

LATE TRIASSIC ENVIRONMENTAL EVOLUTION IN SOUTHWESTERN PANGEA: PLANT TAPHONOMY OF THE ISCHIGUALASTO FORMATION

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ABSTRACT

The Ischigualasto Formation was deposited in a fluvial system and contains a very well preserved Triassic flora. This flora comprises seven taphofacies: (1) C(St), autochthonous silicified roots of low-statured, woody plants associated with low-sinuosity channels and crevasse-splay deposits; (2) A(Sm/Fm), autochthonous carbonized roots or root impressions of herbaceous plants in crevasse-splay and levee deposits; (3) B(Fsm/Fm), autochthonous root halos of herbaceous plants associated with levee deposits; (4) EI(St), allochthonous silicified tree trunks and charcoal associated with high- and low-sinuosity channel bars; (5) GI(St), leaf cuticles and charcoal associated with trough cross-bedded sandstone; (6) FH(FI/C), leaf cuticles and impressions associated with palynomorphs in abandoned-channel deposits; and (7) D(FI), autochthonous silicified stumps in abandoned-channel deposits. Taphonomically, the Ischigualasto Formation can be divided into four parts, and these partially correspond to changes in the environment. The basal part (~0–45 m) includes the transition from the underlying Los Rastros Formation and is characterized by taphofacies 1 and 2. The fluvial sediments were deposited during tectonic subsidence of the basin, resulting in development of a fluvioaxial system. The next part (~45–300 m) is characterized by taphofacies 1, 2, and 3 and associated with calcic paleosols that formed under a dry seasonal climate. The middle-upper portion (~300–600 m) contains all the taphofacies associated with argillic paleosols, which were formed during a time of increasing humidity. The upper portion (~600–700 m) is characterized by taphofacies 1, 2, and 3, associated with immature paleosols that formed under a dry seasonal climate. The changes in humidity during deposition of the Ischigualasto Formation may have resulted from an increase in rainfall generated on the western side of Pangea by maximal development of the megamonsoon during the middle Carnian Age. The climatic signal in the Ischigualasto Formation was probably modified by the tectonosedimentary development of the basin.

INTRODUCTION

The Ischigualasto Basin of west-central Argentina (Fig. 1) is one of several extensional basins developed on the western margin of Pangea during the early Mesozoic (López Gamundi et al., 1989; review in B.S. Currie et al., in press). The basin has one of the longest and most complete continental Triassic sections in the world and is well known for the important assemblages of paleoflora and fauna preserved there, particularly in the Carnian (Upper Triassic) Ischigualasto Formation. The Ischigualasto Formation comprises fluvial sandstone, mudstone, and paleosols and was deposited during the last stage of synrift tectonics (Milana and Alcober, 1994); there was also active syndepositional subsidence (B.S. Currie et al., in press).

The purpose of this paper is twofold. First, we provide the first description and interpretation of the plant taphofacies in the Ischigualasto Formation. Second, we integrate the taphofacies with information on fluvial architecture and paleosols (Shipman, 2004; Tabor et al., 2004, 2006; B.S. Currie et al., in press) in order to interpret the climate.

Taphonomy is the study of the processes that affect a fossil between the time the organism dies and when it is found by a paleontologist (e.g., Spicer, 1989), and it is particularly useful when combined with sedimentological information. The application of taphonomy to paleobotanical studies is a relatively recent development that has influenced many American and European empirical and experimental studies (Ferguson, 1985; Spicer and Greer, 1986; Spicer, 1989; Demko, 1995; Gastaldo et al., 1996; Campbell, 1999; Gastaldo and Staub, 1999; Fielding and Alexander, 2001; Gupta and Pancost, 2004; Parrish et al., 2004). Several of these were actualistic studies involving statistical and observational analyses of the processes involved in recent mega- and microfloras in order to determine the mechanisms by which plant remains are influenced by taphonomic processes—that is, the disassociation, loss, and sorting of plant parts and their subsequent burial and fossilization. These studies aid in interpretation of the condition of plant fossils with respect not just to the sedimentary context in which they occur but likely to predepositional taphonomic processes as well.

Plant taphonomy has been applied to the study of numerous basins as a tool to interpret paleoclimate, tectonosedimentary evolution, paleoecology, and paleoenvironments (Ferguson, 1985; Spicer, 1989; Demko, 1995; Demko et al., 1998; Campbell, 1999; Parrish et al., 2004). For example, Demko (1995) used complementary taphonomic and sedimentologic studies to yield a complete paleoenvironmental and paleoclimatic interpretation of the Upper Triassic Chinle Formation, resolving previous and apparently contradictory paleoclimatic interpretations (see Dubiel et al., 1991, for a summary of this conflict).

This study is the first to apply plant taphonomic methods to an Argentine basin. Paleofloristic studies in the Ischigualasto Basin have addressed taxonomy and taxon-based paleoecology and have described the flora and the ecological niches that the plants occupied (Herbst, 1970a, 1970b; Spalletti et al., 1999; Zamuner et al., 2001). The Zamuner et al. (2001) study included a compilation of the flora from the entire formation, along with paleoecological interpretations, but it addressed neither stratigraphic nor geographic variations of the flora. Rather, the authors interpreted the paleoecology of the plants for the entire formation without taking into account the highly variable distribution of the flora in the formation or variations in the taphonomy. In this study, we distinguish variations in the taphonomy in order to determine the paleoclimatic and paleoenvironmental evolution of the Ischigualasto Formation.

The Ischigualasto Formation is particularly critical for understanding the climate of the supercontinent Pangea. This climate, particularly that of the Triassic, has been described as a megamonsoon (Kutzbach and Gallimore, 1989; see the Discussion below). In her compilation of information on Pangean climates, Parrish (1993) hypothesized a monsoon maximum in the Late Triassic based primarily on information from the

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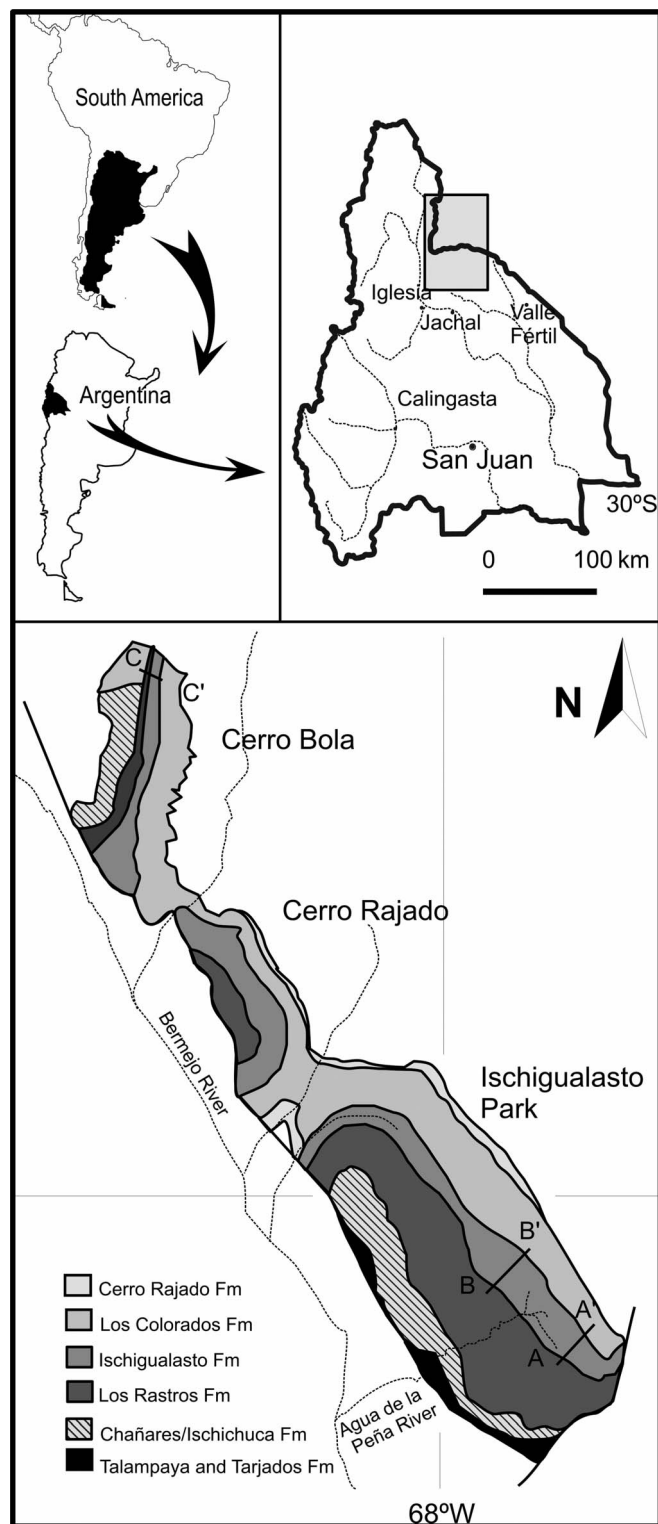


FIGURE 1—Location map of the Ischigualasto Basin and geological map with locations of the measured sections. A–A' = La Gallinita section; B–B' = Agua de la Peña section; C–C' = Cerro Bola section.

northern part of the supercontinent, and important elements of that hypothesis centered around information from the western portion. The record from the Gondwanan half of Pangea, however, is relatively sparse. The Australian record is ambivalent, suggesting an earlier maximum in the south (Parrish et al., 1996), but Australia lay in the southeast quadrant of Pangea. Therefore, information from the Ischigualasto Basin, by far

the best exposed low-paleolatitude Triassic basin in the southwest quadrant of Pangea, is especially critical to resolving the possible inconsistency between the northern and southern Pangean records. We will return to this point in the Discussion.

Geological Setting and Age of the Ischigualasto Formation

The Ischigualasto Basin lies in northeastern San Juan and southwestern La Rioja provinces, Argentina (Fig. 1), and was an extensional half-graben, part of a series of Triassic basins that developed parallel to and cratonward of the proto-Andean arc (Uliana and Biddle, 1988; Ramos and Kay, 1991; López-Gamundi et al., 1994); the basin lay between 40°S and 45°S (Golonka, 2007). Deposition in the basin began in the Early Triassic and continued throughout the period. Triassic rocks are overlain by Cretaceous and Cenozoic rocks, and basin inversion occurred during the Quaternary, when the bounding Valle Fértil and Altos normal faults were reactivated as reverse faults (Milana and Alcober, 1994). Milana and Alcober (1994) proposed that the Ischigualasto Formation was deposited during active subsidence (synrift), but Shipman (2004), on the basis of fluvial architecture and paleosols, argued that at least the upper part of the formation was deposited during postrift passive subsidence. Regardless, subsidence was syndepositional (B.S. Currie et al., in press).

