologic Record*. Columbia University Press, New York, 338 pp.

**Pilskaln, C.H.** (2004) Seasonal and interannual particle export in an African rift valley lake: A 5-year record from Lake Malawi, southern East Africa. *Limnol. Oceanogr.*, **49,** 964–977.

**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.

**Prezzi, C., Vizán, H.** and **Rapalini, A.** (2001) Marco paleogeográfico. In: *El Sistema Triásico en la Argentina* (Eds A.E. Artabe, E.M. Morel and A.B. Zamuner), pp. 255–267. Fundación Museo de La Plata, La Plata, Argentina.

**Raiswell, R.** (1988) Chemical model for the origin of minor limestone-shale cycles by anaerobic methane oxidation. *Geology*, **16,** 641–644.

**Ramos, V.A.** (1994) Terranes of southern Gondwanaland and their control in the Andean structure (30°–33° S lat.). In: *Tectonics of the Southern Central Andes, Structure and Evolution of an Active Continental Margin* (Eds K.J. Reutter, E. Scheuber and P.J. Wigger), pp. 249–261. Springer Verlag, Berlin.

**Ramos, V.A.** and **Kay, S.M.** (1991) Triassic rifting and associated basalts in the Cuyo Basin, central Argentina. In: *Andean Magmatism and its Tectonic Setting* (Eds R.S. Harmon & C.W. Rapela), *Geol. Soc. Am. Spec. Pap.*, **265,** 79–91.

**Renaut, R.W.** and **Tiercelin, J.J.** (1994) Lake Bogoria. Kenya Rift Valley – A sedimentological overview. In: *Sedimentology and Geochemistry of Modern and Ancient Saline Lakes* (Eds R.W. Renaut and W.M. Last), *SEPM Spec. Publ.*, **50,** 101–123.

**Roberts, S.M., Spencer, R.J.** and **Lowenstein, T.K.** (1994) Late Pleistocene saline lacustrine sediments, Badwater basin, Death Valley, California. In: *Lacustrine Reservoirs and Depositional Systems* (Eds A.J. Lomando, B.C. Schreiber and P.M. Harris), *SEPM Core Workshop*, **19,** 61–103.

**Rogers, D.A.** and **Astin, T.R.** (1991) Ephemeral lakes, mud pellet dunes and wind-blown sand and silt: reinterpretations of Devonian lacustrine cycles in north Scotland. In: *Lacustrine Facies Analysis* (Eds P. Anadón, Ll. Cabrera and K. Kelts), *Int. Assoc. Sedimentol. Spec. Publ.*, **13,** 199–221.

**Romer, A.S.** and **Jensen, A.** (1966) The Chañares (Argentina) Triassic Reptile Fauna II. Sketch of the Geology of the Río Chañares-Río Gualo region. *Breviora, Museum of Comparative Zoology*, **252,** 1–20.

**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.

**Rossello, E.A., Mozetic, M.E., Cobbold, P.R., Urreiztieta, M. de Gaspais, D.** and **López-Gamundí, O.R.** (1996) The Valle Fértil flower structure and its relationships with the Precordillera and Pampean Ranges, (30–32°S, Argentina). In: *III International Symposium on Andean Geodynamics*, pp. 481–484. Proceedings of ORSTROM-Géosciences Rennes, Saint Malo.

**Rossello, E.A., Limarino, C.O., Ortiz, A.** and **Hernández, N.** (2005) Cuencas de los bolsones de San Juan y La Rioja. In: *Frontera Exploratoria de la Argentina* (Eds G.A. Chebli, J.S. Cortiñas, L.A. Spalletti, L. Legarreta and E.L. Vallejo), pp. 147–173. Instituto Argentino del Petróleo y del Gas, Buenos Aires.

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

**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.

**Smoot, J.P.** and **Olsen, P.E.** (1988) Massive mudstones in basin analysis and paleoclimatic interpretation of the Newark Supergroup. In: *Triassic-Jurassic Rifting, Part A* (Ed. W. Manspeizer), *Developments in Geotectonics*, pp. 249–274, **22,** Elsevier, Amsterdam.

**Smoot, J.P.** and **Olsen, P.E.** (1994) Climatic cycles as sedimentary controls of rift-basin lacustrine deposits in the Early Mesozoic Newark basin based on continuous core. In: *Lacustrine Reservoirs and Depositional Systems* (Eds A.J. Lomando, B.C. Schreiber and P.M. Harris), *SEPM Core Workshop*, **19,** 201–237.

**Soreghan, M.J.** and **Cohen, A.S.** (1993) The effects of basin asymmetry on sand composition: examples from the Lake Tanganyika, Africa. In: *Processes Controlling the Composition of Clastic Sediments* (Eds M.J. Johnsson and A. Basu), *Geol. Soc. Am. Spec. Pap.*, **284,** 285–301.

