LINKS BETWEEN SEDIMENT ACCUMULATION RATES AND THE DEVELOPMENT OF ALLUVIAL ARCHITECTURE: TRIASSIC ISCHIGUALASTO FORMATION, NORTHWESTERN ARGENTINA

by

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TABLE OF CONTENTS

TABLE OF CONTENTS-*Continued*

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS-*continued*

LIST OF ILLUSTRATIONS-*continued*

LIST OF ILLUSTRATIONS-*continued*

LIST OF ILLUSTRATIONS-*continued*

LIST OF ILLUSTRATIONS-*continued*

LIST OF TABLES

ABSTRACT

The Late Triassic Ischigualasto Formation, located in northwestern Argentina, was deposited during the late Norian Age in a continental rift valley. Detailed field descriptions revealed a connection between sedimentation rates and a change in the mean annual precipitation rates. The mean annual precipitation in the lower half of the Ischigualasto Formation is estimated at >760 mm and the upper half is estimated at <760 mm to 1400mm. Increases in the mean annual precipitation affected the architecture of the alluvial deposits such as decreased paleosol profile thickness and increased channel interconnectedness. Avulsion frequencies were calculated from paleosol successions sandwiched between channel sandstones and showed a decrease in the avulsion frequency through time as the Ischigualasto Formation was deposited. Since these channel sandstones were deposited along the axis of the a rift valley and avulsion should increase with increases in fault movement along the main rift valley fault, it is proposed here that the avulsion frequency suggests that there is a decrease in fault activity and extension in the upper half of the Ischigualasto Formation.

Initial models of the Ischigualasto Basin have been compared to field data collected and a newer model of the active rift systems, and after review, a new revised model is proposed. The new model suggests that there are three main phases of rift development that are related to the amount of crustal extension: sub-basin, single basin, and passively subsiding basin phases. Positions of lava flows within the basin fill were also considered as signs of local volcanic activity; these are absent in the upper portions

of the basin fill. Chronostratigraphic frameworks developed for the entire basin fill also support a decrease in the sedimentation rate through time during the deposition of the basin fill.

CHAPTER 1: LITERATURE REVIEW AND STATEMENT OF PROBLEM

STATEMENT OF PROBLEM

The purpose of this study is to determine tectonic and climatic influences from alluvial architecture in the Ischigualasto Formation (northwestern Argentina) and, using this information, to develop a model for deposition within the Ischigualasto Basin. Recent studies suggest that the stratigraphic architecture of fluvial-dominated depositional systems is controlled primarily by factors such as base-level, basin subsidence rates, sediment supply, and fluvial discharge (Bridge and Leeder, 1979; Posamentier and Vail, 1988; Wright and Marriott, 1993; Mackey and Bridge, 1995; Heller and Paola, 1996; Currie, 1997; Ethridge *et al.*, 1998; Mack and Leeder, 1999). This research has generated interest in the controls that influence alluvial architecture and their expression in the rock record (Miall, 1986; Blair and Bilodeau, 1988; Frostick and Reid, 1989a, 1989b; Frostick *et al.*, 1992; Leeder *et al.*, 1996; Mack and Leeder, 1999). Most models produce conflicting interpretations such that a sheet sandstone could be a product of decreased accommodation or increased avulsion frequency (Allen, 1978; Leeder, 1978; Bridge and Leeder, 1979; Posamentier and Vail, 1988; Gawthorpe *et al.*, 1994; Heller and Paola, 1996; Ethridge *et al.*, 1998; Mack and Leeder, 1999). Decreased accommodation can be a product of either equilibrium of base-level or a cessation of subsidence. Increase in the avulsion frequency can be a product of increased sedimentation rates, flood frequency, or fault activity. Features from the alluvial record are also influenced by lateral changes in the basin morphology. Any analysis of the alluvial record needs to identify regional changes related to controlling factors (tectonics, climate, and base-level) and lateral changes related to basin morphology.

Combined tectonic, climatic, and base-level changes are thought to control the magnitude of accommodation development and overall rate of sediment-accumulation within a basin. This, in turn, can strongly influence fluvial channel geometry and channel interconnectedness, preservation of overbank lithologies, and the morphology and spatial distribution of paleosol horizons (Currie, 1997). ield observations collected from the alluvial record will be used to discern controlling factors for the deposition of the alluvial rift sediments of the Ischigualasto Formation.

The Triassic Ischigualasto Formation of northwestern Argentina provides an opportunity to evaluate changes in alluvial architecture within a well-constrained temporal and spatial context as the formation contains numerous dateable horizons and offers continuous exposure over 100's of km^2. Dating of the intraformational ashes was conducted to establish a record of relative sedimentation rates within the deposits.