The Ischigualasto Formation is underlain by carbonaceous shale, siltstone, and sandstone of the Los Rastros Formation, which exhibits an overall coarsening-upward trend, with Gilbert-type deltaic clinoforms, and has been interpreted as lake-basin fill (Milana and Alcober, 1994; Rogers et al., 2001). The Ischigualasto is overlain by the Los Colorados Formation, which consists of evaporites, red siltstone, sandstone, and conglomeratic sandstone interpreted as playa and fluvial deposits (Stipanovic and Bonaparte, 1979; Milana and Alcober, 1994). The Ischigualasto has been divided into four stratigraphic members on the basis of the fluvial architectural elements and the types of paleosols (B.S. Currie et al., in press). From the base to the top of the formation, these are La Peña, Cancha de Bochas, Valle de la Luna, and Quebrada de la Sal members (B.S. Currie et al., in press); Tabor et al. (2006) referred to these as Units I–IV. Brief descriptions of these members along the most representative section (B.S. Currie et al., in press) are summarized in Table 1.

The Ischigualasto Formation contains many ash layers and a basalt at the base of the formation on the southeastern end of the outcrop belt. Using K/Ar techniques, Odin and Letolle (1982) dated the basalt at 229 ± 5 Ma. Sandstone from a tuff 20 m above the base yielded an age of 227.8 ± 0.3 Ma (Rogers et al., 1993). Shipman (2004) reported a date of 218 ± 1.7 Ma from 29 m below the top of the formation in the southeastern part of the basin; Tabor et al. (2006) also reported a date of 223 ± 0.4 Ma from near the top. These dates indicate an age of Carnian-earliest Norian on the timescale of Gradstein et al. (1995). This age is supported by the vertebrate fossils (Rogers et al., 1993).

Overview of Flora

The Upper Triassic flora of the Ischigualasto Formation is distinguished by the presence of plant remains assignable to the Corystospermaceae. This family of seed ferns was widespread in Gondwana; they appeared in the Early Triassic, diversified in the Middle Triassic, and declined in the Late Triassic (Zamuner et al., 2001). More cosmopolitan elements are also present in these communities, including equisetophytes *Neocalamites* and *Equisetites*, and peltasperm remains assignable to *Lepidopteris* and *Scytophyllum* (= *Dellephyllum*). According to Zamuner et al. (2001), the Triassic megafloora of Argentina comprises 236 species, and the Ischigualasto contains 21 of these (Table 2).

METHODS

Both field and laboratory methods were used in this study. Field methods included detailed measured sections, sedimentological descriptions, and descriptions of the plant remains *in situ*—that is, type of organs,

TABLE 1—Summary of the characteristics of the members of the Ischigualasto Formation, including overall thickness, percentage of channel deposits (average vertical thickness in the measured sections), percentage of floodplain deposits (average vertical thickness in the measured sections), types of channels represented, main type of channel, types of paleosols, and paleoenvironmental interpretation. Channel types: 1 = single-story, sandy, multichannel (braided) fluvial systems (Miall, 1996); 2 = multistory, sandy, multichannel (braided) fluvial system (Miall, 1996) or, alternatively, superimposed channel belts (Willis, 1993); 3 = point-bar or associated deposits in single-channel fluvial systems (Puigdefábregas, 1973); 4 = single-story, low sinuosity, laterally stable, single-channel fluvial systems (Eberth and Miall, 1991). Paleosol types from Tabor et al. (2006).

Member	Overall thickness (meters)	Channel deposits %	Floodplain deposits %	Types of channels	Main type of channel (see caption)	Paleosols	Description and paleoenvironmental interpretation
La Peña	50	49	51	1–2	2	Protosols Argillisols	Fluvial deposits containing multiple-story channel deposits, sandstone and conglomerate, representing principally low-sinuosity, braided rivers, with green and grey, fine-grained floodplain deposits interbedded with crevasse-splay deposits
Cancha de Bochas	125	12	88	1–2–3–4	3	calcic Vertisols Calcisols argillic Calcisols Protosols gleyed Vertisols	Fluvial deposits dominated by red, green and red-gray-mottled fine-grained rocks of floodplain deposits, interbedded with channel sandstone representing principally high-sinuosity channels, associated with levee and crevasse-splay deposits; also contains basalt and red bentonite beds
Valle de la Luna	470	55	45	1–2–3–4	1–2	Protosols gleyed Vertisols Argillisols Calcisols argillic Calcisols	Fluvial deposits dominated by channels of different types interbedded with dark grey and red-grey, fine-grained floodplain deposits, associated with abundant abandoned channel, crevasse-splay and levee deposits
Quebrada de la Sal	65	41	59	1–2	1	Protosols (dominant) gleyed Vertisols Argillisols Calcisols	Floodplain deposits dominated by brown, red, grey, and green mudstone interbedded with single-story braided channel, crevasse-splay, and levee deposits and many layers of altered volcanic ash

sorting, orientation, degree of degradation, density, and positional relationship to other plant (and vertebrate, if present) remains, in all horizons in which plant remains were found. Vertical and lateral variations in the taphofacies were evaluated in order to determine the mechanisms responsible for the spatial and temporal distribution of the floral assemblages. The sections were measured with a Jacob's staff, and sedimentary rock texture and structures were described for each bed and subsequently classified according to the methods established by Miall (1996). The color of each lithofacies was determined using the Munsell system.

Field work objectives were to select the zones to be described in detail, to sample and correlate horizons across as much of the lateral extent of the basin as possible, and to sample in detail the richest fossiliferous zones of the formation. We sought out plant-rich beds for analysis, so the sampling was not random but rather intentionally biased toward plant-rich zones. The principal reason for this is that the formation as a whole is poor in plant materials (see the Discussion below).

Three areas were selected for detailed study, two on each margin of the basin and one near the apparent depocenter. The southeastermost

TABLE 2—Paleofloristic composition of the Ischigualasto Formation (Zamuner et al., 2001). Division Tracheophyta. Note that workers elsewhere place the Corystospermeaceae within the Corystospermales, but we retain the Argentine classification here.

Class	Order	Family	Species
Sphenopsida	Equisetales	Apocalamitaceae	<i>Neocalamites carrerei</i> (Seiller) Halle
Filicopsida	Filicales	Osmundaceae	<i>Cladophlebis mendozaensis</i> (Geinitz) Frenguelli
Gymnospermopsida	Caytoniales (Pteridosperms)	Corystospermeaceae	<i>Dicroidium lancifolium</i> (Morris) Gothan <i>Dicroidium odontopteroides</i> (Morris) Gothan <i>Zuberia papillata</i> (Townrow) Artabe <i>Zuberia zuberi</i> (Szajnocha) Frenguelli <i>Johnstonia coriacea</i> (Johnston) Walkom <i>Johnstonia stelzneriana</i> (Geinitz) Frenguelli <i>Xylopteris argentina</i> (Kurtz) Frenguelli <i>Xylopteris elongata</i> (Carruthers) Frenguelli <i>Rhexoxylon piatitzkyi</i> Archangelsky and Brett <i>emend.</i> Brett
		Peltaspermeaceae	<i>Lepidopteris stormbergensis</i> (Seward) Townrow <i>Scytophyllum neuburgianum</i> Dobruskina
	Cycadales	Zamiaceae	<i>Michelilloa waltonii</i> Archangelsky and Brett
	Cycadales <i>incertae sedis</i>		<i>Yabiella</i> sp. <i>Yabiella brackebuschiana</i> <i>Yabiella mareysiaca</i>
	Bennettitales		<i>Pterophyllum</i> sp.
	Cycadophytes <i>incertae sedis</i>		<i>Taeniopteris</i> sp.
	Ginkgoales		<i>Ginkgoites</i> sp.
	Coniferales	Podocarpaceae Araucariaceae Protopinaceae	<i>Heidiphyllum elongatum</i> (Morris) Retallack <i>Araucarioxylon</i> sp. A <i>Protojuniperoxylon ischigualastensis</i> Bonetti

stratigraphic section we referred to as La Gallinita section and the north-westernmost section as the Cerro Bola section; the section in the middle of the basin is the Agua de la Peña section (Fig. 1). We also analyzed much of the area in between the sections, by observation and classification of taphofacies in plant-bearing horizons and correlation of those horizons with the detailed sections where possible.

Paleosols were classified according to a system proposed for the Ischigualasto Formation by Tabor et al. (2006). This classification separated the paleosols into Protosols, Vertisols, calcic Vertisols, gleyed Vertisols, Argillisols, Calcisols, calcic Argillisols, and Andisols; these are similar to those identified by Shipman (2004), who also identified vitric Protosols and basaltic Vertisols where basalt layers are pedogenically altered.

The sedimentology and plant taphonomy were analyzed in greatest detail in the Agua de la Peña section, partly because this section is richest in plant remains. The data obtained from this section were the primary basis for definition of the preservational styles and taphofacies, after which the taphofacies classification was extended to the rest of the basin. This analysis began with development of tables for taphonomic data collection in the field, based on the method of Behrensmeier (1991) for vertebrates, subsequently adapted for plants by Demko (1995). The taphonomic information is portrayed on a graph with a scale appropriate to each variable, which may be quantitative, as in the case of concentration of remains, or qualitative, as in the case of style of permineralization, for example. This allows a rapid comparison among taphofacies using all the different parameters.

The sedimentologic data provided information about the energy of the depositional processes, surface and subsurface paleoenvironmental conditions, and hydraulics of the paleocurrents and allowed definition of the sedimentary environment and the conditions of entrainment, transport, and burial of the plant remains. The spatial pattern was useful for determining the characteristics of the floral community and the transport regime, whether the taphocoenosis was autochthonous or allochthonous, the source of the remains, and the type of sedimentary processes responsible for burial.

The mode of fossilization provided information about the geochemical environment to which the remains were subjected during deposition and subsequent diagenesis, particularly those conditions that are useful as indicators of paleoclimate. Information about preburial damage was used to determine the importance of abrasion and breakage during transport and the degree and type of decay, in order to distinguish these processes from later alteration, such as change in structure during fossilization or volumetric and morphologic changes during compaction and diagenesis. Presence or absence of adjacent root systems, soil development, degree of abrasion, characterization of the architectural elements according to their transport characteristics, relationship between vegetation and sedimentary structures, as well as other variables, were essential for determining whether the remains were autochthonous, parautochthonous, or allochthonous and, thus, the relationship between the plant community and its environment. Finally, the association with other organic structures was useful for evaluating the entire community structure. The relationships among the different components—plant-vertebrate-invertebrate—as well as comparisons of the preservational potential of each type of remains (e.g., animal bones may undergo more weathering in the environments that are favorable for plant preservation, thus limiting their preservational possibilities) and the taxonomy of paleofloristic assemblages and dominant organs helped in determining the paleoecologic characteristics of the community.

Taphofacies were mapped and tied to measured sections. The taphofacies were given designations composed of a combination of letter codes for the preservational styles and lithofacies following the classification of Miall (1996).

RESULTS

Preservational Styles

We identified nine preservational styles: (A) fibrous root traces and root impressions, (B) root halos, (C) silicified stumps and roots of low-statured woody plants, (D) vertical silicified stumps of large-statured

woody plants (trees), (E) horizontal or subhorizontal silicified trunks, (F) horizontally oriented cuticles and impressions, (G) cuticles oriented obliquely with respect to bedding, (H) palynomorphs, and (I) charcoal fragments. Each letter is incorporated in the descriptions of the taphofacies in the following section, and preservational styles are illustrated in Figures 2A–I and described in the following paragraphs.

