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## Stratigraphy and architecture of the Upper Triassic Ischigualasto Formation, Ischigualasto Provincial Park, San Juan, Argentina

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## ABSTRACT

The Ischigualasto Formation in northwestern Argentina contains abundant fluvial channel sandstones, overbank mudstones, and paleosols that were deposited in a northwest-trending continental-rift basin during Late Triassic time. In the study area the formation progressively thins from ~700 m in the west to ~400 m in the east, over a distance of 7 km. This thinning is accompanied by a relative decrease in the abundance of fluvial channel sandstones and an increase in mud-rich overbank deposits and paleosols. While preserved channel deposits in the formation are highly variable in terms of their size and stratigraphic distribution, four general channel forms can be recognized based on their overall cross sectional geometry and internal sedimentary structures. Of these, the dominant channel-body types are interpreted as the deposits of sandy multi-channel fluvial systems. The internal stratigraphic architecture of the Ischigualasto Formation indicates that during deposition, the central part of the basin was the location of a long-lived, north flowing, fluvial channel belt that received relatively continuous channel and proximal overbank deposition. To the east, however, channel-related deposition was more infrequent, resulting in enhanced pedogenic modification of alluvial deposits. The overall thickness and facies trends observed in the Ischigualasto Formation most likely correspond to variations in fault-related accommodation development within the basin during the time of deposition.

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## RESUMEN

La Formación Ischigualasto, en el NO argentino, esta formada por areniscas de canales fluviales, pelitas de desbordamientos y paleosuelos. Estos sedimentos fueron depositados en una cuenca rift continental, orientada NW-SE, durante el Triásico Superior. En el área de estudio la Formación se adelgaza progresivamente desde ~700 m en el oeste a ~400 m en el este, a lo largo de una distancia de 7 km. Este adelgazamiento esta acompañado por una disminución relativa en la abundancia de canales fluviales areniscosos y un incremento de los los depósitos pelíticos de desbordamiento y paleosuelos.

Si bien los depósitos de canales son altamente variables en tamaño y distribución estratigráfica, se han podido clasificar cuatro tipos de canales en función de rasgos geométricos y estructuras sedimentarias internas generales. De estos depósitos, los tipos de canales dominantes son los sistemas fluviales areniscosos multicanales. La arquitectura estratigráfica de la Formación Ischigualasto indica que durante su depositación, el centro de la cuenca fue el depocentro prolongado de depósitos de canales y de desbordamiento de una faja de canales fluviales que fluía hacia el norte. Sin embargo, en el este de la cuenca la depositación relacionada a canales fluviales fue menos importante, dando como resultado un incremento de las modificaciones pedogenéticas en los depósitos aluviales. Las tendencias generales de los espesores

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y las facies observadas en la Formación Ischigualasto parecen corresponder a variaciones en el espacio de acomodamiento de fallas ubicadas dentro de la cuenca durante su depositación.

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## 1. Introduction

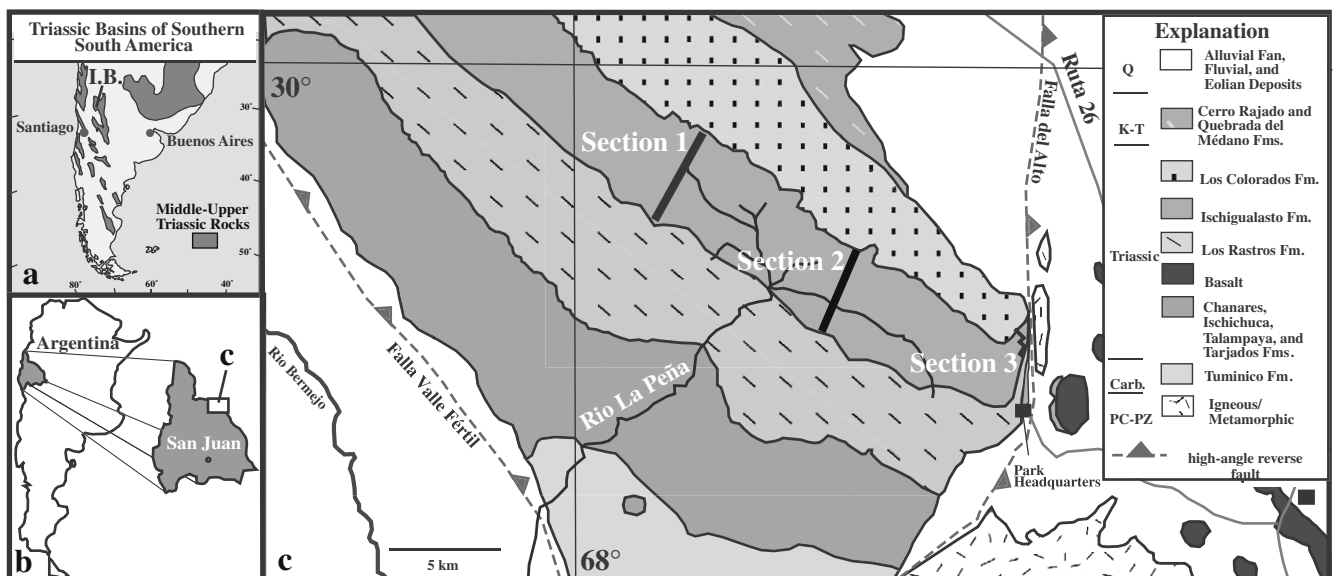
The three-dimensional geometry of alluvial successions in continental rift basins can provide significant information on the factors influencing deposition. One of the primary results from both theoretical and numerical models on rift basin evolution is that spatial and temporal variations of syndepositional faulting can produce lateral variations in the magnitude and rate of basin subsidence and strongly influence the character and distribution of basin depositional systems (Bridge and Leeder, 1979; Leeder and Gawthorpe, 1987; Mackey and Bridge, 1995). Fault-related processes, such as along-strike changes in basin-bounding fault displacement, lateral tilting of hanging wall depositional surfaces, and activity on intrabasinal fault systems can control thickness of lithostratigraphic units, the geometry, interconnectedness and stacking patterns of fluvial channel deposits, as well as preservation of overbank lithologies, and the distribution of paleosols (Allen, 1974; Bridge and Leeder, 1979; Schlische, 1993). As such, documenting the architecture of alluvial successions can provide insight into the structural and tectonic controls on rift basin evolution.

In rifts, as in other alluvial basins, overall architecture is strongly influenced by rates and magnitude of sediment accumulation, which on the formation scale is roughly equal to basin subsidence. There are, however, two points of view on this topic. Numerical models such of those by Leeder (1978), Allen (1978) and Bridge and Leeder (1979), predict that the overall architectural arrangement of fluvial channel sandstones varies according to the amount and rate of subsidence. These models, which assume a constant channel avulsion frequency, predict that fluvial channel sandstones will become vertically and laterally separated by higher percentages of fine-grained overbank deposits during periods of increased subsidence. In turn, when subsidence rates decrease, flu-

vial channel deposits will become amalgamated both vertically and laterally.

Heller and Paola (1996) questioned the validity of the above architectural models in view the potential effects that channel-avulsion frequency may have on overall fluvial architecture. Their argument was that the overall thickness and connectivity of channel sandstones is highly dependant on the relationship between avulsion frequency and aggradation rate. During periods of rapid subsidence, a higher frequency of avulsion may potentially produce greater lateral continuity in fluvial channel bodies. In turn, when aggradation rate slows, a corresponding reduction in the frequency of stream-channel avulsion may produce fluvial channel bodies that are geometrically isolated.

The Ischigualasto Formation of northwestern Argentina provides an excellent opportunity to test current ideas on the relationships between alluvial architecture in response to variations in basin accommodation development. The Ischigualasto Formation is a fluvial-dominated stratigraphic unit that was deposited in a continental extensional basin during Late Triassic time (Alcober, 1996). Despite pronounced lateral changes in formation thickness (~300 m over a distance of 7 km), the lack of intraformational unconformities and lateral continuity of lithostratigraphic members indicates that deposition was relatively continuous (Milana and Alcober, 1994). This allows overall formation architecture to be viewed within the context of lateral variations in basin subsidence. By focusing on the relationships between the geometry and stratigraphic arrangement of fluvial channel sandstones and associated floodplain deposits in both low and high accommodation zones within the basin, current ideas concerning the alluvial architectural response to changes in basin subsidence can be evaluated. These relationships can also be used to discern the overall structural controls on Ischigualasto Formation deposition, and serve as a basis of comparison with other fluvial-dominated rift assemblages.



**Fig. 1.** Location maps of the Ischigualasto Basin. (a) Distribution of Triassic basins in southern South America. "I.B." marks the location of the Ischigualasto-Villa Unión Basin in NW Argentina and the study area depicted in Figure 1c. (b) Map of San Juan Province, Argentina. White rectangle shows location of Figure 1c. (c) Geologic map of the southern part of the Ischigualasto-Villa Unión Basin. Ischigualasto Fm. measured Sections 1–3 shown in Figs. 3 and 4. Modified from Alcober (1996).