PREVIOUS WORK

Initial investigations in the Ischigualasto Basin deposits were conducted by paleontologists studying the rich fossil record contained within the sediments (Frenguelli, 1948; Grober and Stipanícic, 1953; Romer and Jenson, 1966; Alcober and Parrish, 1997; Alcober *et al.*, 1997). They divided the Ischigualasto Basin fill into seven formations which comprise two Groups: (1) the Early Triassic Paganzo III Group (containing the Talampaya Formation and the Tarjados Formation) and (2) the Middle to Late Triassic Agua de la Peña Group (containing the Chañares/Ischichuca Formations, the Los Rastros Formation, the Ischigualasto Formation, and the Los Colorados Formation), which are tied into a tectonostratigraphic framework developed by Milana and Alcober (1994). Preliminary reconstructions of the paleoenvironment of the Ischigualasto Formation was performed by Rogers *et al.* (1993) and Martínez (1994).

METHODS

Two months were spent in the field collecting data between the summers of 2000 and 2001. Three sections were measured perpendicular to the main half-graben fault and progressively along the basin axis to the southeast edge of the basin. Paleosols and channel sandstones were categorized and compared to modern analogues to ascertain the paleoclimatic conditions, tectonic activity, and sediment accumulation rates indicated by their presence. Ash locations were recorded as stratigraphic measurements were made. Dating and extraction of sanidine crystals were performed at New Mexico Technological Institute, in Dr. Bill McIntosh's lab. Sandstones were also mapped along a 1.5 km wide zone along the thickest stratigraphic section measured within the basin.

EXPLANATION OF DISSERTATION FORMAT

The following appendices consist of three manuscripts that form the bulk of this dissertation. The first paper, entitled *Depositional environments of the upper Triassic Ischigualasto Formation, Agua de la Peña Group, San Juan Province, Argentina,* is a detailed look at the depositional environments in which the Ischigualasto Formation was deposited. This paper establishes the paleoenvironmental framework for the second and third papers. The second paper, entitled *Sedimentation rate and its effects on fluvial architecture and paleosol development within the Ischigualasto Formation*, addresses the connection between the alluvial architecture and extra-basin forcing. The third paper, entitled *Model for the tectonosedimentary basin fill of the Triassic Ischigualasto Basin, northwestern Argentina*, examines the current basin model for the Ischigualasto Basin and develops a new model from newly collected information. These manuscripts are followed by the measured stratigraphic sections used in this project with the identified paleosols and channel sandstones. Section 1 was measured by, Dr. Brian Currie, Dr. Neil Tabor, Dr. Isabel Montanez, Kelly Moore, and myself. Section 2 was measured by myself, Dr. Brian Currie, and Carina Colombi. Section 3 was measured by Dr. Brian Currie and myself. Paleosol classification was established by Dr. Neil Tabor and implementation of this classification on the stratigraphic columns was performed by Dr. Brian Currie and myself. All channel sandstone classification and mapping was performed by myself. All dates and extraction of sanidine crystals were performed at New Mexico Technological Institute, in Dr. William McIntosh's lab.

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CHAPTER 2: PRESENT STUDY

The methods for this study were presented in the previous chapter. The results and conclusions of this study are presented in the manuscripts appended to this dissertation. The following is a summary of the most important findings in these papers.

Exposures of the Ischigualasto Formation exhibit a marked change in their paleoenvironments upsection and laterally along the basin's axis. Paleoenvironments along the basin axis develop with a direct relationship to the main half-graben normal fault. High subsidence areas are poorer drained, less mature paleosols with respect to other portions of the basin, wetter due to the related depression, and have a high aerial density of channels. Low subsidence areas are better drained, more mature paleosols with respect to other portions of the basin, drier due to the related basin high, and have less aerial extent of channels. In the lower half of the Ischigualasto Formation the mean annual precipitation is estimated to have been <750 mm as indicated by paleosol evidence and in the upper half of the formation the mean annual precipitation increases. Increase indicates increase in the intensity of the megamonsoon that is also seen in paleosol data of similar age in Australia.

Evidence collected from the Ischigualasto Formation suggests that a change in the climate directly affected the alluvial architecture. Alluvial architecture exhibit several trends upsection which are related to extra-basin forcing agents such as active faulting, climate, and base-level. Cross-referencing these relationships and then canceling each other out produced a dominant forcing agent for the alluvial architecture for the

Ischigualasto Formation. A climate shift from drier to wetter likely caused the increase in the sedimentation rate that is interpreted during the deposition of the Ischigualasto Formation.

The Ischigualasto Basin developed in three phases that relate to active extension of the rift valley to passive subsidence. Phases of basin development are related to the relative amount of extension of the crust, which is broken down into three developmental stages: sub-basins, singular basin, and underfilled basin. Ischigualasto Basin fill's lithology and depositional environment corresponds these three developmental stages. Sub-basin phase of the rift basin produced alluvial fan deposits within isolated internally draining small basins. Singular basin phase produced fluvial and lacustrine deposits within a large internally draining basin. Underfilled basin phase produced fluvial and alluvial fan deposits within a passively subsiding basin. Basalt flows are related to the stage of development and are not found within the underfilled basin phase.