A. Fibrous Root Traces.—These are autochthonous root traces consisting of thin, vertical traces with lateral branching, generally at right angles to the axis (Fig. 2A). The traces can vary in length from millimeter to centimeter scale, with a maximum length of 10 cm; diameters are always submillimeter scale. The root traces are present in medium-to-high concentrations and apparently are distributed randomly, although clustered in some cases. The orientation of the traces with respect to the bedding plane is usually about 90°, although in some cases they are oblique or even parallel; the parallel traces may represent branches of vertical traces that are not exposed. Generally the traces are preserved as impressions with carbon films, occasionally as hematite, although in some cases, all evidence of organic material is missing, and the traces are outlined by clay.

B. Root Halos.—These are pedogenic features preserved as halos varying in coloration and found surrounding root traces, root impressions, or molds (Fig. 2B). The original organic material is in most cases completely gone, leaving a halo as the last vestige of the root's existence, although halos are also not necessarily exposed at the root axis. The halos vary in dimension according to the original dimensions of the root, the degree of pedogenesis of the enclosing strata, or the exposure, but generally range in size from millimeters to centimeters wide and a few centimeters to ~60 cm long. The coloration is gray-green in oxidized (red or orange) soils or, more rarely, reddish halos in reduced (gray or green) soils. Some halos of this latter type are preserved with the original organic material oxidized to hematite, and these are included in preservational style A.

C. Silicified Stumps and Roots of Low-Statured Woody Plants.—These are autochthonous stumps with roots; they are oriented vertically and average 5 cm in diameter up to 20 cm (Fig. 2C). In some cases, the roots can be traced obliquely, with respect to bedding, as far as 1 m or horizontally as far as 5 m. The diameters of the roots vary from 3.5 cm at the bases of the stumps to 1 cm at the apices of the lateral roots.

The stumps are always associated with the upper surface of the strata in which they are found, in some cases truncated by the upper bedding plane and sometimes with a vertical component that penetrates the overlying deposit. Laterally, they are distributed randomly or form concentrated clusters. The stumps and roots are permineralized with silica, and it is interesting to note that the sediments surrounding the roots also appear to be silicified close to the roots, grading away from the roots to the carbonate cement that typifies the sandstone beds of the Ischigualasto Formation. The silicified halos of the roots, generally 5 cm in diameter, are commonly lighter than the surrounding sediment. It is possible to see silica-filled holes, ~2 mm in diameter, in the larger stumps, distinguished from the stump by massive structure and dark brown and black colors; these may be insect borings.

D. Vertical Silicified Trunks and Stumps of Large-Statured Woody Plants.—These are autochthonous stumps and bases of tree trunks (Fig. 2D), specifically of *Rhexoxylon piatnitzkyi* Archangelsky and Brett emend. Brett (Zamuner et al., 2001). The diameter of the figured specimen is ~20–50 cm, although the length is indeterminate because the lower portion is buried. The concentrations of these are low, generally no more than two trunks per stratum. The stumps are oriented vertically or slightly inclined relative to stratification. They are always in each upper layer of the deposit in which they occur. The fossils are permineralized by amorphous silica that is streaked in dark brown, black, and white. Internal structure of the trunks is well preserved; tracheids, rays, and growth rings are all visible, although only in patches, preventing growth-ring analysis (e.g., Creber and Chaloner, 1984). A zone of friable charcoal 0.2–4 cm thick forms the outer layer of every trunk except on exposed

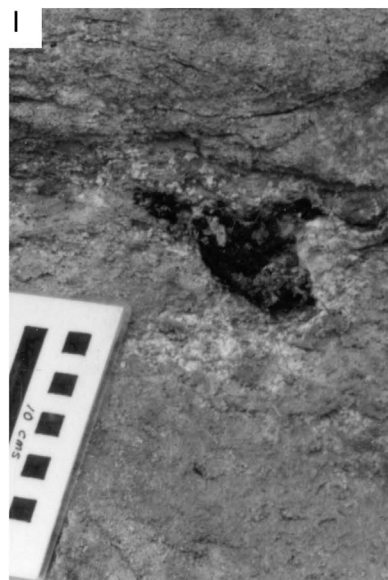
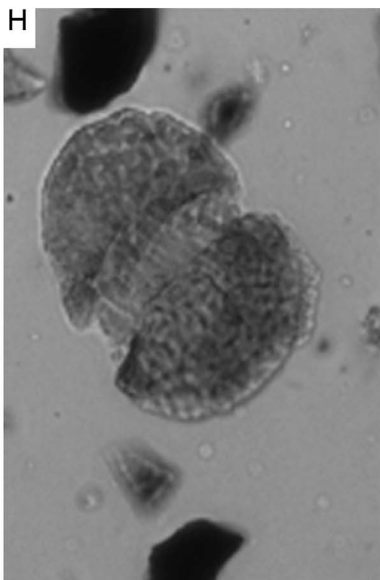
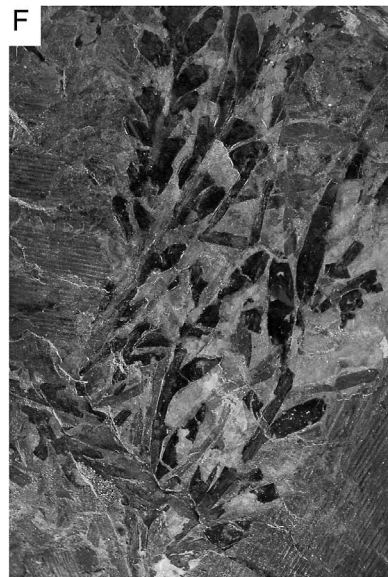
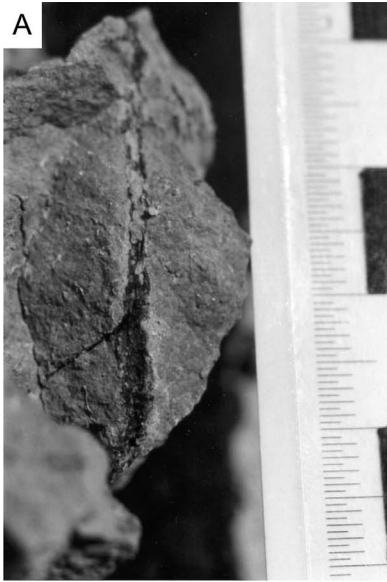




FIGURE 3—Trunk of preservational style D. Arrow points to the friable charcoal forming the outer layer. Valle de la Luna Member, Agua de la Peña section.

surfaces from which it has crumbled or been abraded away by recent erosional processes.

E. Horizontal or Oblique Silicified Tree Trunks.—*Rhexoxylon piatnitzkyi* also occurs as allochthonous trunks lacking roots and branches (Fig. 2E), including specimens with root flares. A few specimens were interpreted as isolated branches. Most of these specimens are partially buried, and measuring the actual dimensions is thus difficult. The visible portions of the trunks are, on average, ~2 m in length (<7.7 m), with an average diameter of 40 cm (≤ 1 m) where measurable above the substrate. The much smaller branches average 45 cm in length and 12 cm in diameter where visible.

Both trunks and branches are permineralized by amorphous silica, and the internal structures are sometimes well preserved, including the tracheids, rays, and growth rings. Some trunks are poorly preserved, with significant alteration to iron oxyhydroxides; in the most altered portions, goethite may preserve relicts of the axial system. These are smaller, on average, than the well-preserved specimens. A zone 0.2–4 cm thick of charcoal covers every buried trunk (Fig. 3). The trunks are distributed randomly and generally lie parallel to bedding and oriented with the paleocurrents.

F. Horizontally Oriented Cuticles and Impressions.—These are parautochthonous and autochthonous plant cuticles and impressions in layers ~1 cm thick (Fig. 2F). The layers are dark and parallel to stratification, which is characteristic of the lower parallel flow regime or of standing water. Tentative identification of the fossils with cuticle, based on Archangelsky et al. (1995), Artabe et al. (2001), and Zamuner et al. (2001), among others, yielded the following taxa: *Johnstonia stelzneriana* (Geinitz) Frenguelli, *Xylopteris argentina* (Kurtz) Frenguelli, *X. elongata* (Caruthers) Frenguelli, and several species of *Dicroidium*. Impressions are very common and are mostly *Neocalamites carrerei* (Zeiller) Halle. The *Neocalamites* impressions, particularly of the larger stems, are usually preserved with a thin layer of vitrinite. The taphocoenosis is based mostly on the thicker cuticles, which have wrinkled textures, stomata, are dark colored (N1), and often are easily extracted whole from the rocks, where they represent entire pinnae. Where broken, they always have angular edges, suggesting postburial or even possibly postexhumation breakage. Thinner cuticles are less common and appear to be mostly fragmented, with smooth textures and reddish-orange colors (5YR5/6); they are much harder to extract and identify.

G. Cuticles Oriented Obliquely with Respect to the Bedding Plane.—These are parautochthonous or allochthonous plant cuticles forming millimeter-thick laminae (Fig. 2G). Within each lamina, the density of cuticular material is high, but the laminae are discontinuous and often no thicker than a single cuticle. The cuticles identified in these deposits are corystospermaceous, principally *Dicroidium* and, less abundantly, *Xylopteris elongata*, *X. argentina*, and *Johnstonia stelzneriana* (Archangelsky et al., 1995; Artabe et al., 2001; Zamuner et al., 2001). These are similar in preservation to the cuticles in the previous preservational category but are predominately fragmented.

H. Palynomorphs.—Pollen and spores are well preserved (Fig. 2H) and amber in color. Most of the palynomorphs are spores. The preservation is sporopollenin mummification.

I. Charcoal.—Allochthonous charcoal fragments (Fig. 2I) are black and fibrous, with a satiny luster, which distinguishes them from coaly fragments, which are more vitric in appearance. They are commonly slightly abraded. The largest piece is 15 cm long, but generally the fragments are around 1 cm. The smaller fragments are aggregated on the margins of small, interbar troughs of ~5 m lateral extension. The larger fragments are isolated and randomly distributed in channel-bar deposits.

Definition and Interpretation of Taphofacies

The term taphofacies was originally defined in order to facilitate understanding of the taphonomic history of a taphocoenosis and to link the preservation of fossils with the geologic and biologic processes that are characteristic of the original environment. The term is defined as “suites of sedimentary rock characterized by particular combinations of preservational features of the contained fossils [defined] on the basis of consistent preservational features” (Brett and Speyer, 1990, p. 258). Behrensmeyer and Hook (1992, p. 15) used the term taphonomic mode to designate “a set of fossil occurrences that result from similar physical, chemical, and biological processes. The processes may be only broadly similar . . . or may be more specifically defined according to detailed sedimentological and taphonomic evidence.”

An important consideration in plant taphonomy is that different plant organs (i.e., roots, shoots, stems, trunks, leaves, pollen, and spores) have different responses to the same processes and environmental conditions. Different plant organs result in different preservational styles under the same taphonomic history, as illustrated by the preservational styles outlined above. Therefore, some taphofacies may be characterized by more than one preservational style.

Finally, although a single taphofacies is almost always associated with the same environment, it is not true that the same environment will always preserve that taphofacies. This is because during necrological, biostratigraphic, and diagenetic events, the conditions existing during deposition of organic remains in a particular environment are not always the same, and the lithostratigraphic characteristics may not be as vulnerable to auto- and allocyclic processes as are the organic remains.