## 2. Geologic setting

During Mesozoic time, oceanic–continental plate interactions along the southwestern margin of Pangea produced a region of extensional deformation cratonward of the proto-Andean magmatic arc (Ramos and Kay, 1991; Lopez-Gamundi et al., 1994). Extension was focused along the NW-trending boundary between Paleozoic accreted terranes and the Precambrian Gondwanan craton (Uliana et al., 1989). The Ischigualasto basin of northwest Argentina is one of a series of continental-rifts that developed in the region as a result of this extension (Fig. 1) (Uliana and Biddle, 1988). Rift-related deposition in the Ischigualasto Basin began during Early Triassic time, as northeast-directed normal displacement on the paleo-Valle Fértil fault and the antithetic paleo-Alto fault led to the development of a structural half-graben (Milana and Alcober, 1994; Lopez, 1995). The Valle Fértil fault is interpreted as the main, basin-bounding normal fault separating Proterozoic–Paleozoic crystalline and sedimentary rocks of the footwall from the Triassic sedimentary rocks of the hanging wall. Deposition in the basin continued throughout Triassic time and resulted in accumulation of >3.5 km of nonmarine and volcanic strata (Alcober, 1996).

Pleistocene shortening within the foreland of the Andes produced reverse-displacement reactivation of Mesozoic normal faults and structural inversion of Ischigualasto Basin strata (Zapata and Allmendinger, 1996). Uplift and erosion of basin strata has resulted in near-complete exposure of the Ischigualasto Triassic stratigraphic interval in the hanging wall of the Valle Fértil and Alto faults (Fig. 1). In the study area the Ischigualasto Fm. dips up to 25° NW along the contact with the Alto Fault (Section 3), but has a regional dip of 4–10° NE in the western parts of the study area (Sections 1 and 2) (Fig. 1).

## 3. Ischigualasto Formation stratigraphy and age

As part of our investigation we measured three detailed stratigraphic sections through the Ischigualasto Formation in the eastern part of the Ischigualasto Provincial Park (Fig. 1). An Upper Triassic age of the Ischigualasto Formation is based on vertebrate fossils and radiometric ages of altered ash beds from the unit and basalt flows immediately underlying the formation (Fig. 2). Abundant vertebrate fossils in the lower 2/3 of the formation (including the rhynchosaur *Scaphonyx*, the cynodont *Exaeretodon*, and primitive theropod dinosaurs *Eoraptor* and *Herrerasaurus*) indicate a Carnian age of deposition (Rogers et al., 1993; Martinez, 1994; Alcober, 1996). Altered ash beds in the Ischigualasto Formation have provided additional chronostratigraphic control. Sani-

dine crystals from a bentonite sampled ~80 m above the base of the formation near Section 2 yield an  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $227.8 \pm 0.3$  Ma (Rogers et al., 1993) while plagioclase crystals from a bentonite ~70 m from the top of the formation in Section 1 (Fig. 3) provide a date of  $217.0 \pm 1.7$  Ma (Shipman, 2004). In addition, to the east of the study area, in the footwall of the Alto fault is a thick accumulation of basaltic dikes and flows (Fig. 1). A K/Ar date of  $229 \pm 5$  Ma on these basalts (Odin et al., 1982) suggests they may be correlative with the basalt flows preserved in the lower part of the Ischigualasto Formation in Section 3. Collectively, these ages support a Carnian age of deposition based on the Triassic time-scale of Gradstein et al. (1995) (Fig. 2).

The Ischigualasto Formation consists of ~300–700 m of mudstone, sandstone, conglomerate, and basalt (Figs. 3 and 4). The sedimentary rocks of the formation are primarily channel and overbank deposits of fluvial systems sourced in highlands southwest of Valle Fértil paleofault and south-southeast of El Alto paleofault, whereas the basalts were formed by flows originating from volcanic centers located at the east and northwest margins of the basin (Alcober, 1996). From west to east across the study area, the Ischigualasto Formation exhibits dramatic changes in thickness and lithologic variability. In the west (Section 1), the formation is 691 m thick and is dominated by fluvial channel sandstones, particularly in the upper half of the formation (Fig. 3). To the east, the formation thins from 413 m in Section 2 to 397 m in Section 3, and contains a larger percentage of mudstone (Fig. 4). Internally, the Ischigualasto Formation can be subdivided into four lithostratigraphic members, including the basal La Peña Member, the Cancha de Bochas Member, the Valle de la Luna Member, and the Quebrada de la Sal Member. Formal designation and a detailed description of these members are presented in Appendix A.

## 4. Alluvial architecture

Lithofacies in the Ischigualasto Formation indicate deposition in fluvial channel and overbank environments (Alcober, 1996). Lithofacies characteristics, which were classified using the scheme of Miall (1981), are listed in Table 1. Lithofacies assemblages in the Ischigualasto Formation can be subdivided into nine different architectural elements based on associations, geometry, paleocurrent orientation, and bounding-surface hierarchy (Table 2). Each element is interpreted to be the depositional product of a particular process or suite of processes occurring within the Ischigualasto alluvial system (Miall, 1985). Of these elements, four are interpreted to have formed in fluvial channel and five in overbank environments. Channel elements include the deposits of gravel bedforms, sandy bedforms, and downstream and lateral accretion elements. Overbank elements include levee deposits, crevasse splay deposits, floodplain fines, abandoned channel deposits, and paleosols.

### 4.1. Channel elements

#### 4.1.1. Gravelly bed elements

Gravelly bed elements consist of horizontally-stratified, clast-supported, pebble–cobble conglomerate beds (lithofacies Gh) that are bounded by fourth-order surfaces (e.g. Miall, 1991), the bases of which may exhibit erosional scours with up to 2.0 m of relief. In some cases, however, the base of these elements corresponds to the fifth-order bases of channel bodies. Gravelly bed elements are found primarily in the lower parts of channel-form bodies and are commonly overlain by sandy bed, downstream accretion, and lateral accretion elements (see below). Gravelly bed elements are interpreted as the deposits of low-relief gravel bedforms or

Ma	Period	Series/Stage	Formation/Member	Radiometric Age (Ma)		
220	Triassic	Upper	Norian	Los Colorados Fm.	217.0 ± 1.7	
			Carnian	Ischigualasto Fm.		Quebrada de la Sal Mbr.
				Valle de la Luna Mbr.		
				Cancha de Bochas Mbr.		
				La Peña Mbr.		
230	Middle	Ladinian	Los Rastros Fm.	229 ± 5		

Fig. 2. Time-stratigraphic chart for Middle–Upper Triassic rocks of the Ischigualasto basin including newly defined lithostratigraphic members of the Ischigualasto Fm. and relative position of radiometrically dated horizons. Time scale adapted from Gradstein et al. (1995) and Alcober (1996).