APPENDIX A: DEPOSITIONAL ENVIRONMENTS OF THE UPPER TRIASSIC ISCHIGUALASTO FORMATION, AGUA DE LA PEÑA GROUP, SAN JUAN PROVINCE, ARGENTINA

ABSTRACT

The Triassic Ischigualasto Basin is located in northwestern Argentina and is interpreted as a rift basin. This investigation focused on the depositional environments and their change through time in the Upper Triassic Ischigualasto Formation. Changes are tracked by detailed description of the alluvial architecture at three key locations along the basin axis. These locations exhibit lateral change in basin morphology, which is related to position along the main half-graben fault. Changes in the paleoenvironment reflect changes in the climate or fault activity within the basin and the position of the depositional environment along the basin axis.

Regional shift in the paleoenvironment from arid to semi-arid conditions occurs in the middle of the Ischigualasto Formation. Features reflecting this environmental shift include secondary carbonate, which dominates paleosols in the lower Ischigualasto Formation and is diminished in the upper half. Channels become wider and shallower, and plant material becomes more common in the upper portions of the formation.

INTRODUCTION

The Ischigualasto Basin, located in northwestern Argentina, contains one of the most complete sedimentologic records of the Triassic Period. Climatic data for this time period and region are limited. This study uses data collected from alluvial deposits to reconstruct the paleoenvironment and paleoclimate during deposition of the Carnian (Upper Triassic) Ischigualasto Formation. This reconstruction incorporates the reported lateral and temporal shifts in the paleoenvironments within the basin. Reconstruction of the climate during the Carnian Stage is important because researchers have suggested intensification in the megamonsoon at that time (Parrish *et al.*, 1996).

This investigation focuses on the Ischigualasto Formation in the southeastern portion of the Ischigualasto Basin, northwest of the Agua de la Peña, through the exposures to the southeast just west of Cerro Morado (Fig. A-1). The outcrop in our study area provides the most complete sedimentologic record available for reconstructing the paleoenvironment of the Ischigualasto Formation. The southeastern portion of the basin provides data with which to evaluate changes in alluvial deposits within a well-constrained temporal and spatial context.

Previous Work

The rich fossil record and stratigraphic completeness of the Ischigualasto Formation has made it the focus of extensive paleotologic investigation. The Ischigualasto Formation is one of the primary sources for early dinosaur and reptile fossils in South America (Rogers *et al.*, 1993; Bonaparte and Crompton, 1994; Rogers *et al.*, 2001; Alcober, 2000). Researchers have suggested that the rise of the dinosaurs may have been induced by environmental change (Rogers *et al.*, 1993). This has led to analysis of the sediments and their associated paleoenvironments to try to identify a possible environmental change (Frenguelli, 1948; Romer and Jensen, 1966; Bossi, 1971; and Stipanícic and Bonaparte, 1972).

The Ischigualasto Basin lies along the border of the San Juan and La Rioja provinces in northwestern Argentina. The Ischigualasto Basin extends ~ 120 km northwest from the Valle de la Luna Provincial Park to Cerro Bolla and is ~ 50 km wide (Fig. A-1). The deposits of the Ischigualasto Basin have been divided into seven formations which further form two groups: (1) the lower Triassic Paganzo III Group, containing the Talampaya Formation, and the Tarjados Formation, and (2) the middle to upper Triassic Agua de la Peña Group, containing the Chañares/Ischichuca Formations, the Los Rastros Formation, the Ischigualasto Formation, and the Los Colorados Formation (Romer and Jensen, 1966; Frenguelli, 1948; Grober and Stipanícic, 1953) (Fig. A-2).

The Talampaya and Tarjados Formations (Romer and Jensen, 1966) are composed of red sandstone and conglomerate. They unconformably overlie Carboniferous or Permian rocks and are bounded on the top by an unconformity. The Talampaya and Tarjados Formations have been interpreted to be alluvial fan deposits that formed within sub-basins during the early stages of basin development (Milana and Alcober, 1994). The Chañares Formation (Romer and Jensen, 1966) is composed of alluvial mudstones and sandstones with massive debris flows identified on the eastern margins of the basin (Rogers *et al.*, 2001). The Chañares Formation has been interpreted to represent marginal lake deposits that interfinger with the lake deposits of the

Ischichuca Formation (Rogers *et al.*, 2001). This interfingering occurs near the base of Ischichuca Formation proximal to the location of the Valle Fértil fault and laterally along the basin margins (Fig. A-2). The Ischichuca Formation is composed of clinoform deltaic sandstone and siltstone deposited in a lacustrine environment. The Ischichuca Formation grades into the Los Rastros Formation. The Los Rastros Formation is composed of lacustrine and alluvial sediments. Basalts between the Los Rastros and Ischigualasto Formations have been dated at 229 ± 5 Ma, using K/Ar methods (Fig. A-2) (Odin and Létolle, 1982). Above the Los Rastros Formation is a regional unconformity. The unconformity is overlain by the Peña Conglomerate that represents the base of the Ischigualasto Formation. The Ischigualasto Formation is composed of fluvial and alluvial mudstone and sandstone, which have been interpreted to represent axial fluvial rift valley fill. Rogers *et al.* (1993) dated a tuff near the base of the formation at 227.78 ± .3 Ma (Fig. A-2), which places the lower half of the Ischigualasto Formation in the middle Carnian Stage. The Los Colorados Formation, the uppermost formation in the Ischigualasto Basin rift fill sequence, lies unconformably in the north and conformably to the south on top of the Ischigualasto Formation (Fig. A-2) (Stipanícic and Bonaparte, 1972). The Los Colorados Formation is composed of laterally continuous thin red sandstone and interbedded mudstone beds. It has been interpreted to be alluvial fan to playa-lake deposit (Stipanícic and Bonaparte, 1972).