In this paper, we frame the taphofacies in the context of lithofacies established by Miall (1996) for fluvial environments, adding the alphabetical code (A–H) used above to describe the preservational styles. The first letters, in upper case, represent the preservational styles, in order of importance, and the second letters, in parentheses, represent the Miall (1996) lithofacies codes in which the preservational style occurs.

Seven taphofacies were identified in the Ischigualasto Formation: (1) C(St), silicified roots of low-statured, woody plants associated with low-sinuosity channel and crevasse-splay deposits; (2) A(Sm/Fm), carbonized

←

FIGURE 2—Preservational styles defined for the Ischigualasto Formation. A) Fibrous roots and root impressions. B) Root halos. C) Silicified stumps and roots of low-statured, woody plants. D) Vertical silicified trunks and stumps of large-statured, woody plants. E) Horizontal or oblique silicified trunks. F) Horizontally oriented cuticles and impressions (specimen PBSJ 250, Museo de Ciencias Naturales, San Juan, Argentina). G) Cuticles oriented obliquely with respect to bedding. H) Palynomorphs (specimen PBSJ 251, Museo de Ciencias Naturales, San Juan, Argentina). I) Charcoal fragments.

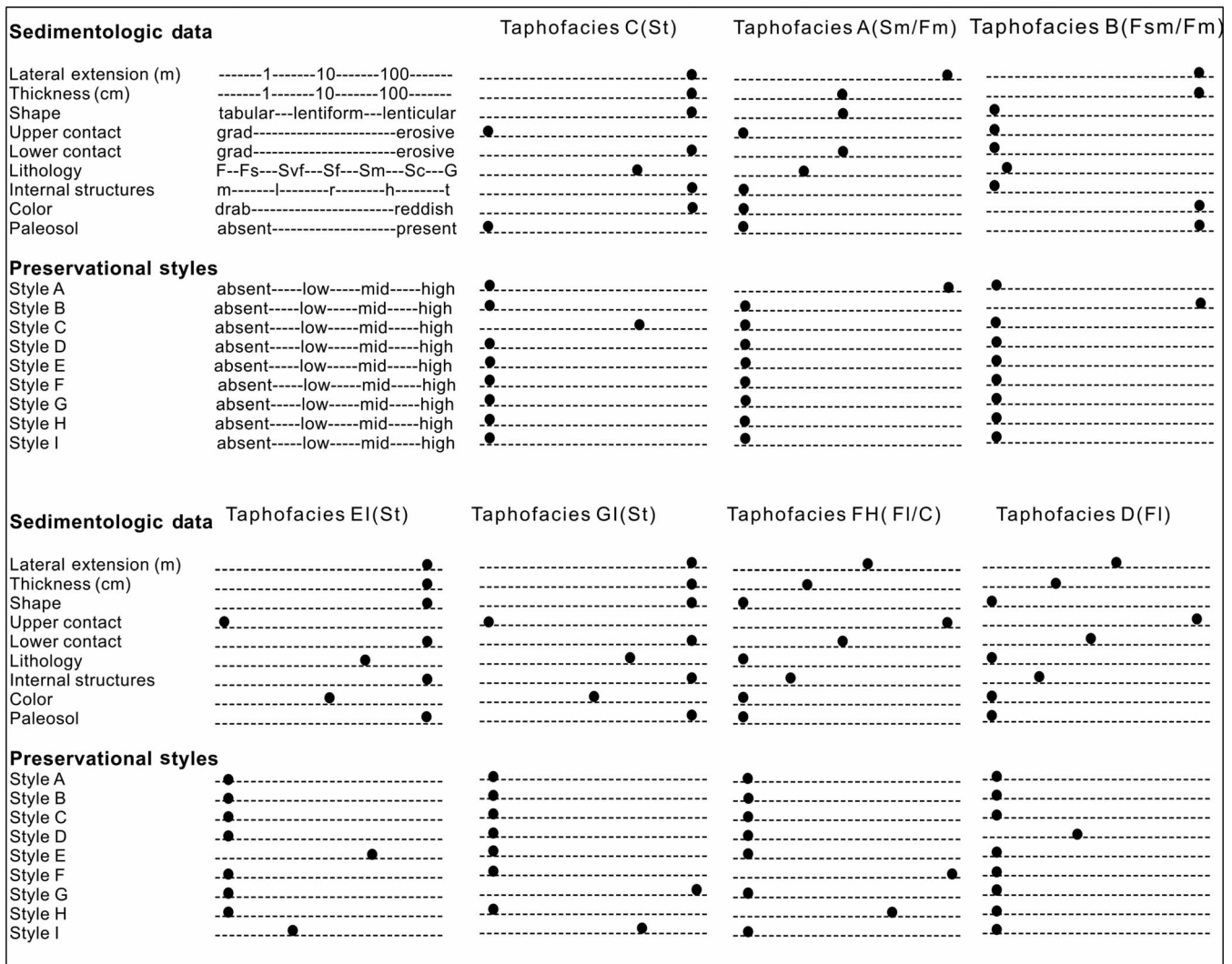


FIGURE 4—Comparative graphs of taphofacies characteristics, including sedimentologic data and preservational styles for each taphofacies. The scales for each graph are in the first column. See Methods for an explanation of the codes for preservational styles and lithofacies.

or argillic roots or root impressions, probably from herbaceous plants, associated with crevasse-splay and levee deposits; (3) B(Fsm/Fm), root halos in levee and distal floodplain deposits; (4) EI(St), horizontal or oblique silicified tree trunks associated with charcoal fragments in high-sinuosity channel deposits; (5) GI(St), leaf cuticles and charcoal associated with trough cross-bedded sandstone; (6) FH(FI/C), leaf cuticles and impressions associated with palynomorphs in abandoned-channel deposits; and, finally, (7) D(FI) vertical silicified stumps and roots in abandoned channels. A comparative graph of Ischigualasto taphofacies is shown in Figure 4, and the geographic and stratigraphic distribution of the taphofacies are illustrated in Figure 5.

Taphofacies C(St).—This taphofacies consists of lenticular bodies of cross-bedded, medium-to-coarse sandstones that are amalgamated into laterally extensive sandstone beds, generally yellow gray in color (5Y), and characterized by the unique presence of preservational style C, silicified roots of low-statured, woody plants (Fig. 6). This taphofacies also includes this same preservational style in a reworked red (10R) ash lithofacies.

Taphofacies C(St) normally occurs in channel deposits designated by Shipman (2004) as type 2 channels, that is, amalgamated sheet sandstone beds interpreted as mobile belts of low-sinuosity channels dominated by transverse bars, equivalent to the braided systems of Miall (1985). The development of this type of channel deposit is the result of high discharge

or large seasonal variations of discharge (Miall, 1977; Schumm, 1985), a sedimentary load of mixed-to-coarse grains (Schumm, 1985), low gradients (Schumm, 1993), and areas with little or no vegetation (Baker, 1978; Miall, 1985; Stanistreet et al., 1993).

The deposits are consistent with seasonal waning of channel flow. As the flow wanes, gradually restricting the channel to the deeper portions, it leaves the rest of the channel dry, but the water table remains close to the surface, permitting colonization of the channel sand by plants. The distribution of plants is patchy, an adaptation characteristic of plants that grow near rivers with variable discharge under seasonal climates. Plant growth may be concentrated on the tops of bars and may diminish the force of currents during high flood stages, when the discharge might increase by four orders of magnitude. Examples of these are communities of trees that grow in riparian regimes under tropical and subtropical climates in northern Australia (Fielding and Alexander, 2001) and in the Amazon River basin (Salo et al., 1986; Kalliola et al., 1991).

The ash-rich crevasse-splay deposit is likely to have started with an event of maximum discharge, magnified by choking of the rivers by volcanic ash during an explosive episode. The amount of ash that fell directly into the rivers or was transported from its tributaries would have generated a huge amount of bedload that choked the channel, generating a spontaneous overflow onto the floodplain. The lower permeability of

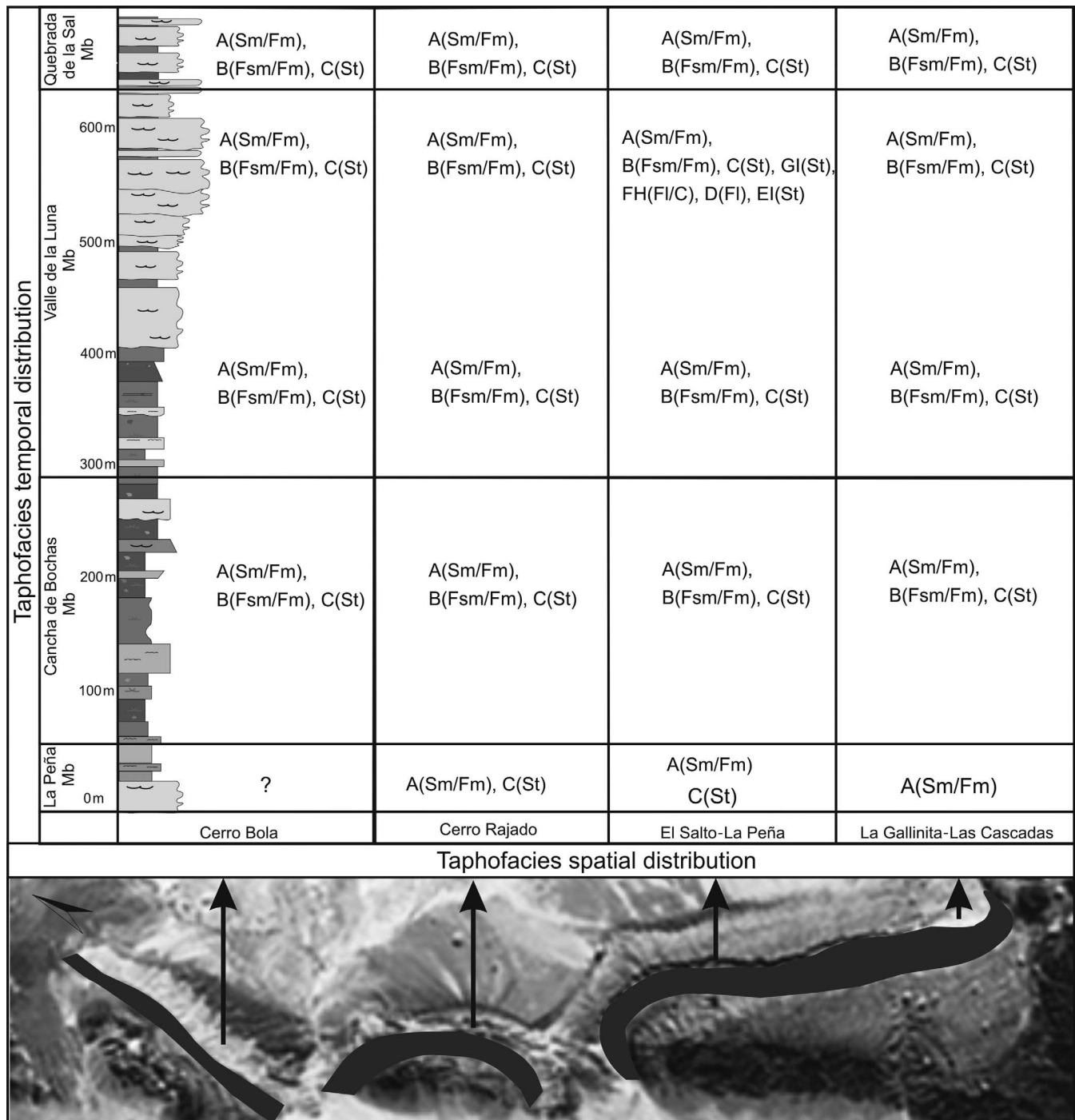


FIGURE 5—Geographic and stratigraphic distribution of taphofacies. The lower part of the figure shows an aerial photo of the basin. Dark lines = Ischigualasto Formation outcrops. See Methods for an explanation of the codes for preservational styles and lithofacies.

these argillaceous deposits likely also helped to maintain a higher water-table level in these zones, as well as contributing minerals favorable to the development of plant growth and preservation. In both cases, the presence of vertical stumps associated with roots suggests that the death of the plants was linked to progressive scarcity of nutrients or oxygen as successive deposits buried the plants.