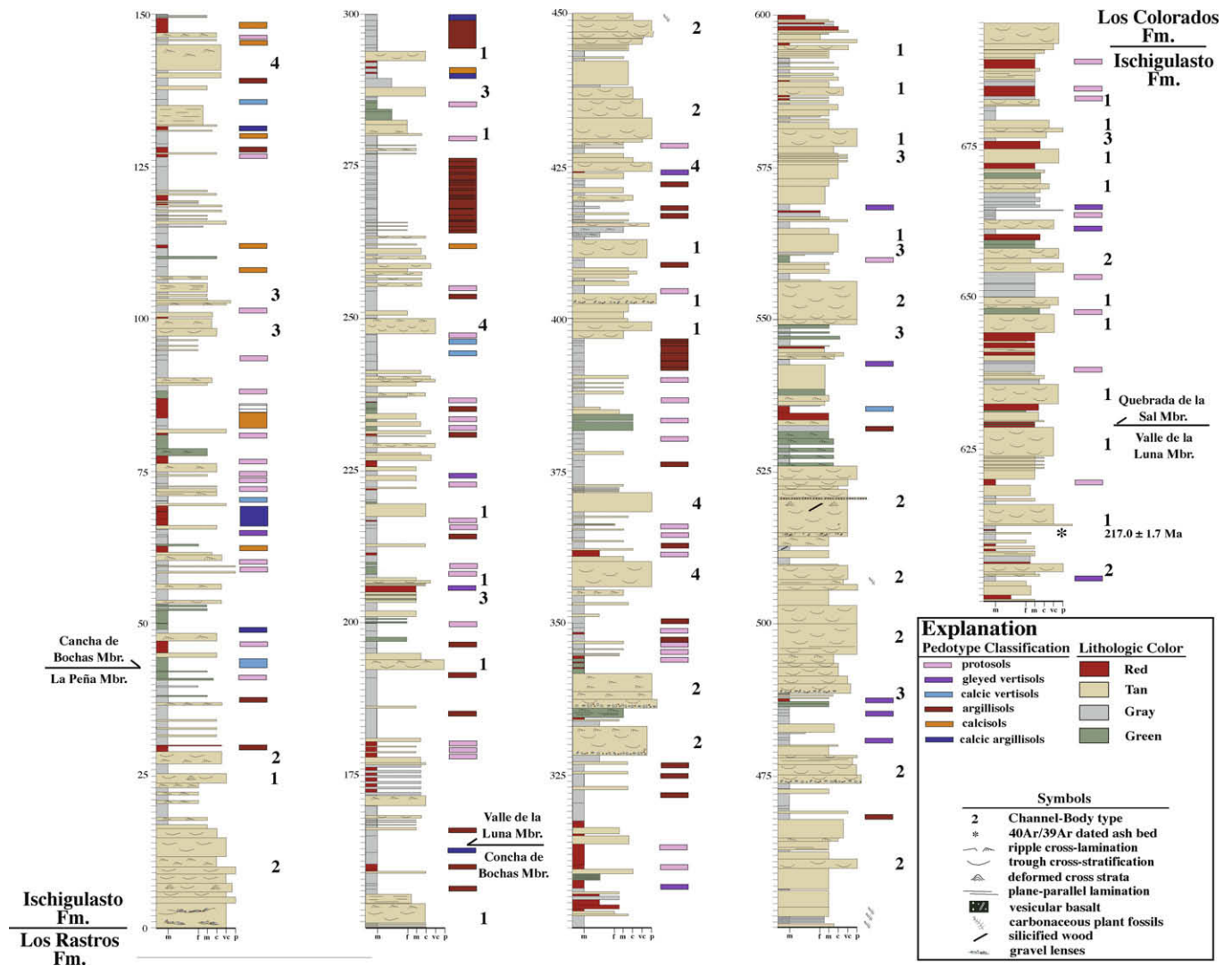


Fig. 3. Log of Ischigualasto Formation measured Section 1. See Fig. 1 for location.

bedload sheets or, where occurring along basal scoured surfaces, channel-lag deposits (cf. Hein and Walker, 1977).

4.1.2. Sandy bed elements

Sandy bed elements consist of trough- and planar cross stratified sandstone, ripple cross laminated sandstones, and plane-parallel laminated sandstones (lithofacies St, Sp, Sr, Sh) bounded by second- and third-order surfaces. In some cases, however, the base of these elements correspond to the fourth- and fifth-order scoured bases of minor channel fills and channel bodies, respectively. Sandy bed elements are interpreted as the deposits of bedforms (lithofacies St and Sp) that filled Ischigualasto fluvial channels as a result of vertical bed aggradation or accumulated along channel margins and the tops of macroforms during falling stages of flow (lithofacies Sr and Sh) (Cant and Walker, 1978; Miall, 1996).

4.1.3. Downstream accretion elements

Downstream accretion elements are bounded by fourth-order surfaces, except where lower surfaces correspond to the fifth-order bases of channel bodies. Internally, downstream accretion elements contain second- and third-order surfaces that bound sets and cosets of trough-stratified, plane-parallel laminated, and ripple

cross laminated sandstone. These bounding surfaces dip at low angles (<10°) in the direction of paleoflow. These elements are interpreted to have formed as a result of downstream accretion of bar complexes in sand-dominated fluvial channels (Allen et al., 1983; Miall, 1985).

4.1.4. Lateral accretion elements

Lateral accretion elements are bounded by fourth-order surfaces, except where lower surfaces correspond to the fifth-order bases of channel bodies. In some cases, lateral accretion element tops are gradational with vertically accreted floodplain deposits (element FF, see below). Internally, lateral accretion elements contain second- and third-order surfaces that dip <20° perpendicular/oblique to the direction of paleoflow and bound sets and cosets of trough cross stratified and ripple cross laminated sandstone, as well as beds of plane-parallel laminated sandstone. In some cases these inclined strata contain intercalated ripple cross laminated sandstones and mudstones. Lateral accretion elements are interpreted as the deposits of point bars in single-channel fluvial systems (Allen, 1963; Puigdefábregas, 1973), or mid-channel bars and bar complexes in sand dominated, multi-channel fluvial systems (Miall, 1993). Interbedded cross laminated sandstones and mudstones contained in these lateral-accretion strata indicate

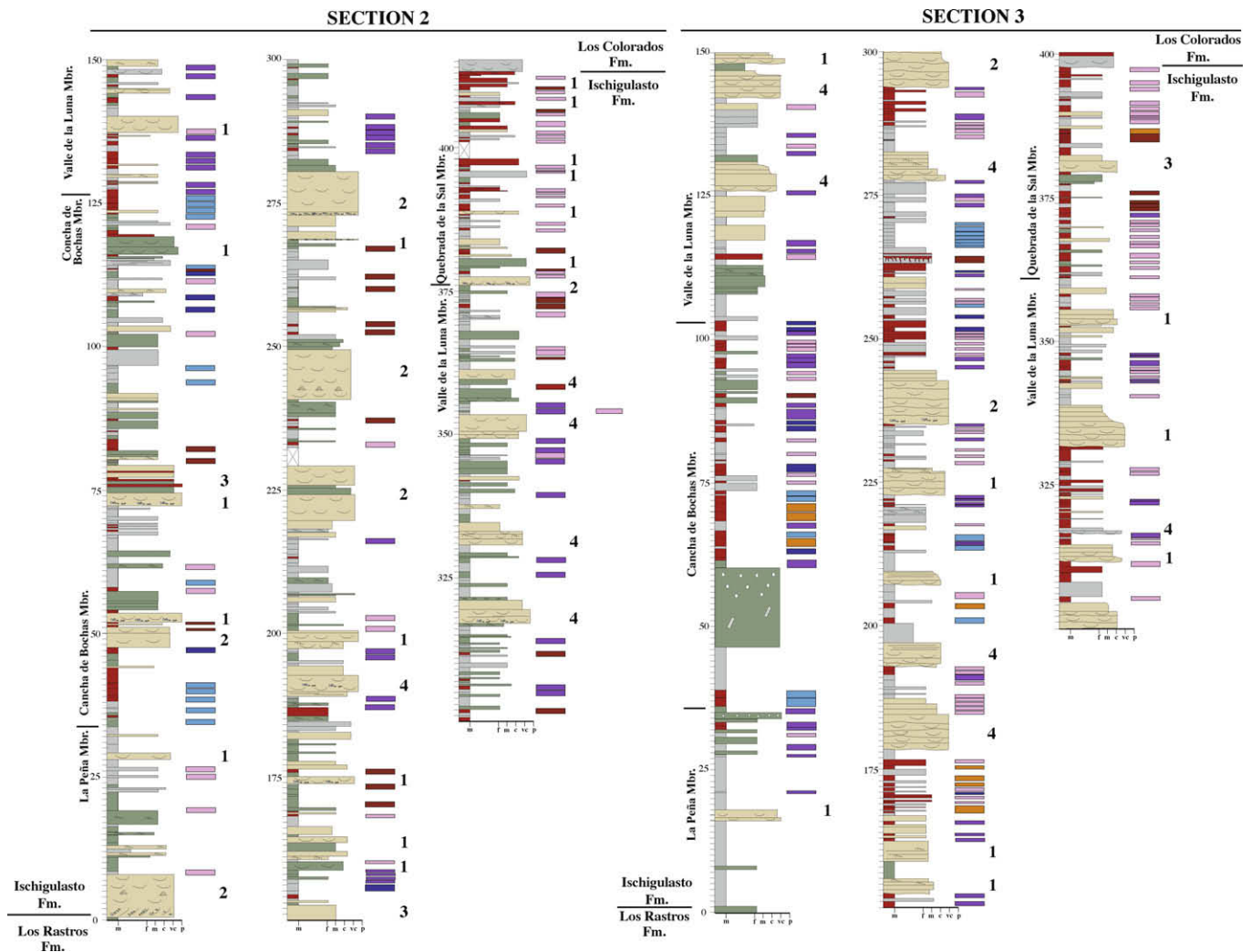


Fig. 4. Log of Ischigualasto Formation measured Sections 2 and 3. See Fig. 1 for location.