Tectonic, Climatic, and Depositional setting

The Ischigualasto Basin is a continental extensional half-graben, part of a network of such basins extending the length of Argentina (Uliana and Biddle, 1988; Ramos and Kay, 1991; Veevers *et al.*, 1994; López-Gamundí *et al.*, 1994). The extension of these basins along the Panthalassan margin of Gondwanaland coincides with location of accreted late Paleozoic fore-arc and arc terrains (Uliana and Biddle, 1988). Rifting occurred along this suture that extended from northwestern Chile to the Falkland Islands. Marine deposits encroached from the northwestern rift margin (Stipanícic, 1983; López-Gamundí *et al.*, 1994). Veevers *et al.* (1994) proposed that the Triassic extension of the basin was due to back-arc spreading created by the steeper angle of the subducting slab. Intraformational basalt flows found within the lower portions of the Ischigualasto Formation are identified as basalt to trachyte (Page *et al.*, 1997). Page *et al.* (1997) reported that "these flows were extruded through fracture-related vents and/or monogenetic volcanoes constructed of piles of thick viscous lava." Seismic profiles show evidence of fault motion on the Valle Fértil and Alto faults (Georgieff, 1992) during the Triassic Period, with additional minor fault activity noted perpendicular to the main faults.

Paleoclimate

Paleomagnetic evidence from intraformational basalt flows within the upper Chañares Formation, near the base of the Ischigualasto Formation, place the basin at 30°S during the Middle Triassic (Veevers *et al.*, 1994; Valencio *et al.*, 1975; López Gamundí *et al.*, 1994). Stipanícic and Bonaparte (1972) suggested that sediments in the Ischigualasto Basin were deposited as a single climatic cycle, from relatively dry and seasonal, to more humid and back again, with temperature and ranging from moderate to hot. Stipanícic and Bonaparte's (1972) reconstruction primarily relied on lithologic evidence in the Paganzo III Group and on lithologic and flora/faunal evidence in the Agua de la Peña Group. They also considered the possibility that some of the change in the rock record could be a result of tectonic influences and that the climate was relatively uniform. Volkheimer (1969) supported an interpretation of moderate to hot temperatures mostly based on paleofloral data.

Previous researchers argued that the Ischigualasto Formation was subject to a seasonal climate that was water limited. Root size inferred from rhizoliths from the Ischigualasto Formation are consistent with sizes typical of 500-800 mm of mean annual precipitation (Alcober *et al.*, 1997). Bossi (1971) proposed a dominantly fluvial setting that experienced seasonal variations in water availability, and Martínez (1994) suggested an arid climate with seasonal precipitation, supported by secondary soil carbonate, slickensides, and blocky peds. Further, Spalletti *et al.* (1999) analyzed biozonation in relation to the chronostratigraphy of the basin and that indicated the existence of a mixed forest plant assemblage for the Ischigualasto Formation. Paleoclimate during the deposition of the Ischigualasto Formation was dry, and moderate to hot in temperature, with a pronounced seasonality. The landscape of the Ischigualasto Formation was sparsely forested with a dominance of herbaceous plants, although some large trees, represented by *Rexoylon*, are common in the upper half of the formation.

METHODS

Three sections were measured along strike (Fig. A-1) to capture the variability in accommodation along the Valle Fértil fault. Environments in a rift valley change along the strike of the main basin bounding fault (McCarthy *et al.*, 1991) because faults control the drainage area and accommodation. In measuring the sections, we focused on paleosols and channel sandstone to constrain depositional environmental changes within the basin.

Stratigraphic sections were measured and recorded as schematic columnar diagrams that included information on lithology, bedding, sedimentary structures, fossils, paleosols, and paleocurrent indicators (appendices D, E, and F). Paleosol profiles were characterized using the criteria proposed by Kraus and Aslan (1993). Profile tops were identified on the basis of marked changes in grain size or changes in style of sedimentation, and profile bases were delineated at the lowest occurrence of unaltered parent material. Field descriptions of paleosol thickness, color, type, and distribution of mottling, soil structure, mineralogy, grain size, morphology and distribution of authigenic minerals were completed following Retallack's (1990) methods. The classification of rooting structures and their distribution followed the outline of Pfefferkorn and Fuchs (1991). Paleosol and sediment colors were identified in dry samples using Munsell soil color charts. The paleosol classification system outlined by Mack *et al.* (1993) was chosen because the USDA Soil Taxonomy system requires specific knowledge of the soil during its formation, information that is not available from paleosols.