Taphofacies A(Sm/Fm).—This taphofacies is characterized by the scattered preservation of fossils from preservational style A, that is, fibrous roots or root impressions (Fig. 7). The remains occur in muddy sandstone or massive mudstone, some with relict lamination (Sm/Sr to Fm/FI) that is greenish in color (SGY). The composition of the sand is >90% quartz

with silica cement. The geometry of the sandstone beds is tabular with a high aspect ratio, that is, lateral extension of >1 km and a thickness of 30 cm.

The environment is interpreted as a crevasse-splay deposit with high amount of volcanic ash. The sizes of the roots found in this taphofacies are consistent with a taphocoenosis composed mainly or exclusively of herbaceous plants, whose leaves are rarely preserved because they are generally thin and decay or wither rapidly after the death of the plant (Burnham, 1989; see also LePage and Pfefferkorn, 2000). These are the first colonizers, plants with minimum ecological requirements of water and nutrients that prepare the soil of recent deposits to be colonized by



FIGURE 6—Exposed silicified roots of a low-statured, woody plant. La Peña Member, Agua de la Peña section.

more complex plants (Wing and DiMichele, 1992). In this taphofacies, however, there is no evidence of more complex plants. Once successive deposits buried the roots and rootlets, the remains were carbonized during diagenesis. The carbonized material was easily degraded, leaving an impression that might be filled later by argillic material.

Taphofacies B(FI/Fm).—This taphofacies is represented by fine-grained rocks that are characterized by preservational style B, root halos (Fig. 8). The rock occurs in tabular bodies, is reddish in color (5YR), extends laterally more than 1 km, and is of variable thickness, generally >1 m; the environment is interpreted as proximal and distal floodplain deposits. The presence of root halos is a feature used to identify pedogenic alteration. In many instances, the paleosol profiles preserve little or no direct evidence of plants, but their presence may be inferred. The paleosols related to this taphofacies are Protosols, gleyed Vertisols, Calcisols, calcic Vertisols, Argillisols, and calcic Argillisols (Tabor et al., 2006). The lack of association with other plant parts suggests an herbaceous or very low-statured, slightly woody vegetation.

The roots preserved in these beds are the diagnostic feature that characterizes these deposits, along with paleosols. The presence of the roots indicates that these deposits represent well-drained environments, where the position of the water table is below the surface during most of the year, permitting the biota to colonize and interact with the sediments, altering them and converting them to soils (Behrensmeier and Hook, 1992).

Preservation follows the same mechanism as in the previous taphofacies except that no carbonaceous material is found. Although this taphofacies is very similar to the previous one, we break it out as a distinct taphofacies because the two do not completely overlap (discussed below), suggesting some subtle difference in the taphonomic histories.

Taphofacies EI(St).—This taphofacies consists of lenticular, coarse-to-medium, cross-bedded, yellowish-gray (5Y8/1) sandstone beds (St) characterized by the presence of two preservational styles, E (horizontal or oblique silicified tree trunks, occasionally preserved as iron oxyhydroxides) and I (charcoal). These rocks are interpreted as channel-bar deposits, and exceptional flood deposits initiated this taphofacies. As mentioned previously, during these floods, discharge can intensify by four orders of magnitude and occupy inactive or sporadically active channels, as well as the bordering regions of the floodplain. During discharge, the competency and capacity of the rivers increases, the grain sizes and amount of sediment that the river can carry increase, and consequently the river also becomes more erosive. The erosive capacity during flooding can uproot riparian vegetation and transport plants until they are buried in the channel bars or bedforms during waning flow.

Riparian vegetation, like *Rhexoxylon* trees in the Ischigualasto Formation (Spalletti et al., 1999), was uprooted and transported along with other tree trunks and remains from the levees and floodplains close to the channel. The positions of the trunks as well as their orientations



FIGURE 7—Fibrous roots of preservational style A. La Peña Member, Agua de la Peña section.

parallel to the paleocurrent indicate that these trunks are allochthonous. They are unlikely to have been derived from extrabasinal areas, however, because the thickness of the channel deposits never exceeds 4 m (Shipman, 2004). Such channels are not able to transport trunks bigger than 1 m in diameter, so the effects are limited to toppling of the trees and reorientation of the trunks along the currents. The absence of roots on the trunks is not indicative of long-distance transport. A very similar situation occurs in the Chinle Formation (Triassic, United States), where, among hundreds of trunks, few have root systems preserved. This is not surprising, as the woody tissue of roots is much weaker than that of the stems. The roots commonly act as anchors, allowing the trunk to swivel and point downstream, leaving the roots exposed to the most powerful flow (unpublished observations from modern braided and meandering rivers; J.T. Parrish, 2002).

Although it cannot be verified with *in situ* remains in the study area, the presence of autochthonous trees in the upper horizons of some abandoned channels (taphofacies D(FI), described below) supports the hypothesis that these trees grew near channels and were incorporated into them during the discharge peaks.

Charcoal fragments caught by the currents can be transported variable distances, although the angularity of most fragments suggests they were not transported far. The specific weight of charcoal is low, which allows it to be transported floating on the surface with no frictional contact with the streambed or channel margins (Spicer, 1989).

After peak discharge, the flow decreased exponentially, and the current lost capacity and competency, depositing coarse material together with



FIGURE 8—Root halos of preservational style B. Valle de la Luna Member, Agua de la Peña section.



FIGURE 9—Bedding-plane exposure of a trough cross-bed showing interlayering of clastics (lighter-colored laminae) and organic remains (darker-colored laminae). Valle de la Luna Member, Agua de la Peña section.

trunks and charcoal, forming transverse bars and bedforms in the channel. Diagenesis began when the trunks were buried in the channel bar sediments. The trunks that characterize the channel bar deposits are silicified. Diagenesis does not affect charcoal fragments because the charcoal is already chemically stable.

Taphofacies *GI(St)*.—This taphofacies occurs at the tops of trough cross-bedded, very-fine to coarse sandstone beds and is characterized by two preservational styles, G (cuticles oriented obliquely respect to the bedding plane) and I (charcoal). In these deposits, the cuticles form thin laminae that alternate with laminae of fine sandstone or siltstone and commonly form concentric layers on the tops of bedding planes (Fig. 9). These laminae are the horizontal exposure of trough cross-beds, and the cuticle layers are similar to mud drapes in waning-flow deposits.

These deposits are interpreted as end-stage waning flow and slackwater pool deposits in active channels. The taphonomic history began when, during the seasonal discharge, large numbers of leaves from trees and short-statured shrubs, along with charcoal fragments, were introduced to the channel by cut-bank erosion during flood stage and subsequently incorporated into the channel deposits. The leaves could not have been transported far before they were fragmented and decayed (Spicer, 1981; Ferguson, 1985), so they probably are leaves that came from areas nearest the channel. The charcoal, however, could have been transported variable distances.

During waning discharge, the leaves that survived mechanical and biological destruction, together with small charcoal fragments, accumulated and were deposited together with the last of the suspended load by lateral and vertical accretion on interbar troughs along the thalweg. For cuticle

to have been preserved and to form this taphocoenosis, rapid sedimentation rates and anaerobic conditions after burial must have occurred (Spicer, 1989).

Taphofacies *FH(Fl)*.—This taphofacies comprises thin, lenticular or tabular, gray-greenish to black (N5, 5Y4/1) siltstone and claystone beds with low-angle ripple lamination, characterized by preservational styles F (horizontally oriented cuticle and impressions) and H (palynomorphs). The cuticles, which are oriented parallel to bedding, occur in greatly variable but generally high or very high concentrations, including horizons consisting entirely of cuticle. Thin layers of fine sediment between cuticles layers are also common and facilitate splitting of the laminae.

These are interpreted as periodically flooded abandoned-channel deposits that formed when the river underwent avulsion. In one area, these deposits can be characterized as a marsh, suggesting a continuously high water table, and the entire flora is clearly autochthonous, with abundant, *in situ* *Neocalamites*. The preservation of the cuticles suggests a rapid onset of anaerobic conditions. Accompanying these remains are the conchostracan, *Eusteria*, characteristic of seasonal environments.

Taphofacies *D(Fl)*.—This taphofacies consists of lenticular sandstone beds interbedded with mudstone. Vertical, silicified tree trunks and stumps characterize this taphofacies (Fig. 10) and are located in the upper layers of the strata.

The environment is interpreted as well-drained abandoned channels. The history of this taphofacies began when the trunks colonized the tops of the sediment that filled abandoned channels. After the trees died and their roots were buried, siliceous mineralization began, resulting in exquisite preservation of the internal cellular structure. The literature contains many examples of fossilized tree trunks in place. This usually occurs when the flow of water that buries the trees is not forceful enough to fell them (Gastaldo, 1986, 1987; Behrensmeier and Hook, 1992).

Distribution of Taphofacies

Taphofacies are not uniformly distributed spatially or temporally in the Ischigualasto Basin (Figs. 5 and 11). In order from most to least abundant, the taphofacies in the Ischigualasto Formation are B(Fsm/Fm), A(Sm/Fm), and C(St). The remaining taphofacies are restricted both temporally and spatially; they occur only in the upper portion of the Valle de la Luna Member and in a zone ~4 km wide in the depocenter of the basin.