**Table 1**  
Ischigualasto Formation lithofacies.

Lithofacies code	Thickness	Description	Interpretation
Gh	0.25–1.0 m	Horizontally-stratified, pebble–cobble conglomerate and mudstone rip-up clasts	Longitudinal gravel bars, scour fills
Sh	0.2–2.0 m	Plane-parallel laminated, fine- to very coarse-grained/pebbly sandstone	Upper flow-regime plane beds
St	0.2–4.0 m sets up to 7.0 m	Trough-cross stratified, medium to very coarse-grained/pebbly sandstone	3-D dunes
Sp	0.15–1 m	Planar-cross stratified, medium- to very coarse-grained/pebbly sandstone	2-D dunes
Sr	<5 cm sets up to 2.5 m	Ripple cross-laminated, very fine- to coarse-grained sandstone	Ripples
Sm	<.5 m	Structureless, very fine- to coarse-grained sandstone containing root and vertical/horizontal burrow traces	Original structures destroyed by bioturbation
Fl	<2 m	Interlaminated, mudstone, siltstone, and fine-grained sandstone; commonly contains abundant carbonaceous plant fossils	Suspension and traction deposits
Fm	<5 m	Structureless sandy/pebbly mudstone	Suspension and traction deposits amalgamated by bioturbation and pedogenesis

deposition of sand and mud during periodic fluctuations in flow (Thomas et al., 1987).

#### 4.2. Channel classification

As part of this study, channel elements bounded by fifth-order surfaces were classified based on their overall geometry and inter-

nal organization. In general, Ischigualasto Fm. channel deposits consist of both sheet and ribbon sandstones (e.g. Friend et al., 1979; Friend, 1983) that, when viewed perpendicular to paleoflow, display concave-up to planar fifth-order scoured bases. Similarities in overall geometry, grain size, and internal organization, allow Ischigualasto fluvial sandstones to be further subdivided into four different classes (Fig. 5). Below is a description of the primary char-

**Table 2**  
Ischigualasto Fm. Architectural Elements.

Channel elements	Lithofacies	Bounding surfaces	Interpretation
Gravelly beds	Gh	4th–5th order	Gravel bedforms, bedload sheets, channel lags
Sandy beds	St, Sp, Sr, Sh	2nd–5th order	Dunes, ripple, upper-regime plane beds
Downstream accretion	St, Sh, Sr	4th–5th order	Down-stream accretion of sandy macroforms
Lateral accretion	St, Sh, Sr, Fm	4th–5th order	Lateral accretion of sandy macroforms and point bars
Overbank elements	Lithofacies		Interpretation
LV	Sr, St, Sh, Sm, Fl		Levee deposits
CS	St, Sr, Sm, Fl		Crevasse splay deposits
FF	Fm, Sr, Sm, Fl		Floodplain deposits
CH (FF)	Fl, Fm, Sr, Sm		Abandoned channel deposits
CR	Fm, Sr, Sm		Crevasse-channel deposits

### Type 1



**Single-storey sheet sandstones:** single-storey fills containing GB, SB, DA, LA elements; coarse median grain size ~80–500 m wide, 2–6 m thick; W:T 40–85.

**Interpretation:** sandy, braided channel deposits

### Type 2



**Multi-storey sheet sandstones:** vertically stacked, laterally coalesced, "Type 1" sandstones; ~200–2000 m wide, 5–20 m thick; W:T 50–100.

**Interpretation:** braided channel-belt deposits.

### Type 3



**Laterally accreted, ribbon and sheet sandstones:** fill dominated by LA elements; ~30–200 m wide, 2–8 m thick; W:T 10–25.

**Interpretation:** single-channel, point-bar deposits.

### Type 4



**Solitary, ribbon sandstones:** fills dominated by SB elements with rare GB, DA, LA; ~10–100 m wide, 3–8 m thick; W:T 5–13.

**Interpretation:** laterally stable, single-channel deposits

**Fig. 5.** Generalized flow-perpendicular cross sections and descriptions of Ischigualasto Fm. channel sandstones.

acteristics of each channel-sandstone type, information on their stratigraphic distribution within the formation, and an interpretation of the fluvial systems that resulted in their deposition.

#### 4.2.1. Type 1 channels

Type 1 channel forms are characterized by single-storey sheet sandstones 1–6 m thick. The width of these sandstone bodies, measured perpendicular to paleoflow direction, ranges from ~80 m to 500 m (Fig. 5). These channel forms have a median grain size of coarse sand. Internally, they consist primarily of sandy bed elements (Fig. 6A), but also contain downstream accretion, lateral accretion, and gravelly bed elements that can be both vertically and laterally juxtaposed. The uppermost elements display root and burrow traces that are overlain by gradational fourth-order contacts with overbank elements. Type 1 channels occur throughout the Ischigualasto Formation, but are most abundant in the Valle de la Luna Member of Section 1.

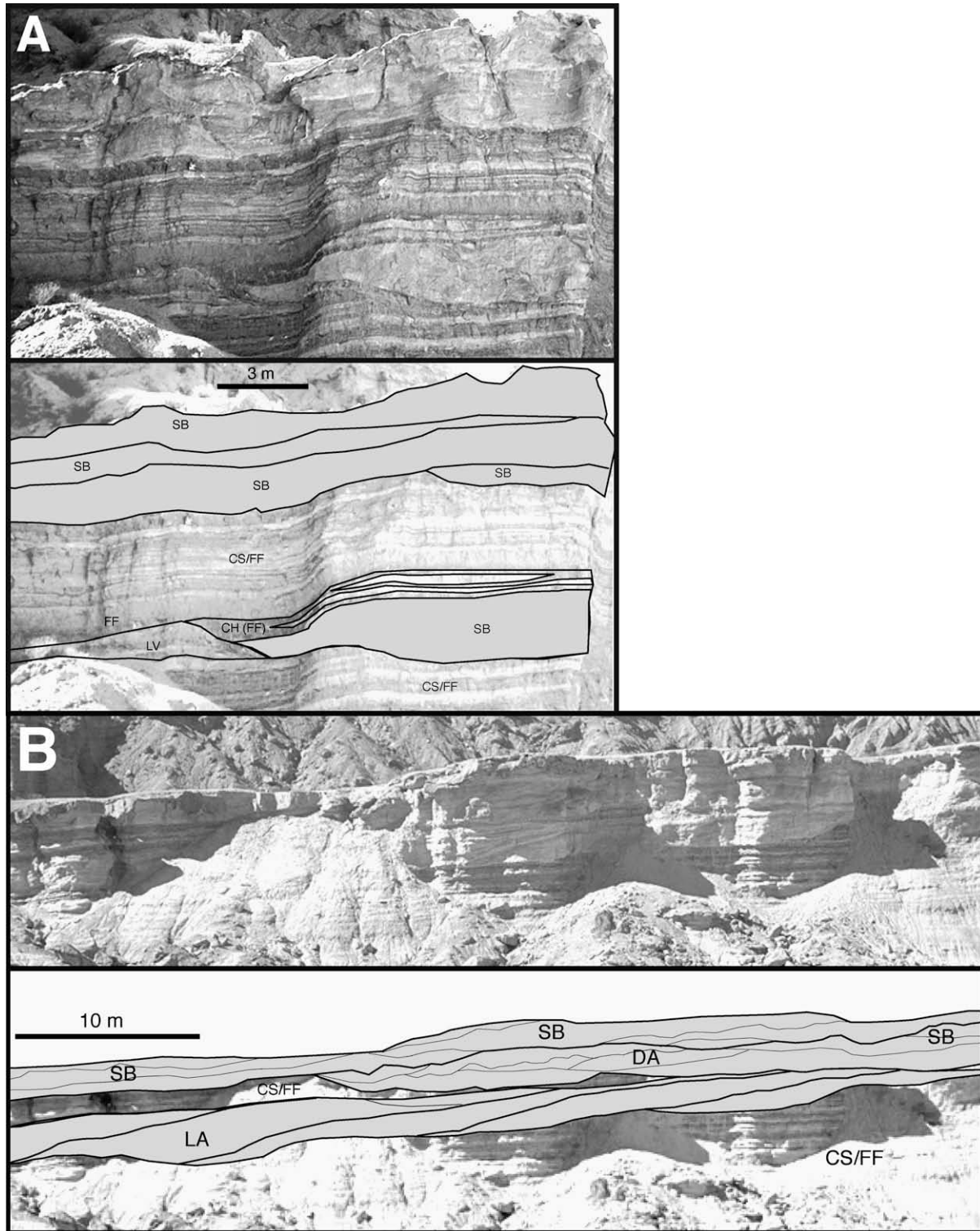
Type 1 channel forms are interpreted as the deposits of sandy, multi-channel (braided) fluvial systems (Miall, 1996). The single-storey nature of these channel forms suggests deposition within

channel belts with low aggradation rates relative to rates of channel migration (Willis, 1993).

#### 4.2.2. Type 2 channels

Type 2 channel bodies are multi-storey sheet sandstones, 5–20 m thick and ~200 m to >2 km wide (Figs. 5 and 6B). Width/thickness ratios in Type 2 sandstones range from ~50 to 135. Individual storeys contain elements similar to Type 1 bodies described above. The tops of the uppermost storeys display root and burrow traces and are separated from overlying overbank lithologies by gradational fourth-order surfaces. In some instances remnants of similar gradational contacts are preserved beneath the erosional bases of overlying storeys. Type 2 channels occur throughout the Ischigualasto Formation, but are most abundant in the Valle de la Luna Member of Section 1.