Channels were classified in the field and also from field descriptions using alluvial architecture, structure, channel morphology, grain size, paleocurrents, and interconnectedness. An area greater than 1.5 km wide was mapped in detail along measured section 1, which is 700 m long, to document the distribution of the sandstone beds and associated facies. Data collected for each sandstone bed included bed morphology, associated alluvial architecture both laterally and vertically, interconnectedness, and paleocurrents. Sandstone beds that did not lie directly along the section were assigned a stratigraphic position on the section. In both sections 1 and 2, beds dip at an average 17° to the northeast, and in section 3 the dip was between 50-80° to the northwest; the paleocurrent directions presented in the figures have been restored to horizontal.

The presence or absence of flora and fauna was noted within the measured stratigraphic sections.

RESULTS

Paleosol Classification

Seven pedotypes, designated A-G, were identified in the Ischigualasto Formation (Fig. A-3).

Pedotype A consists of sandy soils that contain tabular to vermicular mottles (Fig. A-4 (A)) and high hues. Sandstone lenses are common within this pedotype. Primary depositional features are obliterated, and there are abundant root traces.

Pedotype B contains horizons with angular blocky peds and abundant pseudoslickensides (Fig. A-4 (B)). Root traces and clastic dikes (Fig. -4 (B)) are common structures in the upper portions of this pedotype; in the lower portions of the pedotype, remnant bedding is preserved. Low hues dominate this pedotype.

Pedotype C is clay rich with angular, blocky peds with carbonate nodules that are millimeters to a decimeter in diameter (Fig. A-4 (D)). Pedotype C contains pseudoslickensides and clastic dikes extending down to 1.5 m. Generally the upper portions of the pedotype C do not display low hues.

Pedotype D contains abundant clay (Fig. A-4 (C)) and angular, blocky peds with cutans. Pseudoslickensides are absent, yet there are abundant root mottles and clay-filled root traces.

Pedotype E is well developed with coarse, blocky peds and abundant carbonate nodules and tubules. Vadose textures exhibited in these carbonates suggest that they are pedogenic in origin (Fig. A-4 (F)). Tubules are 10-30 mm in diameter and often coalesce.

Pedotype F contains abundant clay and sub-angular to angular peds (Fig. A-4 (E)) with cutans. Beneath the zone of clay accumulation coalesced carbonate nodules are present. Color of this pedotype varies, with no dominant hue.

Pedotype G has thick petrocalcic horizons surrounded by illuviated clay horizons with abundant blocky peds. The carbonate horizon has a laminar texture, with remnant disseminated nodules contained therein. Additional clay accumulations appear below and above the carbonate accumulation.

Channel Classification

Six types of channel sandstone beds (Types 1 through 6 below) were identified within the Ischigualasto Formation, based on morphology, associated alluvial architecture, sedimentary structures, and paleocurrents (Fig. 5).

Type 1 sandstone beds (Fig. A-6 (B)) are single-story, shallowly incised, broadly lenticular sheets 10-100 m wide and 1-6 m thick, dominated by coarse-grained trough cross-stratified sandstone and pebble conglomerate. Paleocurrent directions within the channel stories of these sheets vary little (Fig. A-7). Foresets are mantled by coarser grains.

Type 2 sandstone beds are multi-story, amalgamated sheets similar to the type 1 sandstone beds except that they are vertically stacked and laterally coalesced (Fig. A-6 (A) and A-6(B)). Type 2 beds are generally 100-1000 m wide and 5-20 m thick. Soft-sediment deformation structures are common in both type 1 and 2 sandstone beds.

Type 3 sandstone beds contain channels that are moderately to steeply incised, laterally discontinuous, ribbon sandstone bodies that range from 10-100 m wide and 1-8 m thick. They are dominated by inclined heterolithic strata (Fig. A-6(A) and A-6(E)) composed of medium-fine grained, trough cross-stratified or ripple cross-laminated sandstone with interbedded mudstone. Paleocurrent directions also vary widely within the stories (Fig. 7). Type 3 sandstone beds are laterally associated with abundant thin splay sandstone beds and fine-grained overbank deposits.

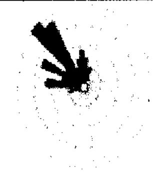
Type 4 sandstone beds are interpreted as channels that contain composite ribbon and sheet sandstone beds, in which a type 3 bed is overlain by a type 1 or 2 bed (Fig. A-6 (A)).

Type 5 sandstone beds contain channels that are lenticular, isolated from other channel sandstone beds, and commonly surrounded by muddy overbank deposits. The channels are moderately to steeply incised and filled with coarse- to medium-grained, trough cross-stratified and ripple cross-laminated sandstone. Some of the type 5 channels display lateral branching and evidence of contemporaneous "islands" (Fig. A-6(F)).

Type 6 sandstone beds contain channels that are thin, laterally discontinuous packages that are mudstone dominated with ribbon sandstone bodies, 5-15 m wide, and 0.5-4.5 m thick. The channel scour fill commonly consists of lenticular to inclined heterolithic strata composed of mudstone and thin ripple cross-laminated sandstone beds (Fig. A-6 (C)). Type 6 channels are difficult to identify in outcrop due to their fine-grained nature, similar to the composition of the surrounding overbank deposits.