Taphofacies B(Fsm/Fm) is present throughout the basin, beginning with the deposition of Cancha de Bochas Member, near the base of Ischigualasto Formation, through the top at the contact with the overlying Los Colorados Formation (Fig. 11). Notably, the sizes of the root halos increase into the Valle de la Luna Member, then decrease again. Laterally, this taphofacies is present in the entire study area, from Las Cascadas in

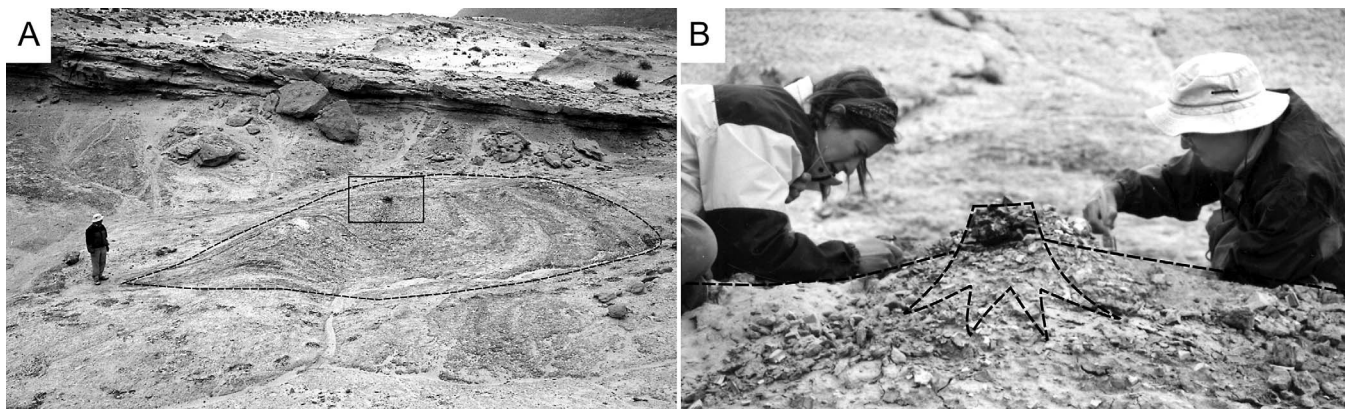


FIGURE 10—Vertical stump of taphofacies D(Fl). Valle de la Luna Member, Agua de la Peña section. A) Abandoned-channel deposit is outlined; outlined area shown in B. B) Close-up of stump, with schematic diagram of its extent in the subsurface.

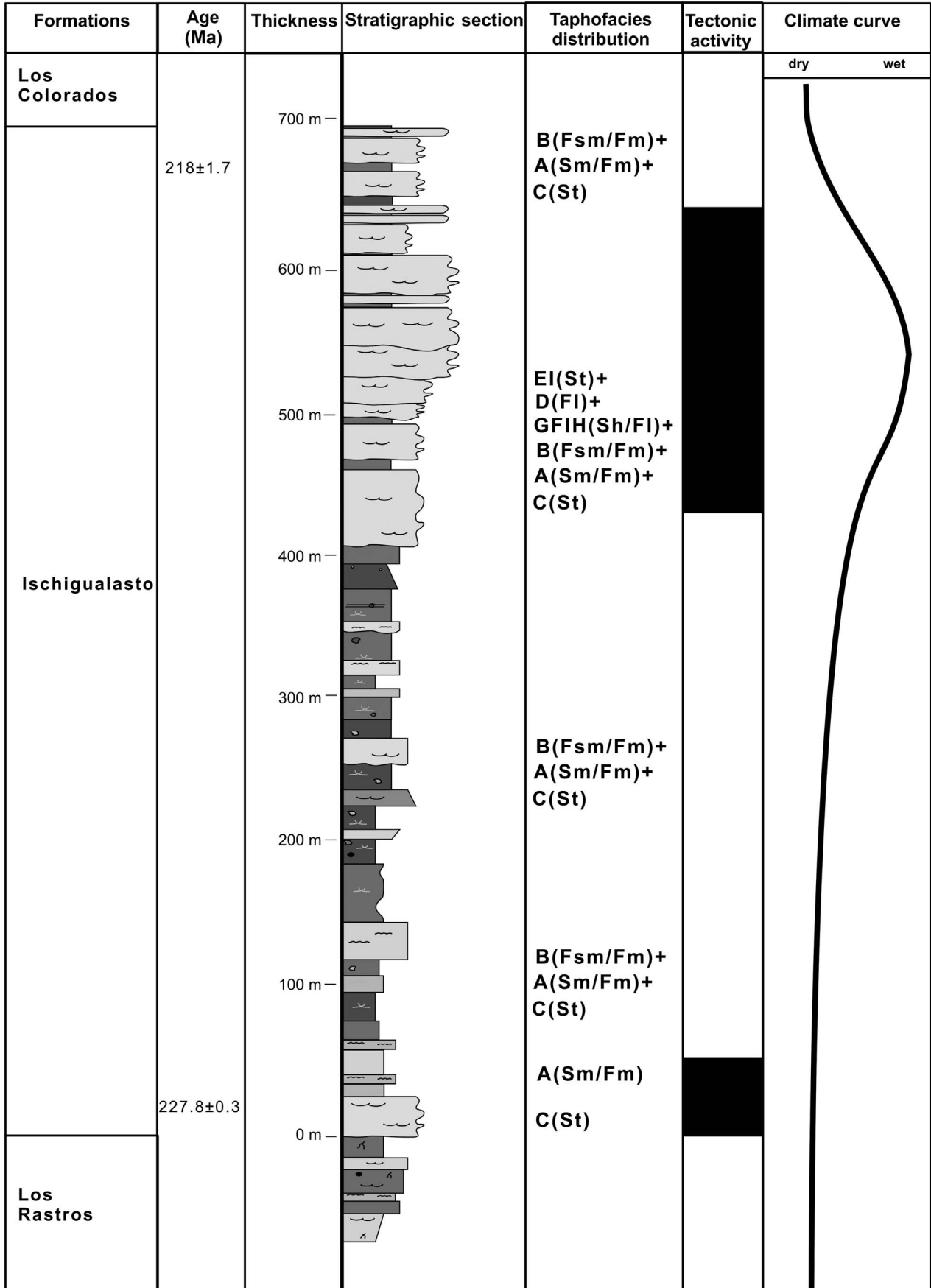


FIGURE 11—Summary diagram of the stratigraphy, stratigraphic distribution of taphofacies, and events in the Ischigualasto Formation. Black bars indicate times of active subsidence. See Methods for an explanation of the codes for preservational styles and lithofacies.

the southeastern portion of the basin, to Cerro Bola, the northwestern boundary of the basin.

Taphofacies A(Sm/Fm) appears in the muddy sandstone deposits of the La Peña Member and extends into the upper layers at the top of Ischigualasto Formation (Fig. 11). Laterally, it is distributed along the entire basin. It is more common, however, in the middle portion of the basin, in the Agua de la Peña section, in the La Peña Member, and in the base of the Cancha de Bochas Member, which is 40–125 m from the base of the Ischigualasto Formation. Approximately 40% of the overbank deposits in the La Peña Member are characterized by this taphofacies, whereas in the upper part of the formation, this taphofacies is present in only 5% of the deposits. Taphofacies C(St) is distributed throughout the Ischigualasto Formation, from the base of La Peña Member to the top of the formation (Fig. 11). Laterally, it is present along the entire basin, but the abundance is very low.

Taphofacies EI(St), GI(St), FH(Fl), and D(Fl) have restricted temporal and, particularly, spatial distributions through the basin. Temporally, they are limited to the upper-middle portion of the Valle de la Luna Member, 330–515 m from the base of Ischigualasto Formation (Fig. 11). The lateral distribution is more conspicuous; they are distributed in the middle area of the basin in a block that extends 4 km laterally.

DISCUSSION

In the following sections, the overall climate of the Ischigualasto Formation is interpreted based on the taphofacies and what they reveal about the vegetation. Changes in taphofacies are correlated with trends in the fluvial architecture and paleosols to arrive at an evolution of climate during deposition of the Ischigualasto Formation. Finally, we compare the climate interpretation to the record of Pangean climate elsewhere in the world.

Plant Taphofacies and Vegetation

The diversity of the megafloora in the Ischigualasto Formation in the basin was low, consisting of about 20 species (Table 2; see Zamuner et al., 2001). This low diversity, coupled with the evidence from root traces and the overall paucity of plant remains (see Parrish et al., 2004), suggests that the vegetation consisted mostly of opportunists that grew quickly in an environment that was frequently perturbed. Although the palynology for the Ischigualasto is incomplete, a relatively high diversity of palynomorphs would support this conclusion (e.g., see Spicer and Parrish, 1986; Parrish et al., 2004). Opportunists tend to be primarily herbaceous or slightly woody plants that have short life spans and develop nonwoody root systems. Roots of herbaceous plants do not generally have woody resistant material, and the grain size, energy, and oxygenation of the environment makes their preservation unlikely. Herbaceous plants can live in almost any climate because their life cycles are rapid and can be completed during brief periods favorable to growth. The broad distribution of taphofacies A(Sm/Fm) and small forms of B(Fsm/Fm) is a testament to their adaptability. These are the only taphofacies found in the dry overbank deposits.

Root halos are indicative of seasonality of moisture. The genesis of root halos has been discussed widely, but always in connection with oxidizing seasonal environments, that is, water tables that are well below the surface seasonally (e.g., Retallack, 1990). The more accepted hypothesis of root-halo formation is anaerobic microbial decay of the organic matter immediately after the soil is submerged during the humid season (Retallack, 1988). In the overall context of the formation, the dominance of herbaceous vegetation is indicative of a seasonally dry climate.

Woody roots and stems and the leaves of woody plants are more resistant, particularly if the leaves have thick cuticles. The preserved megafloora indicates a low-diversity standing vegetation that likely consisted of facultatively phreatophytic, low-statured shrubs that could withstand all but the most violent floods. These plants had taproots, which are

woody roots adapted to penetrate deep into the substrate to the water table in order to access nutrients and water during drier intervals. The exclusive association of these kinds of root traces with riparian environments is a characteristic of arid or semi-arid climates, because it is in these environments that the water table is closest to the surface. Likewise, the presence of trees solely in riparian and low-lying overbank deposits is an indication that the water table in the Ischigualasto was well below the surface through much of the year, limiting the growth sites for more complex plants. Many of the megafloora taxa are limited to taphofacies GI(St) and FH(Fl/C).

Trends in Fluvial Architecture, Paleosols, and Plant Taphofacies

The distribution of taphofacies in space and time can be related to variations in fluvial environments and paleosols throughout the deposition of the Ischigualasto Formation. Using the paleoenvironmental information from measured sections in the formation, along with the members defined by B.S. Currie et al. (in press) and the paleosols defined by Tabor et al. (2006), the taphonomic variability can be correlated with the paleoenvironmental variability of the formation.

Shipman (2004), Tabor et al. (2006), Colombi (2007), and B.S. Currie et al. (in press) observed a number of vertical and lateral trends in the Ischigualasto Basin:

1. Predominance of braided-stream channels, including ephemeral streams, relatively high aggradation rates, and poorly drained overbank deposits in the La Peña Member.
2. An increase in wider, unincised channels of anastomosing or meandering streams and an increase in the number of channels in the Valle de la Luna Member, especially where the formation is thickest (Agua de la Peña section).
3. Greater thicknesses and maturity of paleosols and fewer channel deposits to the southeast.
4. Well-drained, predominantly calcic paleosols in the Cancha de Bochas Member and lower part of the Valle de la Luna Member and toward the southeastern part of the basin.
5. Poorly drained, argillic paleosols in the upper part of the Valle de la Luna Member and an increase in the abundance of abandoned-channel deposits close to the water table, which are limited to that member in the center of the basin, in the Agua de la Peña section.
6. Predominantly poorly drained, argillic paleosols in the Quebrada de la Sal Member throughout the basin.

Tabor et al. (2006) interpreted the geographic trends in the paleosols to be indicative of a catena, consisting of relatively well drained, mature soils in the southeast and seasonally poorly drained soils in the center of the basin. This interpretation is consistent with the concentration of channel deposits and a higher overall sedimentation in the center related to the behavior of different tectonic blocks in the basin (B.S. Currie et al., in press).