Sandstones with Type 2 geometries are interpreted as deposits of braided fluvial channels similar to Type 1 channels. However, the multiple-storey character of Type 2 sandstones suggests deposition within channel belts with relatively high rates of aggradation relative to rates of channel migration. Alternatively, these



**Fig. 6.** Ischigualasto Fm. channel forms. (a) Type 1 and 2 channel forms, Valle de la Luna Mbr., Section 3. (b) Lateral accretion surfaces in Type 3 channel form overlain by Type 2 channel sandstones, Valle de la Luna Mbr., Section 1.

sandstone bodies may represent the deposits of superimposed channel belts (Willis, 1993).

#### 4.2.3. Type 3 channels

Type 3 channel forms are single-storey sandstones consisting primarily of fining-upward lateral accretion elements (Figs. 5 and 6B). However, in some instances lateral accretion elements in Type 3 channels are capped by lenticular beds (<1 m thick) con-

taining sandy bed elements, above which are gradational fourth-order contacts with vertically accreted overbank lithologies. Individual Type 3 sandstones have a median grain size of medium sand, are 30–200 m wide and 1–8 m thick, and have width/thickness ratios between 10 and 25. With the exception of the La Peña Mbr., Type 3 channels occur throughout the Ischigualasto Formation and are most abundant in the Valle de la Luna Member of Section 1.

Type 3 channel sands are interpreted as the deposits of point-bars in single channel fluvial systems (Allen, 1963; Puigdefábregas, 1973). Associated lenses of sandy bed elements are interpreted as scroll bar or chute-channel fills deposited on the upper parts of point bars (Miall, 1996).

#### 4.2.4. Type 4 channels

Type 4 channel forms consist of single-story, ribbon sandstones, 10–100 m wide and 3–8 m thick (Fig. 5). Internally, Type 4 channels are filled primarily by sandy bed elements (Fig. 6A), although gravelly bed, downstream accretion, and rare lateral accretion elements have been observed. Aside from their dominantly sandy bed fill elements, Type 4 channels differ from Type 3 channels due to their lower width/thickness ratios (5–13) and overall coarser median grain size (coarse sand). Type 4 channels occur throughout the Ischigualasto Formation, with the exception of the La Peña Member. They are most abundant in the Valle de la Luna Member of Section 3.

Type 4 sandstones are interpreted as the deposits of low sinuosity, laterally-stable, single-channel fluvial systems. Single-storey channel forms similar to Ischigualasto Fm. Type 4 channels have been described by Allen et al. (1983) and Eberth and Miall (1991).

#### 4.3. Paleocurrent orientations

Paleocurrent indicators in Ischigualasto Formation channel sandstones indicate dominantly northwest to northeast paleoflow directions (Fig. 7). We measured the orientations of over 500 trough axes from cross-stratified sandstones to determine the flow direction of Ischigualasto fluvial systems. Although there are no observed trends in paleoflow directions between the stratigraphic members or individual channel types, there are distinct flow orientations in each of the three sections. For example, in Section 1, paleoflow was the most variable, with the majority of the paleocurrent orientations indicating paleoflow directed towards the northeast and northwest ( $020^\circ$  and  $330^\circ$ ). In Section 2, flow was predominately towards the north ( $005^\circ$ ), while in Section 3, flow was directed towards the northwest ( $330^\circ$ ) (Fig. 7). In general, the paleocurrent orientation of Ischigualasto fluvial systems was roughly perpendicular to the strike of the current outcrop exposures.

The calculated flow orientations indicate a sediment source area to the south-southeast of the study area. For Sections 1 and 2, this source area was located in the vicinity of juncture between the present-day Valle Fértil and Alto faults, suggesting a possible structural control on the position of the highland drainages entering the basin (cf. Gupta et al., 1999). For Section 3, a northwest paleoflow direction parallels the trend of the Triassic basalts outcropping to the east of the study area (Fig. 1) (Page et al., 1997). This indicates that there may have been a volcanic highland within the northeast part of the basin which diverted paleoflow to the

northwest during Ischigualasto Formation deposition and suggests that the fluvial systems in Section 3 may have been tributaries to those in Sections 1 and 2.

#### 4.4. Overbank architectural elements

Overbank elements in the Ischigualasto Formation consist of crevasse splay and levee deposits, floodplain fines, crevasse channels, abandoned channel deposits, and paleosols (Table 2). Each element is described in more detail below.

##### 4.4.1. Crevasse splay and levee deposits

Crevasse splay and levee deposits consist of tabular to wedge-shaped beds of ripple-cross laminated, trough cross stratified, plane-parallel laminated, and structureless sandstone (lithofacies Sr, St, Sh, and Sm). Individual beds are upward fining with sharp, non-scoured bases, and range in thickness from a few centimeters to over 2 m (Fig. 6). Both elements are associated with interbedded Fm. Differentiating between crevasse splay and levee deposits is often difficult because of facies similarities and lateral transitions between the two. However, levee deposits are generally coarser-grained, thicker bedded and commonly display an overall wedge-shaped geometry that tapers and fines away from adjacent channel elements. Levee deposits exposed at the margins of fluvial channel bodies are commonly gradational or interbedded with sandy bed channel elements. Crevasse splay deposits are generally thinner bedded, finer grained, and have an overall tabular geometry. Where associated with crevasse channel elements (see below), these tabular beds may be characterized as avulsion deposits (cf. Kraus and Wells, 1999).

##### 4.4.2. Floodplain fines

Fine grained floodplain deposits consist primarily of tabular, sheet-like deposits of structureless to weakly laminated sandy/pebbly smectitic mudstone (lithofacies Fm) with subordinate interbeds of fine-grained Sr and Sm. Individual beds range in thickness from a few centimeters to over 2 m and commonly display root traces as well as evidence of pedogenic modification (see below). These elements are commonly interbedded with distal crevasse-splay deposits.

##### 4.4.3. Crevasse channels

Crevasse-channel deposits consist of mudstone-dominated ribbons that contain u-shaped and inclined heterolithic strata consisting of interbedded mudstone and ripple cross laminated/structureless sandstone lithofacies (Fm, Sr, and Sm). Crevasse channels are 5–15 m wide and between 0.5 and 4.5 m thick, have scoured bases, and are commonly interbedded with crevasse splay elements. However, due to the dominantly fine-grained nature of their fill, they are commonly poorly exposed and difficult to recognize in outcrop. Crevasse channels are interpreted as having been

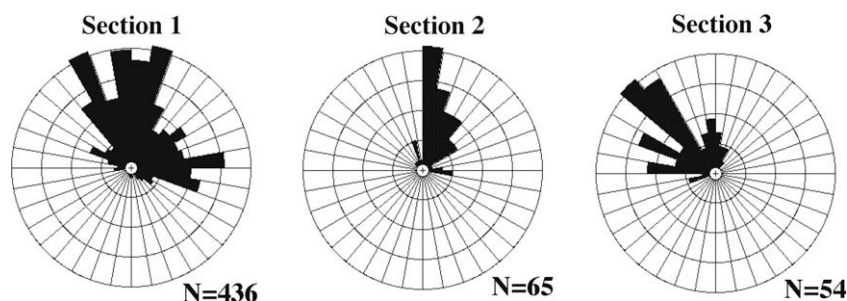


Fig. 7. Rose diagrams of Ischigualasto Fm. paleocurrent orientations in Sections 1–3. Each rose diagram shows dominant paleoflow directions determined from trough axis orientations in cross stratified fluvial channel sandstones. Maximum interval = 40%.

low- to high-sinuosity and mud-dominated. Their geometries and constituent lithofacies are similar to crevasse channels described by Smith et al. (1989), Eberth and Miall (1991), and Kraus and Wells (1999).

4.4.4. Abandoned channel deposits

Abandoned channel elements consist of lenses of interlaminated mudstone, siltstone, and fine-grained sandstone (lithofacies Fl, Fm, Sr, and Sm) that immediately overlie fluvial channel elements (in a gradational fourth-order contact). These elements commonly contain abundant, finely-disseminated carbonaceous material and plant fossils.