Axial Basin Stratigraphy

Data collected from sections 1, 2, and 3 (Fig. A-1) are presented in Table 1. Each of these sections is integrated into a paleoenvironmental model of the Ischigualasto Formation. Complete sections are available in Appendices D, E, and F.

	SECTION 1	SECTION 2	SECTION 3
THICKNESS	700 m	415 m	380 m
PLANT MATERIAL	14 locations	1 location	0 locations
PALEOSOL FREQUENCY	1 paleosol/4.5 m	1 paleosol/3.4 m	1 paleosol/2.0 m
CHANNEL SANDSTONE FREQUENCY	1 channel sandstone/ 13.5 m	1 channel sandstone/ 14.3 m	1 channel sandstone/ 17.3 m
PALEOCURRENT DIRECTION	 N = 256	 N = 54	 N = 54
NUMBER OF CHANNEL SANDSTONE BEDS	52	29	22
NUMBER OF PALEOSOLS	155	121	186

Data collected from the measured sections exhibit the lateral trends within the Ischigualasto Formation, including drainage direction, channel sandstone frequency, paleosol frequency, and general total numbers of alluvial features. The thickest portion of the Ischigualasto Formation (section 1) has the largest number of channel sandstones, the fewest paleosols, and the most fossil plant sites. The thinnest portion of the Ischigualasto Formation (section 3) has fewer channel sandstones, more abundant paleosols, and no fossil plant sites. Section 2 is similar to the sandstone frequency in section 1 and similar to the paleosol frequency in section 3.

DISCUSSION

Each pedotype represents different environmental settings that vary according to proximity to active channels, relative accommodation within the basin, drainage, exposure, time, and climate. The seven pedotypes can be divided into two categories: (1) pedotypes associated with fluvial-alluvial deposits (pedotypes A-F) and (2) a polygenic pedotype (pedotype G).

Paleosol Interpretation

Paleosols with the characteristics found in pedotype A are classified as Protosols (Mack *et al.*, 1993). Protosols form on levee-splay deposits in areas with short exposure times due to successive depositional events or high sediment accumulation rates. Pedotype A occurs in floodplain deposits proximal to a channel.

Paleosols with the characteristics found in pedotype B are classified as Gleyed Vertisols. Redoximorphic colors are common among the Gleyed Vertisols with abundant mottling suggesting that pedotype B experienced extended periods of waterlogging in poorly drained areas on the floodplain (Vepraskas *et al.*, 1994). Gleyed Vertisols commonly form in climates with an average mean annual precipitation of 250 mm-2100 mm (Gyllenhall, 1990). Pedotype B occurs in locations proximal to channel belts or topographically low areas on the floodplain.

Paleosols with the characteristics found in pedotype C are classified as Calcic Vertisols. Generally the upper portions of pedotype C were not found to contain redoximorphic colors, which suggests that the pedotype was not waterlogged for any extended period of time. These paleosols most likely experienced episodic wetting and drying from seasonal precipitation and were well drained. The presence of secondary carbonate in this pedotype makes these soils significant for estimating the paleoclimate of this pedotype, because such soils are found today in climates with less than 760 mm mean annual precipitation (Royer, 1999). Pedotype C occurs in portions of the floodplain that are well drained and medial to channel belts.

Paleosols with the characteristics found in pedotype D are classified as Argillisols. Argillisols form in climates without excessive precipitation and are not waterlogged for extended periods of time. Pedotype D is similar in maturity to pedotype C, except it lacks secondary carbonate. A lack of carbonate can be the product of increased precipitation or well-developed drainage with a restriction in the carbonate source (Machette, 1985). Pedotype D formed on stable, moderately to well-drained surfaces, medial to distal to a channel belt with a greater mean annual precipitation than the climate that formed pedotype C.

Paleosols with the characteristics found in pedotype E are classified as Calcisols (Machette, 1985). Paleosols with coalesced nodular secondary carbonate develop over 10,000 years (Machette, 1985) in arid to semi-arid climates with precipitation below 760 mm per year. Pedotype E is relatively more mature than pedotype C, due to the more developed nodular secondary carbonate. Pedotype E forms in zones of low sediment accumulation distal from channel belts.

Paleosols with the characteristics found in pedotype F are classified as Calcic Argillisols. Pedotype F is a very mature soil, based on the stage of secondary carbonate development and associated clay illuviation (Birkeland, 1984; Machette, 1985). Machette (1985) argues that 10,000 to 100,000 years is required to reach this stage of carbonate development. Pedotype F forms on interfluves in the best-drained portions of the floodplain.

Pedotype G is a composite soil. The composite pedotype represents multiple phases of pedogenesis, often on topographically high surfaces, and represent the longest exposure time in the Ischigualasto Basin for a surface within the Ischigualasto Formation (Atkinson, 1986).

Paleosols found within the Ischigualasto Formation support a climate that varied from arid to humid.