The basal portion of the formation, the La Peña Member, comprises single-story or multistory, low-sinuosity channels, with some gleyed and incipient paleosols. The base of this member in the central and northern area of the basin is dominated by channels containing only taphofacies C(St); that is, the only preserved plant materials are silicified stumps and roots of woody, low-statured shrubs. Although we have no direct evidence of taproots, these plants were likely facultative phreatophytes: plants that grow in seasonal channels and have both lateral roots for anchoring and taproots for uptake of water when the channels dry up. The channel beds were likely the only places close enough to the water table for the plants to have survived. The upper part of the member is characterized by a succession of fine-grained, poorly drained overbank deposits interbedded with crevasse-splay deposits. Taphofacies A(Sm/Fm) appears in these deposits, representing the establishment of herbaceous plants on the floodplain. In the southeastern part of the basin, the La Peña Member is of variable thickness, and the only facies present is A(Sm/Fm). Thus, deposition of the La Peña Member appears to represent the

initiation of an axial fluvial system produced by an increase in subsidence associated with the Valle Fértil fault; this time was characterized by great instability of rivers. That instability generated frequent avulsions over the floodplain, inhibiting the growth of complex plants and rarely allowing pedogenic processes to progress far. The climate was seasonal, but not arid. Seasonality is demonstrated by the presence of the conchostracan, *Eusteria*, which characterizes seasonal climate (Frank, 1988), at the basal contact (Gallego et al., 2004).

The overlying member, Cancha de Bochas, is characterized by channel deposits that indicate greater channel stability and meandering rivers (Shipman, 2004). The first paleosols appear in floodplain deposits that border the channels in this member (Tabor et al., 2006). They are calcic, with carbonate nodules and rhizoliths. Laterally, paleoenvironmental conditions were uniform throughout the basin except that paleosols are better developed in the southeast. Taphofacies C(St) is present in channel beds of this member, and taphofacies A(Fl/Fm) and B(Fl/Fm) characterize the overbank deposits. The distribution of taphofacies corresponds to a dry, seasonal climate, indicating either a decrease in precipitation or an increase in temperature, mostly likely the former, because calcic features need 1000–10,000 years without burial by flood events to reach this level of maturity (Gile et al., 1966; Machette, 1985). Colonizing plants had more than enough time to prepare the floodplain soils for plants with more complex ecological requirements and the pedogenesis that accompanies plant growth.

We interpret the Cancha de Bochas Member to have been deposited under a dry seasonal climate, in which herbaceous plants with few ecological requirements developed throughout the fluvial valley and woody shrubs grew only in riparian environments. The riparian areas were wetter because periodic floodwaters remained for a relatively prolonged time during the humid season and, during the dry season, the water table remained closer to the surface than in the rest of the floodplain. Woody shrubs could grow, developing the double system of roots characteristic of facultatively phreatic plants (Dubiel et al., 1991). The low humidity of this environment was not sufficient, not even in the riparian environments, for the growth of arboreal vegetation.

During deposition of the Valle de la Luna Member, paleoenvironmental conditions changed gradually. Most of the channel deposits of the formation are in this member. The paleosols become argillaceous, with the calcic soils restricted to isolated layers in the lower third of the member (Shipman, 2004; Tabor et al., 2006). Laterally, the proportion of channels diminishes toward the southeast, with a concomitant increase in the proportion of paleosols, creating a more marked lateral variation than occurs in the member below. This lateral variation coincides with changes in the distribution of taphofacies. The southeastern part of the basin has the same taphofacies features as in the Cancha de Bochas Member: taphofacies A(Sm/Fm) and B(Fsm/Fm) in the overbank deposits and C(St) in the channel beds. In the central part of the basin, however, a mosaic of all the taphofacies is observed, particularly in the upper part of this member. Taphofacies EI(St), GI(St), FH(Fl), and D(Fl)—taphofacies preserved in bar deposits and related to abandoned channels—occur only within this fluvial valley and always in relation to channel deposits. In addition, the size of root halos in taphofacies B(Sm/Fm) increases in the upper part of the Valle de la Luna Member. These taphofacies indicate that the water table was higher, owing to an increase in precipitation or possibly a decrease in temperature. A higher water table would have allowed the development of woody and arboreal vegetation on the channel margins, development of argillic paleosols in the overbank, and less ephemeral standing water bodies in the floodplain. The amount of soil moisture, in turn, permitted the development of anaerobic conditions and resultant preservation of cuticles, palynomorphs, and the only invertebrates preserved in the formation. These changes all correspond with the pattern of channel and pedogenic changes (Shipman, 2004; Tabor et al., 2006; B.S. Currie et al., in press).

Although the climatic conditions changed during deposition of the Valle de la Luna Member, as reflected by paleoenvironmental features and

paleosols throughout the basin, internal tectonic events of the basin during the deposition of this member are superposed on the climate signal. In the Agua de la Peña section, close to the depocenter, humid climate was augmented by the relatively high water table resulting from subsidence along the master fault, giving a clear example of compound signatures (Speyer and Brett, 1991). In the block that subsided more slowly, however, the evidence of an increase in humidity is diminished because the water table is farther underground.

Finally, the uppermost member of the Ischigualasto Formation, Quebrada de la Sal, displays uniform sedimentological characteristics throughout the entire basin, making it more similar to the overlying Los Colorados Formation than the Ischigualasto itself, although the color range in these sediments allows us to tie it to the latter. The paleoenvironment is characterized by a decrease of channels deposits, dominated by monoepisodic, low-sinuosity channels, and floodplain deposits characterized by the development of argillic paleosols (Shipman, 2004; Tabor et al., 2006). These deposits have the highest percentage of immature soils, close to 80%, as opposed to a maximum of 40% in the other members. The deposits preserve evidence of herbaceous plants of taphofacies A(Fl/Fm) and B(Fl/Fm), with halos the same size as those preserved in the Cancha de Bochas Member. In the channel deposits, the only taphofacies present is C(St). Although paleosols are argillic, sedimentological characteristics, together with taphofacies characterization, indicate that arid conditions began to return during the development of the Quebrada de la Sal Member, caused by either a decrease in precipitation or an increase in temperature. These conditions were maintained and then intensified toward the top of Los Colorados Formation and also Cerro Rajado Formation, as demonstrated by pedogenic, sedimentological, and taphonomic features of the former formation (Carrizo Paez and Colombi, 2004).

In summary, the plant taphofacies and paleosols, along with evidence of seasonality from paleosols and fluvial architecture (Shipman, 2004; Tabor et al., 2006), suggest an overall seasonal climate with respect to rainfall, with moderate humidity in the La Peña Member, increased aridity in the Cancha de Bochas Member, a gradual increase in humidity in the lower part of the Valle de la Luna member with a peak in the upper part, and return to a drier climate in the Quebrada de la Sal Member. Overprinted on this change was a tectonic signal that meant that the southeastern part of the basin was better drained than the central part of the basin at the Agua de la Peña section. It should be emphasized, however, that while the climate did change, the peak in humidity was not dramatic (Tabor et al., 2006). Rather, the climate varied within a fairly narrow range, similar to that proposed for the Morrison Formation by Parrish et al. (2004). Shipman (2004) explicitly suggested a change from around 750 mm per year precipitation (760 mm is the upper limit for calcic soil formation) in the lower part of the Ischigualasto to 760–2100 mm in the upper part of the Valle de la Luna Member (2100 mm is the upper limit for the formation of vertic features).

The Ischigualasto Formation and the Pangean Megamonsoon

The climate of the Upper Triassic is interesting because of the unusual global geography and the resulting climate changes that might be expected (Parrish, 1993). As noted above, the Ischigualasto Basin is potentially very important for understanding Pangean climate because it is the most complete Triassic sequence and is one of the few exposures of that age for southwestern Pangea (Volkheimer, 1969; Stipanovic and Bonaparte, 1979; López Gamundi et al., 1989; Veevers et al., 1994; Tabor et al., 2004).

A complete review of the Pangean megamonsoon is beyond the scope of this paper. The most recent review of the entire history can be found in Parrish (1993). A considerable amount of work has been done on the Late Carboniferous, Permian, and Jurassic climatic history since Parrish's (1993) review (e.g., Fluteau et al., 2001; Loope et al., 2001; Soreghan et al., 2002a, 2002b, 2007; Tabor and Montanez, 2002; Tramp et al., 2004;

Rowe et al., 2007; Soreghan and Soreghan, 2007), but the Triassic has remained relatively unstudied. Robinson (1973) was the first to refer to the climate during the development of Pangea as a monsoon system. In the 1980s and 1990s, Pangean climate came under scrutiny by a number of groups (e.g., Parrish and Curtis, 1982; Rowley et al., 1985; Parrish et al., 1986; Parrish and Peterson, 1988; Crowley et al., 1989; Chandler et al., 1992; Valdes and Sellwood, 1992; Parrish, 1993), who supported the hypothesis of a nonzonal, monsoonal climate in Pangea with climate models addressing the evolution of Pangean geography from the Carboniferous to the Jurassic. Kutzbach and Gallimore (1989) were the first to refer to the Triassic climate system as a megamonsoon. Although the nonzonal nature of the climate of Pangea has been questioned (e.g., Kent and Olsen, 2000; Olsen and Kent, 2000), these studies were limited to the Triassic rift basins of eastern North America and, as such, may reflect more regional rather than global conditions.

The maximum development of the monsoon in the Triassic as hypothesized by Parrish (Parrish and Peterson, 1988; Parrish, 1993; see also Parrish et al., 1996) was characterized by the extension of dry climates into relatively high latitude regions, marked seasonality of rainfall over much of the continent, and reversal of equatorial atmospheric flow in western equatorial Pangea. These factors had the effect of increasing humidity on the low-latitude western margin of Pangea (Parrish, 1993). In addition, the strong monsoon hypothesis for the peak monsoon (Parrish and Peterson, 1988) proposed that the western equatorial region was relatively wet and the eastern equatorial region dry; seasonally, moisture would have been drawn into low midlatitudes on the western portions of the continent in the summer (Parrish et al., 1986; Parrish and Peterson, 1988; Crowley et al., 1989; Kutzbach and Gallimore, 1989; Dubiel et al., 1991; Parrish, 1993; Fawcett et al., 1994). Alternatively, if the climate were more zonal, the western equatorial region would have been relatively dry, the low, midlatitudinal regions in the west would have been arid, and the eastern equatorial regions would have been the wettest, affected solely by orbital forces (e.g., Olsen and Kent, 1999; Kent and Olsen, 2000).