**Table 3**  
Relative abundances of Ischigualasto Fm. architectural elements.

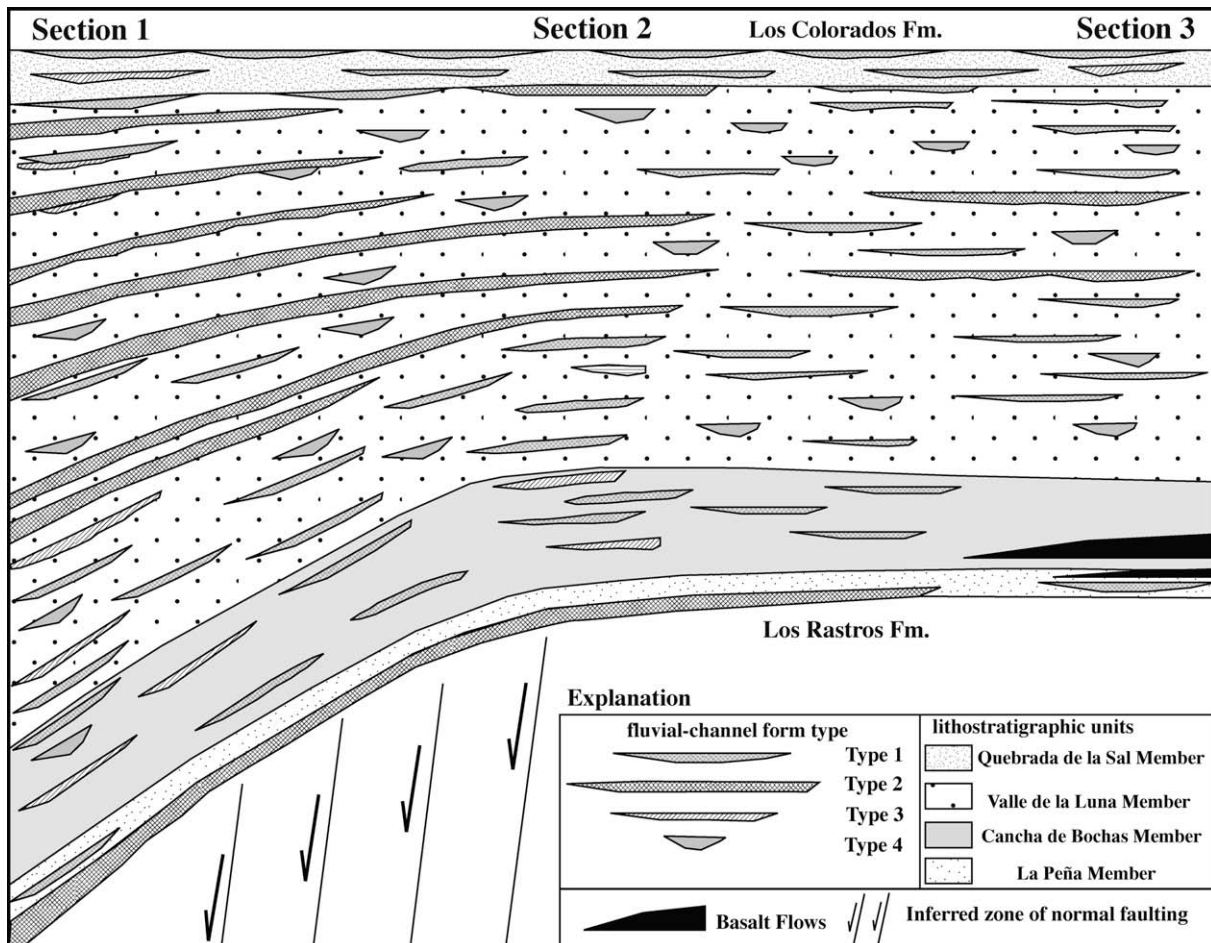
	Section 1	Section 2	Section 3
Thickness	691	413	397
Number of channel forms	52	29	17
% Channel deposits	31%	23%	21%
% Type 1	9% (n = 24)	7% (n = 16)	8% (n = 9)
% Type 2	14% (n = 14)	10% (n = 6)	5% (n = 2)
% Type 3	5% (n = 9)	2% (n = 2)	1% (n = 1)
% Type 4	3% (n = 5)	4% (n = 5)	7% (n = 5)
% CS + CR + LV	23%	23%	24%
% FF + CH(FF)	46%	54%	55%
% Paleosols	23%	30%	38%

4.4.5. Paleosols

The Ischigualasto formation contains abundant paleosols that display a wide range of pedogenic characteristics. Individual paleosols range in thickness from ~10 cm to >3 m and can contain root traces, carbonate nodules and rhizcretions, slickensided beds, gley mottling, and well-developed Bt horizons. Based on morphology and composition, Tabor et al. (2006) identified 6 primary pedotypes in the study area including protosols, gleyed vertisols, calcic vertisols, argillisols, calcisols, calcic argillisols (cf. Mack et al., 1993). Lateral transitions of pedotypes along individual paleosol horizons indicates there is a trend towards more morphologically-mature paleosol profiles away from coeval fluvial channels (Tabor et al., 2006). For example, across individual pedogenic horizons, lateral transitions are commonly observed from multiple stacked protosols to gleyed/calcic vertisols and argillisols/calcisols/calcic argillisols with increasing distance from the channel margins. Based on these considerations, it is probable that all pedotypes observed in the Ischigualasto formation coexisted on the same paleolandscape. However, paleosols in the lower part of the Ischigualasto Formation are dominated by calcic morphologies (i.e. calcic vertisols, calcisols, calcic argillisols) such that they are the lithostratigraphic basis for definition of the Cancha de Bochas Member (Appendix A).

4.5. Distribution of architectural elements

The distribution of Ischigualasto Formation architectural elements in the study area is closely linked to the lateral variations



**Fig. 8.** Generalized W-E basin cross section between Sections 1 and 3 showing thickness changes in Ischigualasto Fm. lithostratigraphic members, location of possible small-scale syndepositional fault zone and positions and relative geometries of and fluvial channel sandstones. See Fig. 1 for location.

in formation thickness observed across the study area. For example, the overall and normalized channel abundance decreases from west to east; 31% of the total vertical thickness of Section 1 (697 m) is made up of channel deposits while only 21% of Section 3 (397 m) contains channel forms (Table 3). While the overall percentage of Type 1 channels comprising each stratigraphic section is relatively constant across the study area (7–9%), the decrease in channel abundance to the east is due primarily to the number and thickness of Type 2 channel forms in each section. Type 2 channels make up 14% of the vertical thickness of in Section 1, while only 5% of Section 3 consists of similar channel forms. Similarly, Type 3 channel forms also decrease between Sections 1 and 3 (5–1%, respectively). The overall decrease of and Type 2 and Type 3 channel bodies is accompanied by a slight increase in Type 4 channel deposits; 3% of Section 1 is comprised of Type 4 channels while 7% of Section 3 is made up of similar forms.

In terms of other overbank elements, the percentage of levee and crevasse deposits in each section is relatively constant (23–24%), while the abundance of overbank fines increases from 46% in Section 1 to 55% in Section 3. In addition, there is an inverse relationship between the percentage of preserved fluvial channel deposits and paleosols in each section. Paleosols comprise 23%, 30%, and 38% of the vertical thickness of Sections 1–3, respectively.

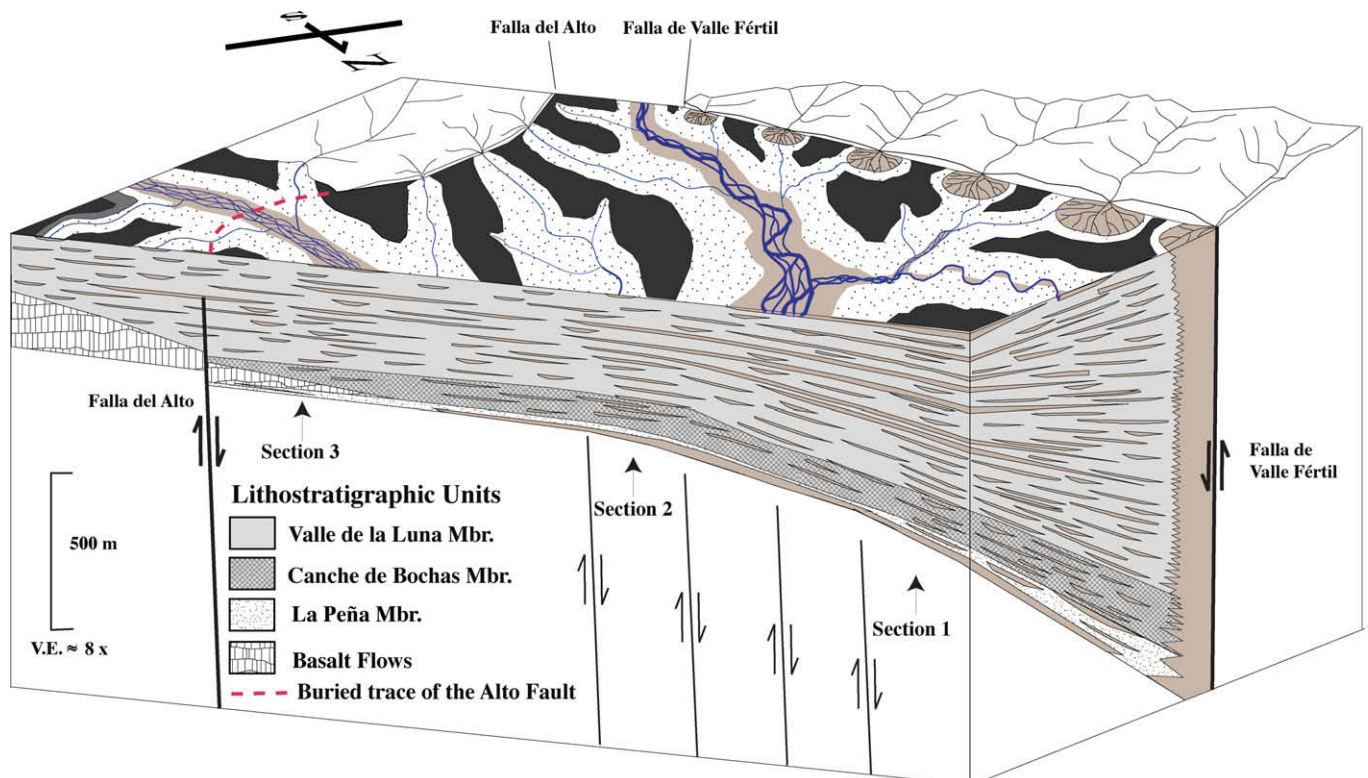
The relationships between Ischigualasto Formation architectural arrangement and stratigraphic thickness may be closely associated with differential subsidence caused by fault activity in the basin at the time of deposition. Evidence for syndepositional faulting is manifested in the drastic thickness change between Sections 1 and 2 where there is a >275 m change in formation thickness (Figs. 3, 4 and 8). This change in thickness may be related to an along-strike increase in displacement on the Valle Fértil paleofault which generated more fault related accommodation to the north-west during deposition (Milana and Alcober, 1994) (e.g. Walsh