Paleosols within the Ischigualasto Formation exhibit upsection trends that are related to of both axial depositional facies and regional basin changes in the paleoenvironment.

Paleosols with secondary carbonate are absent to rare within the upper half of the Ischigualasto Formation, which expresses a regional climate change towards a greater mean annual precipitation. Three pedotypes -C, -E, and -F contain secondary carbonate. These profiles are all but absent in the upper 400 m of section 1, upper 259 m of section 2, and upper 130 m of section 3, with the exception of a polygenic (type G) soil found at the 386 m level (Fig. A-9). Type E pedotypes were absent or rare in section 2. The absence of paleosol carbonate in the upper half of the formation is evident across the basin. Parrish *et al.* (1996) interpreted a shift in the climate at the Carnian-Norian boundary correlates with the shift we see in our paleosols.

Paleosol frequency increases toward the thinnest part of the Ischigualasto Formation (Fig. A-10), which is located above the transfer zone (Fig. A-8). Compared to the thicker section 1, section 3 has a higher density of paleosols and a greater abundance of mature paleosols. Paleosols show evidence of polygenic development near the thinnest portion of the basin in section 3 (Fig. A-9). Axial trends develop as a response to the basin morphology (Fig. A-8) which regulates drainage of the landscape.

Paleosols on average are more mature in the lower half of the Ischigualasto Formation, a feature created by a region-wide change in the paleoenvironment (Fig. A-9). Dissected landscapes produce more mature soils than non-dissected landscapes (Kraus, 1999; Wright and Marriott, 1993; Atkinson, 1986). Increase in maturity paleosols in the lower half of the Ischigualasto Formation further supports the interpretation of lower sedimentation rates in the initial development.

Paleosols express regional and axial change in their depositional environments. The Ischigualasto Formation exhibits a shift in the mean annual precipitation from drier toward wetter conditions. Paleosol frequency represents a lateral change in the drainage of the paleoenvironments. Decrease in the paleosol maturity in the upper half of the formation is due to a decrease in the dissection of the landscape and a shift in the paleoenvironmental conditions.

Channel Interpretation

Channel sandstone types were constructed to differentiate and include channel sandstone outcrop patterns into categories, which have further been interpreted as paleochannel depositional environments. Paleochannel environments are interpreted by the morphology of the sandstone beds, average paleocurrent dispersion, associated floodplain deposits, and internal sandstone structure. Using this information, sinuosity and depositional processes are interpreted.

Type 1 and 2 channel sandstone beds were deposited in low-sinuosity channels. Large-scale foresets in the type 1 and 2 channels have been interpreted to represent transverse bars (Cant, 1978; Miall and Turner-Peterson, 1989), which are common in low-sinuosity channels. Low paleocurrent variability is associated with type 1 and type 2 channels, which suggests a low sinuosity (Fig. A-7). Type 2 channel sandstone beds have the same characteristics as type 1 channel sandstones, but they consist of multiple stacked channel stories (Fig. A-6 (B)). Type 2 channels were produced by repeated avulsions within a confined alluvial belt. Channels this size are almost certainly part of the main axial drainage network within the rift basin (Frostick and Reid, 1989; Gawthorpe and Leeder, 2000).

Type 3 channel sandstone beds are interpreted as high-sinuosity point-bar-dominated channels. Abundant splay sandstone beds are laterally continuous with type 3 channels, which are commonly associated with high-sinuosity channels (Willis, 1993).

High paleocurrent variability is associated with the type 3 channel sandstones, which suggests a high-sinuosity (Fig. A-7).

Type 4 channels develop by avulsion or diversion of flow away from the main channel. Type 1 or 2 channel sandstones cap type 3 channel sandstones, representing the waning flow stages after the channel is abandoned following an avulsion (Smith, 1983). Avulsions shift flow to a topographically lower spot on the floodplain in response to channel aggradation. This process decreases flow in the avulsing channel, changing the flow and affecting the type of deposit. The top of the type 4 sandstone bed has similar structure to type 1 and type 2, suggesting deposition in a low-sinuosity channel on top of a high-sinuosity channel.

Ancient examples of architecture similar to type 5 channels (Eberth and Miall, 1991) have been interpreted as anastomosing. Anastomosing channels are typified by isolated sandstone stringers surrounded by muddy deposits (Makaske, 2001). Laterally associated splay sandstone beds are absent with such channels, as are levee deposits. Avulsions are the primary means of channel migration with anastomosing channels due to sediment accumulation primarily within the channels. Coopers Creek, Australia and upper inner Nile Delta, Egypt, both contain anastomosing deposits similar to the type 5 channel sandstones (Rust, 1981; Makaske, 1998). These anastomosing channels develop on slowly aggrading floodplains with flashy discharge (Rust, 1981).

Type 6 channels are interpreted as low- to high-sinuosity, mixed-load crevasse or tributary channels with high suspension loads. Examples of these sandstones outcrops were described by Ebert and Miall (1991). They explain their genesis as receiving flow during a high discharge event and filled with subsequent slack-water deposits. Type 6 channels represent the post-avulsion channel fill deposit (Makaske, 2001; Ebert and Miall, 1991). Channels with high suspension loads have width-to-depth ratios less than 10 and a sinuosity greater than 2 (Schumm, 1981).