**Soreghan, M.J., Scholz, C.H.** and **Wells, J.T.** (1999) Coarse-grained, deep-water sedimentation along a border fault margin of Lake Malawi, Africa: seismic stratigraphic analysis. *J. Sed. Res.*, **69,** 832–846.

**Spalletti, L.A.** (1999) Cuencas triásicas del oeste argentino: origen y evolución. *Acta Geol. Hisp.*, **32,** 29–50.

**Spalletti, L.A.** (2001) Evolución de las cuencas sedimentarias. In: *El Sistema Triásico en la Argentina* (Eds A.E. Artabe, E.M. Morel and A.B. Zamuner), pp. 81–101. Fundación Museo de La Plata, La Plata, Argentina.

**Spalletti, L.A., Artabe, A.E., Morel, E.** and **Brea, M.** (1999) Biozonación paleoflorística y cronoestratigrafía del Triásico argentino. *Ameghiniana*, **36,** 419–451.

**Stipanicic, P.N.** (1983) The Triassic of Argentina and Chile. In: *The Phanerozoic Geology of the World. The Mesozoic* (Eds M. Moullade and A.E.M. Nairn), pp. 181–199. Elsevier, Amsterdam.

**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.

**Stipanicic, P.N.** and **Marsicano, C.A.** (2002) Triásico. Léxico Estratigráfico de la Argentina, vol. VIII. *Asociación Geológica Argentina, Serie 'B' (Didáctica y Complementaria)*, **26,** 1–370.

**Talbot, M.R.** (1988) The origins of lacustrine oil source rocks: evidence from the lakes of tropical Africa. In: *Lacustrine Petroleum Source Rocks* (Eds A.J. Fleet, K. Kelts and M.R. Talbot), *Geol. Soc. London Spec. Publ.*, **40,** 29–43.

**Talbot, M.R.** and **Allen, P.A.** (1996) Lakes. In: *Sedimentary Environments: Processes, Facies and Stratigraphy* (Ed. H.G. Reading), pp. 83–124. Blackwell Science, Oxford.

**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.

**Tasch, P.** (1969) Branchiopoda. In: *Treatise on Invertebrate Paleontology, Part R, Arthropoda 4, 1* (Ed. R.C. Moore), pp. R128–R191. Geological Society of America and University of Kansas, Lawrence, KS.

**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.

**Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S.** and **Hardenbol, J.** (1988) An overview of the fundamentals of sequence stratigraphy and key definitions. In: *Sea Level Changes: an Integrated Approach* (Eds C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross and J.C. Van Wagoner), *SEPM Spec. Publ.*, **42,** 39–45.

**Van Wagoner, J.C., Mitchum, R.M., Jr, Campion, K.M.** and **Rahmanian, V.D.** (1990) Siliciclastic sequence stratigraphy in well logs, core, and outcrops: concepts for high-resolution correlation of time and facies. *AAPG Methods Exploration Ser.*, **7,** 1–55.

**Volkheimer, W.** (1969) Paleoclimatic evolution in Argentina and relations with other regions of Gondwana. 1st International Symposium on Gondwana Stratigraphy, vol. 2. UNESCO, Paris, pp. 551–587.

**Wells, J.T., Scholz, C.A.** and **Johnson, T.C.** (1994) Highstand deltas in Lake Malawi, East Africa: environments of deposition and processes of sedimentation. In: *Lacustrine Reservoirs and Depositional Systems* (Eds A.J. Lomando, B.C. Schreiber and P.M. Harris), *SEPM Core Workshop*, **19,** 1–35.

**Withjack, M.O., Schlische, R.W.** and **Olsen, P.E.** (2002) Rift-basin structure and its influence on sedimentary systems. In: *Sedimentation in Continental Rifts* (Eds R.W. Renaut and G.M. Ashley), *SEPM Spec. Publ.*, **73,** 57–81.

**Young, M.J., Gawthorpe, R.L.** and **Sharp, I.R.** (2000) Sedimentology and sequence stratigraphy of a transfer zone coarse-grained delta, Miocene Suez Rift, Egypt. *Sedimentology*, **47,** 1081–1104.

**Zavattieri, A.M.** and **Melchor, R.N.** (1999) Estudio palinológico preliminar de la Fm. Ischichuca (Triásico), en su localidad tipo (Quebrada de Ischichuca Chica), provincia de La Rioja, Argentina. *Asociación Paleontológica Argentina Publicación Especial*, **6,** 33–38.

*Manuscript received 7 December 2004; revision accepted 29 May 2007*