and Watterson, 1988; Schlische, 1993). Another explanation for the observed thickening in the Ischigualasto Formation may be related to activity on small-scale (<10 m displacement) north-north-east trending, west-dipping normal faults that have been observed in outcrop in this area. Although there is no observable growth strata in the inferred paleofault zone, displacement on down-to-the-west basement faults during Ischigualasto deposition may have resulted in draping of the overlying strata prior to the faults propagating up section. Alternatively, faulting may have been broadly distributed in the observed zone of thickening, such that there is no apparent change in overall thickness across any one fault exposed at the surface. Although we have not determined which of these possible faulting scenarios occurred (either alone or in conjunction), a proportional westward increase in the thickness of all four lithostratigraphic members between Sections 1 and 2 (Fig. 8) suggests that faulting was continuous throughout Ischigualasto Formation deposition.

As a result of the overall increase in subsidence across the basin, major fluvial channel belts were concentrated in the west of the study area, as is evidenced by the relative abundance of Type 2 channel bodies in Section 1. The increased frequency of fluvial channel and proximal overbank deposits in the western parts of the study area was balanced by an overall increase in the deposition of distal fine-grained overbank deposits to the east. At the same time, there was also an overall increase in the percentage of paleosols formed in the eastern part of the study areas where overall sediment accumulation rates were lower.

## 5. Stratigraphic evolution

The combined sedimentologic and stratigraphic data presented above allows for an interpretation of the structural configuration and geomorphology of the basin during Ischigualasto Formation



**Fig. 9.** Block diagram of the Ischigualasto basin during deposition of the Valle de la Luna Member showing thickness changes of lithostratigraphic members, location of possible small-scale syndepositional fault zones, and relative geometries of fluvial channel sandstones. View is towards the south.

deposition. During Carnian time, the basin was dominated by north flowing fluvial systems draining highlands in the footwall of the Valle Fértil normal fault (Fig. 9). The dominant paleoflow directions were parallel to slightly oblique to the basin axis based on the interpreted NW trend of the basin-bounding Valle Fértil paleofault (Milana and Alcober, 1994). In addition, paleocurrent orientations in channel deposits in the east part of the basin parallel the trend of Triassic volcanic rocks northeast of the study area, suggesting the presence of a volcanic highland in the footwall of the Alto paleofault that directed fluvial systems to the northwest as it was progressively overlapped by alluvial deposits of the Cancha de Bochas, Valle de La Luna, and Quebrada de la Sal members. The absence of coarse-grained lithofacies near Section 3 suggests that there was little to no surface expression of the Alto fault during Ischigualasto Formation deposition (Fig. 9).

During Ischigualasto Formation deposition, major fluvial systems in the basin were concentrated in the western parts of the study area, presumably by the effects of syndepositional faulting. This faulting may have been associated with an along-strike increase in displacement on the basin-bounding Valle Fértil fault and/or displacement on small intrabasin normal faults. In either case this faulting generated greater accommodation in the western parts of the basin and resulted in an east to west increase in formation thickness from ~400 m to ~700 m. As faulting concentrated the majority of the large through-flowing fluvial channels in the western parts of the study areas, less frequent and/or volumetric fluvial channel and overbank deposition to the east resulted in the development of a greater abundance of paleosol horizons in the areas of decreased subsidence.

## 6. Discussion

The observed relationship between subsidence variations and channel and paleosol abundance supports current models on alluvial architectural development. First, the observed distribution of Ischigualasto Fm. channel deposits indicate that lateral increases in basin subsidence can result in the concentration and enhanced preservation of fluvial channel deposits in the areas of increased accommodation. Given that the overall paleocurrent orientation of Ischigualasto fluvial systems was roughly perpendicular to the observed along-strike increase in formation thickness, the distribution of channel deposits is similar to architectural models that predict preferential channel preservation and connectedness due to flow-perpendicular floodplain tilting or valley-parallel intrabasin faulting (Bridge and Leeder, 1979; Mackey and Bridge, 1995). In addition, our observations show that the overall percentage of paleosols preserved in the formation is inversely proportional to the abundance of fluvial channel deposits. The greater abundance of paleosols in the low-accommodation eastern part of the study area is in accord with architectural models that predict paleosols will be more numerous and vertically concentrated in response to reduced rates of subsidence (Wright and Marriott, 1993; Currie, 1997; Kraus 2002).

In terms of ideas regarding the interplay of avulsion frequency and overall alluvial architecture, the inverse relationship between the concentration of vertically and laterally amalgamated Type 2 channel deposits and paleosol abundance in areas that experienced greater amounts of subsidence points to an increase in avulsion frequency accompanying areas experiencing increased rates of sediment accumulation (Currie, 1997; Kraus, 2002).

Collectively, our comparison between high and low accommodation areas of the basin indicates that in areas of higher subsidence, fluvial channel deposits are more numerous, make up a higher percentage of the stratigraphic section, and display more lateral continuity than in low-accommodation areas of the basin. At the same

time, paleosols comprise a lower overall percentage of the stratigraphic section in areas of increased subsidence. These same relationships have been recognized in other fluvial-dominated rift assemblages. For example, Mack and Madoff (2005) reported that the abundance of multi-storey fluvial channels (similar to Ischigualasto Type 2 channel forms) increased in areas of increased fault generated accommodation within Pliocene–Pleistocene deposits of the Rio Grande Rift in the southwest United States. Mack and Madoff (2005) also documented an increase in the overall abundance of overbank deposits and preserved paleosols in areas away from the zones of syndepositional faulting, further corroborating our observations from the Ischigualasto Formation.

Our findings from the Ischigualasto basin also have important implications for the distribution of amalgamated fluvial channel forms in other rift assemblages. For example, we predict that large composite channel form bodies likely to contain economically viable hydrocarbon accumulations will be concentrated in areas that have experienced more fault-related accommodation. This prediction is applicable to rift assemblages dominated by axially-trending fluvial systems, as well as those that experienced intrabasin faulting oriented transverse or oblique to basin-bounding fault trends.

Our observations that amalgamated channel complexes are concentrated in regions experiencing greater fault-related accommodation is most likely to be applicable for both the early and late stages of “syn-rift” deposition in continental rift basins, as those stages are commonly characterized by widespread fluvial deposition (e.g. Lambiasi and Morley, 1999; Gawthorpe and Leeder, 2000). Examples of continental rifts containing syn-rift fluvial deposition include other Mesozoic rift basins in Argentina (e.g. the Cuyo, Colorado, and San Jorge basins; Uliana et al., 1989; Fitzgerald et al., 1990; Macdonald et al., 2003), the Triassic–Jurassic rifts of the North Atlantic margin and North Sea (Tankard and Wellsink, 1987; Ziegler, 1989; Schlische, 1993), and Early Cretaceous rift basins in eastern Asia (Lirong, 1997; Graham et al., 2001), as well as numerous others basins developed in extensional tectonic regimes throughout geologic time.