Around the world, many Triassic basins have been studied for information about the evolution and timing of the monsoon maximum, but progress has been hindered by the fact that Triassic continental sequences are scattered and generally incomplete. In the United States, the Carnian Chinle Formation was deposited at $\sim 10^\circ$ N (Golonka, 2007) and includes ephemeral fluvial systems together with perennial fluvial systems, indicating abundant, but highly seasonal rainfall (DeLuca and Eriksson, 1989). Seasonal rains have been interpreted from plant taphonomic studies as well (Demko, 1995). Growth bands in shells of fresh-water mollusks have been interpreted as seasonal variations in growth rate (Dubiel et al., 1991), and vertebrate and ichnologic taphonomic studies also support an hypothesis of a highly seasonal rainfall (Parrish, 1989; Dubiel et al., 1991; Hasiotis and Dubiel, 1994). Finally, studies on eolian dunes in this and stratigraphically adjacent formations document the change in wind direction from northerly and northeasterly zonal winds to westerly and northwesterly winds consistent with a strong monsoonal circulation (Parrish and Peterson, 1988; Peterson, 1988). The evidence from the Chinle Formation has been interpreted to mean that deposition was under a climate that was both seasonal with respect to rainfall and wetter overall than the climates immediately before and after, as a result of the maximum development of the monsoon in western Pangea (Parrish, 1993). In Nevada, the development of karstic caves during Carnian time is additional evidence of this humidity peak (Carey, 1984; Simms and Ruffell, 1989).

In western Europe, there is evidence for a humid climate in the Carnian with a return to dry conditions at the Carnian-Norian boundary (Simms and Ruffell, 1989, 1990), about the same time climate became drier again in the western United States and the Ischigualasto Basin. Consistent with this evidence was the development of karstic caves in England and the Alps during the Carnian (Bechstadt and Doler-Herner, 1983), extinction of marine invertebrates during the middle Carnian (Schafer and Fois,

1789; Urlics, 1974; Kozur, 1976; Flügel and Stanley, 1984; Budarov et al., 1985; Aldridge, 1988; Boulter et al., 1988; Simms and Ruffell, 1989), appearance of new groups of plants during the same time (Visscher and van der Zwan, 1981; Olsen and Sues, 1986), and extinction of vertebrates not adapted to desert conditions at the Carnian-Norian boundary (Tucker and Benton, 1982; Benton, 1986a, 1986b; Olsen and Sues, 1986).

Simms and Ruffell (1989, 1990) attributed the pluvial peak in Europe to the opening of the Atlantic Ocean, whereas Parrish (1993) attributed the climate change to maximum development of the monsoon. Both factors may have been important, however, because western Europe at this time was far inland from the western margin of Pangea. If equatorial flow was entirely from the west, western Europe might have been dry because it would have been downwind across a wide stretch of continent. The equatorial flow would have been reversed to flow eastward only on the western side of the continent (Parrish and Peterson, 1988; Parrish, 1993). The eastern side, including the Tethyan region, would have experienced normal equatorial easterlies during the spring and fall as the flow changed direction with the seasons (Kutzbach and Gallimore, 1989; Parrish, 1993). With the modern Asian monsoon, this equinoctial flow forms a very narrow wet zone, and a similar process in Pangea may explain Kent and Olsen's observation that the zone of nonevaporative lakes in the eastern North America rift system was very narrow (Kent and Olsen, 2000; Olsen and Kent, 2000). The nascent North Atlantic would have enhanced the moisture required for the easterly equatorial flow to induce rainfall there at this time.

In South Africa, outcrops of red beds and eolian arenaceous evaporites indicate monsoon climates (Parrish, 1993). In China, similar deposits also indicate a monsoon climate in the Triassic (Tong and Parrish, 1999). In neither place is the record detailed enough to discern temporal changes in the monsoon system. In Australia, red beds with fluvial deposits similar to those in the Chinle Formation mark an apparently abrupt and large change in sedimentation at the Permo-Triassic boundary, possibly caused by the maximum strength of the monsoon (Parrish et al., 1996). Although this would be several million years earlier than the proposed Carnian monsoon maximum, it is worth noting that Australia was part of Gondwana, which was itself a supercontinent. Moreover, climate apparently continued to become hotter and more seasonal through the Triassic. It should also be noted, however, that Triassic terrestrial strata in Australia are exceptionally widely scattered in both space and time, making the exact timing and geographic significance of any change a matter of speculation.

In South America, apart from the deposits of the Ischigualasto Basin, there are scattered red beds elsewhere on the continent, with local occurrences of eolian sandstone and evaporites, which are consistent with monsoonal climate (Volkheimer, 1969; Rocha-Campos, 1973; Parrish and Peterson, 1988). In light of the pattern that apparently occurred in Australia, it is worth noting that the onset of Triassic sedimentation in the Ischigualasto Basin was in an arid climate (Milana and Alcober, 1994). Thus, the Ischigualasto Basin may be recording not just the monsoon maximum in the Carnian, with the peak humidity in the upper part of the Valle de la Luna Member, but also the underlying signature of the influence of the large Gondwanan portion of the continent.

A comparison between the Chinle and Ischigualasto Formations is particularly apt for testing the hypothesis of the Late Triassic monsoon maximum (Parrish and Peterson, 1988; Dubiel et al., 1991; Parrish et al., 1996) because both were on the western side of Pangea and both are Carnian in age. The reversal of normal equatorial easterlies would have resulted in transport of moisture into low midlatitude regions in northwestern or southwestern Pangea, depending on the season (Parrish and Peterson, 1988; Crowley et al., 1989; Kutzbach and Gallimore, 1989; Dubiel et al., 1991; Parrish, 1993; Fawcett et al., 1994; Parrish et al., 1996). If this were the case, the two formations should be very similar, with the exception of any differences caused by the differing tectonic and paleogeographic settings. These differences for the Chinle include the fact that it was not deposited in a rift basin, the lower part was deposited

within paleovalleys (Demko et al., 1998), and the setting was as much as 30° closer to the equator than the Ischigualasto (Golonka, 2007). Indeed, the two formations, particularly the Valle de la Luna Member of the upper part of the Ischigualasto and the Monitor Butte Member of the Chinle, are exceedingly similar in both lithology and fossil biota. Both are drab, alluvial deposits with only scattered occurrences of leaves in abandoned channel deposits and riparian trees (Demko, 1995). The similarities extend to evidence of burning of the trees in the form of charcoal. Finally, both ended with the onset of drier conditions. The eolian rocks overlying the Chinle Formation are conformable but poorly dated, whereas the Los Colorados Formation, which overlies the Ischigualasto, contains a Norian fauna, indicating a shift to drier climate consistent in timing with that observed by Simms and Ruffell (1989, 1990) in western Europe.

Temperature

As noted above, changes in apparent humidity as recorded in the geologic record can result not just from drying or tectonic influences but also from changes in temperature. Paleotemperature determinations for the Triassic are scarce and, until the studies by Tabor et al. (2004, 2006), completely lacking for continental sediments. Tabor et al. (2006), analyzing soil carbonates, proposed that temperatures during the deposition of the Ischigualasto Formation were $\leq 11^{\circ}\text{C}$ and as low as freezing ($6 \pm 3^{\circ}\text{C}$ in Tabor et al., 2004). Given the low-latitude position of the basin ($\sim 40^{\circ}\text{S}$), these temperatures are very surprising and, if correct, raise the possibility that the humidity peak was at least partly related to temperature. That there was a genuine increase in rainfall is supported in the Northern Hemisphere Chinle Formation by the transition from eolian and evaporitic sedimentation to fluvial sedimentation and back to eolian sedimentation, although it should be noted that pre-Chinle Triassic formations are poorly dated and incomplete. Likewise, the transition from the Ischigualasto Formation to the overlying Los Colorados Formation is marked by an increase in thin eolian sandstone beds, alluvial fan deposits, and evaporites suggestive of dry climate. The fact that the underlying Los Rastros Formation is lacustrine might have more to do with tectonics than climate (see Parrish, 1998, and references therein regarding the pitfalls of using lakes as indicators of wet climate). The Los Rastros, however, has not been studied in detail for any climatic signature it might contain.

We investigated the possible modern analogs for this basin that would be consistent with vegetation and taphofacies, relative dryness but seasonal rainfall of the climate, and cold temperatures. If the overall temperature structure of the world were similar to today, despite the apparent absence of polar ice in the Triassic, the closest modern analogs are the midlatitude grasslands of North America and Argentina. For example, the climate in central Oklahoma at 35°N has a cold month mean temperature of 2.8°C and mean annual rainfall of 770 mm, and in central Argentina (Laboulaye, 34°S), these values are 8.9°C and 735 mm, respectively (Rumney, 1968).

Grasslands are a good analog for the vegetation in either the Chinle or Ischigualasto Formations (see the discussion in Parrish et al., 2004, which was about the Morrison Formation but presented similar reasoning). Modern grasslands in these climates are characterized by herbaceous plants (grasses and weedy annuals) except in riparian environments, which are characterized by shrubs and trees. Oklahoma is slightly affected by the North American monsoon, which is, however, much weaker than is suggested for the Pangean monsoon (Parrish, 1993). Winter temperatures as low as those in Oklahoma and central Argentina but higher summer rainfall associated with a strong monsoon could be consistent with the paleovegetation and geology of the Ischigualasto Formation, particularly if the soil carbonates were precipitated during the winter dry season. Such soils are thought to form by alternating leaching of cations during the rainy season and precipitation during the dry season (Retallack, 1988), so this is a reasonable suggestion. At this point, however, the ideas put

forth in this section must be regarded as hypotheses that remain to be tested.

SUMMARY AND CONCLUSIONS

Based on the plant taphofacies and supporting information from the paleosols and fluvial architecture, we conclude that the Ischigualasto Formation was deposited under a seasonal climate and unstable tectonic conditions produced by the transition from the lacustrine facies of the Los Rastros Formation to the fluvioaxial facies of the Ischigualasto (Gawthorpe and Leeder, 2000; B.S. Currie et al., in press).

Deposition began under a moderately humid climate, and the unstable tectonic conditions led to instability in the rivers, causing repeated avulsion and preventing the formation of soils or the establishment of vegetation other than opportunistic herbaceous plants. Approximately 40 m from the base of the formation, under a dry seasonal climate, tectonic conditions began to stabilize, diminishing the frequency of floods and allowing development of calcic paleosols. The vegetation consisted of herbaceous plants in the overbank and small-statured woody plants in the channels.

At ~ 150 m above the base, the climatic conditions began to change, gradually becoming more humid. These conditions reached a maximum humidity between 315 m and 450 m in the upper part of the Valle de la Luna Member. These effects are emphasized in the central part of the basin because of tectonic subsidence and consequent raising of the water table relative to the ground surface. After this humidity peak, the conditions became uniform throughout the basin and returned gradually toward dry seasonal climate until the end of deposition of the Ischigualasto Formation. Arid conditions prevailed during deposition of the overlying Los Colorados and Cerro Rajado Formations.

The change in climate and modification of the climate signal by normal rift-basin tectonics is illustrated in Figure 11. The curve (Fig. 11, right side) is similar to the paleoclimatic changes interpreted from other basins on the western side of Pangea. These changes are likely related to those observed in the Carnian record elsewhere in the world, with the peak in humidity a consequence of the maximum development of the monsoon, as proposed by Parrish (1993). The Ischigualasto was deposited between 227.8 Ma and 218 Ma, which is similar to the age of the Chinle Formation. Although the Ischigualasto was deposited farther poleward (40° – 45°S , as opposed to $\sim 10^{\circ}\text{N}$ for the Chinle; see Golonka, 2007), the Chinle is succeeded by eolian sandstone, and climate was also arid following deposition of the Ischigualasto, when the breakup of Pangea began to weaken the monsoon (Parrish and Peterson, 1988). Plant taphofacies have been critical to the interpretation of both records.

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