## 7. Conclusions

In the Ischigualasto Provincial Park in northwest Argentina, the Upper Triassic Ischigualasto Formation consists of ~400–700 m of fluvial channel sandstones, overbank mudstones, paleosols, and basalts. Internally, the Ischigualasto Formation consists of four lithostratigraphic members which in ascending order include the La Peña Member, the Cancha de Bochas Member, the Valle de la Luna Member, and the Quebrada de la Sal Member. Lithofacies assemblages in the Ischigualasto Formation can be subdivided into nine different architectural elements formed in both fluvial channel and overbank environments. Channel elements include the deposits of gravel bedforms, sandy bedforms, and downstream and lateral accretion elements. Overbank elements include levee deposits, crevasse splay deposits, flood plain fines, abandoned channel deposits, and paleosols. Channel deposits can be subdivided into four different classes based on cross-sectional geometry, grain size, and internal organization. Individual channel-form types are interpreted to be the deposits sandy, multi- to single-channel fluvial systems which experienced varying degrees of vertical and lateral amalgamation during deposition.

The internal organization of the Ischigualasto Formation is controlled primarily by stratigraphic variations in the location, size, and geometry of Ischigualasto fluvial channel deposits, as these variables relate directly to the distribution and lithologic/diagenetic characteristics of coeval overbank deposits. As a result of fault related subsidence, major fluvial channel belts were concentrated

in the west of the study area. The increased frequency of fluvial channel and proximal overbank deposits in the west was balanced by an increased abundance of distal fine-grained overbank deposits and paleosol horizons preserved in the Ischigualasto Formation to the east. The overall architectural arrangement is in accord with alluvial-architecture models that predict preferential channel preservation and connectedness in areas that experience flow-perpendicular variations in basin subsidence. Likewise, our observations are similar to other models that predict more numerous and vertically concentrated paleosols in areas of a basin that experience reduced rates of accommodation development.

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## Appendix A. Ischigualasto Formation lithostratigraphic members

Below is a formal designation of lithostratigraphic members for the Triassic Ischigualasto Formation of the Ischigualasto-Villa Union Basin, San Juan Province, Argentina. The Ischigualasto Formation, first described by Frenguelli (1944) and designated as part of the Agua de la Peña Group by Bossi (1971) has in the past been undifferentiated. Further stratigraphic, sedimentologic, and paleontologic descriptions of the formation have been presented by Stipanovic and Bonaparte (1979) and Alcober (1996). The four members presented below are defined for the southeastern end of the Ischigualasto basin in the area within the Ischigualasto Provincial Park. However, preliminary reconnaissance work indicates that they can also be identified in the northern parts of the basin.

The newly designated units are, in ascending order, the La Peña Member, the Cancha de Bochas Member, the Valle de la Luna Member, and the Quebrada de la Sal Member. Vertebrate fossils and isotopic ages of volcanic rocks in the Ischigualasto Formation indicate a Carnian age of deposition for all of the lithostratigraphic members described below (Rogers et al., 1993; Alcober, 1996; Shipman, 2004; Fig. 2). Lithologic descriptions for each of the newly defined members are given below.

### A.1. La Peña Member

The La Peña Member consists of ~35–50 m of tan/gray sandstone and conglomerate and green/gray smectitic mudstone. The member is named after the informal “Conglomerado de la Peña” that occurs in the study area at or near the base of the Ischigualasto Formation (Frenguelli, 1944; Alcober, 1996). The type section for the member is situated between 30.12892°S, 67.90674°W and 30.12773°S, 67.90392°W in the lower part of measured Section 2 (Fig. 4).

The base of the member is placed at base of the first pebble/cobble conglomerate, conglomeratic sandstone, or smectitic mudstone overlying the carbonaceous sandstones and mudstones of the Los Rastros Formation.

Coarse-grained lithologies of the La Peña member consist of Type 1 and Type 2 fluvial channel sandstones and conglomerates (Fig. 5). Fine-grained intervals in the La Peña Member are characterized by green and gray, sandy, smectitic floodplain fines that are interbedded with thin (10–50 cm), very fine- to medium-grained crevasse splay sandstones and siltstones. Paleosol types observed in the member include protosols, gleyed vertisols, and argillisol (Fig. 4) (Tabor et al., 2006).

### A.2. Cancha de Bochas Member

The Cancha de Bochas Member consists of ~65–125 m of mudstone and sandstone, with rare interbeds of bentonite and basalt. The member is named for the “Cancha de Bochas” area of the Ischigualasto Provincial Park in the lower part of Section 2 (Fig. 4). The type section for the member is situated between 30.12773°S, 67.90392°W and 30.11847°S, 67.89830°W. The member is characterized by red, green, and red/gray-mottled mudstones that commonly contain abundant calcareous nodules, rhizoliths, slickensides, peds, and cutans. The base of the member is placed at the first mudstone containing calcareous nodules above the base of the formation. The top of the member is placed at the top of the upper most mudstone containing calcareous nodules in the lower 1/3 of the formation.

Mottled mudstones containing root traces, cutans, peds and abundant carbonate nodules are interpreted as both calcareous (calcic vertisols, calcisols, and argillic calcisols) and noncalcareous (protosols and gleyed vertisols) paleosol horizons (Fig. 4) (Tabor et al., 2006). Individual channel-sandstone bodies in the member display characteristics representative of all four channel-body types (Fig. 5). Associated laterally with the channel deposits are thin tabular siltstone and fine-grained sandstone beds interpreted as crevasse splay and levee deposits. The unit also contains numerous mudstone-dominated lenses that contain u-shaped and inclined heterolithic strata interpreted as crevasse channels.

The Cancha de Bochas Member also contains several thin (<15 cm) yellow, gray, and red bentonite beds, many of which contain very-fine grained, euhedral sanidine and plagioclase crystals. Basalts in the unit outcrop in the eastern part of the study area in the vicinity of Section 3 and range from 1 to 25 m in thickness. These basalts commonly contain plagioclase phenocrysts and display vesicular to amygdaloidal textures. The thin bentonite beds are interpreted as altered volcanic ash deposits, while the amygdaloidal/vesicular basalt beds are interpreted as flow basalts.

### A.3. Valle de la Luna Member

The Valle de la Luna Member of the Ischigualasto Formation consists of 250–470 m of mudstone and sandstone. The member is named after the valley in which the majority of the Ischigualasto Provincial Park is situated. The type section for the member is located between 30.11025°S, 67.90122°W and 30.03723°S, 67.93707°W within Section 1 of the study area (Fig. 3). The base of the member is placed at the top of the upper-most calcareous paleosol in the Cancha de Bochas Member. The top of the unit is placed at the top of the uppermost gray smectitic mudstone or tan/gray sandstone below the dominantly brown, gray, and red mudstones and sandstones of the Quebrada de la Sal Member.

In the eastern part of the study area (Sections 2 and 3), dark gray, structureless smectitic fine-grained flood plain deposits dominates the Valle de la Luna Member. To the west near the type section, however, the member contains a higher percentage of channel sandstones and crevasse splay and levee deposits. Interpreted channel sandstones display all four observed channel-body types (Fig. 5). In Section 1 the unit contains numerous abandoned channel deposits containing abundant carbonaceous mudstone

and plant fossils. In all three sections the member contains heterolithic and sandy crevasse channels. In some parts of the member fluvial channel and overbank deposits are pedogenically modified. Paleosol types observed in the member include protosols, gleyed vertisols, calcic vertisols, argillisols, calcisols, and argillic calcisols (Figs. 3 and 4) (Tabor et al., 2006). The thin bentonite beds preserved in the member are altered silicic volcanic ash deposits.

#### A.4. Quebrada de la Sal Member

The Quebrada de la Sal Member of the Ischigualasto Formation contains 35–65 m of mudstone and sandstone. The type section is situated between 30.08502°S, 67.89191°W and 30.08048°S, 67.89133°W near the mouth of “Quebrada de la Sal”, a large canyon near the top of measured Section 2 (Fig. 4). The base of the member is placed at the first red or brown mudstone or sandstone above the dominantly gray smectitic mudstones and tan sandstones of the Valle de la Luna Member. The upper boundary of the member is placed at the top of the last gray, or red/gray mottled mudstone or sandstone below the dominantly red-colored sandstones and mudstones of the Los Colorados Formation.

Channel sandstone in member is the deposits of Type 1, 2, 3, and 4 channels (Fig. 5). In addition, the member contains abundant crevasse splay, crevasse channel, and levee deposits. Mudstones in the Quebrada de la Sal Member are brown, red, gray, and green in color and are commonly pedogenically modified. Paleosol types recognized in the member include protocols, gleyed vertisols, argillisols, and calcisols (Figs. 3 and 4). The member also contains several thin (<15 cm) gray and red bentonite or siliceous siltstone beds. These lithologies, which are interpreted as altered volcanic ash deposits, contain very-fine grained, euhedral sanidine and plagioclase crystals.

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