Channel paleocurrent directions were used in part, as a tool in the channel morphology interpretations (Fig. A-7). Figure A-7 represents mapping of sandstone beds from aerial photos with rose diagrams of measured paleocurrent directions positioned at the point of collection. Channels with a diverse rose diagram suggest a high-sinuosity channel and a low diversity diagram suggests a low-sinuosity channel. It is important when viewing paleoflow data for channel sandstones that it is viewed in context with lateral position within the sandstone body. Figure A-7 represents a map view of the lateral diversity within the paleocurrent measurements and their associated sandstone outcrops.

Regional Interpretation

Regional environmental change can occur as axial depositional environmental facies and/or general shifts in depositional environment through time. General shifts in the climate or activity on the faults affect the depositional environments of the entire basin and are expressed in the axial depositional environmental facies. Axial depositional facies trends are usually consistent with their relative positions along the range bounding fault. The Ischigualasto Formation exhibits both types of regional environmental change.

The axial depositional environments of a rift basin (axial margin, accommodation zone margin, and hinged margin) change laterally as a result of basin shape (Fig. A-8). Portions of a rift basin's depositional environment develop differently in response to varying subsidence rates, that in turn affect drainage catchment size (Frostick and Reid, 1989; Gawthorpe and Leeder, 2000). Relative throw along the strike of a normal fault decreases away from the zone of maximum accommodation (Gawthorpe and Leeder, 2000), which affects local depositional environmental conditions. Changes occur in the soil exposure, channel size, water availability and preservation of flora (Kraus, 1999; Makaske, 2001; Schumm, 1981). Location within the drainage catchment will dictate the channel size (Strahler, 1964). Channel size data will be used to determine the relative position within the drainage. Drainage within a rift basin is primarily controlled by the structure (Frostick and Reid, 1989; Gawthrope and Leeder, 2000). Structure is the primary control on the lateral depositional environment shifts within the rift basin. Axial trends exhibited within the Ischigualasto Formation suggest (1) an increase channel sandstone frequency in the thicker sections and (2) an increase in the paleosol frequency in the thinner sections.

Regional trends in the paleosols also exist within the deposits of the Ischigualasto Formation. Regional trends suggest that stratigraphic changes are caused by large-scale processes and are not due to local depositional circumstances. Correlation of these trends was compiled using radiogenic dating and outcrop observations. Several regional trends are exhibited throughout the Ischigualasto Formation, including: (1) channel width increase upsection, (2) increase in abundance of abandoned channels lake deposits in the upper half of the formation, (3) lack of secondary paleosol profiles in the upper half of the formation, (4) more dissected and better drained landscape in the lower portions of the formation, and (5) plant material preserved within the upper half of the formation. These regional stratigraphic trends suggest a change in the depositional environment in the middle of the Ischigualasto Formation.

Channel Sandstone Trends within the Basin

Channel type changes with response to the regional and axial changes of the paleoenvironment, just as do the pedotypes. This section interprets the regional trend exhibited in the alluvial rock record of the Ischigualasto basin fill.

Channel morphology changes upsection from deep and narrow to wide and shallow (Fig. A-11). Type 1 and 2 channel sandstones dominate the upper half of the Ischigualasto Formation; these channels are generally thin and laterally continuous (Fig. A-5). Multiple branching channels separated by islands (type 5) were found in the upper half of the Ischigualasto Formation (Fig. A-6 (F)). Type 5 is more common in the lower portions of the Ischigualasto Formation (Fig. A-11). Evidence from the paleosols suggests that this change in the channel morphology coincides with a decrease in the dissection of the landscape. The change in the channel morphology relates to change of channel flowing in isolated valleys to broad, open floodplains.

Lithologic evidence suggests that channels within the lower portion of the Ischigualasto Formation were ephemeral. Type 3 channel sandstone beds found in the lower 150 m of the section 2 contained pedogenically modified, inclined heterolithic strata (Fig. A-6). Ephemeral streams are common features in environments that have pronounced seasonality in their environment.

The channel sandstone frequency increases towards the thickest portion of the Ischigualasto Formation (Fig. A-10, Table 1). Larger channels flow across axial portions of the basin rather than along the accommodation zone (Fig. A-8) (Frostick and Reid, 1989). Channel density change along the basin axis is due to increased subsidence along the trans-axial faults. Increased subsidence rates will direct and concentrate drainage into the areas of maximum subsidence (Strahler, 1964; Mackey and Bridge, 1995). Movement along faults controls the local basin lows, therefore controlling channel density.

Channels with associated lake deposits are only found in the upper portion of the Ischigualasto Formation (Fig. A-6 (D)). Abandoned channel/lake deposits appear to coincide with the disappearance of secondary carbonate in the paleosols. The relationship between the lake deposits and the paleosols suggests that the abandoned lake deposits are products of an increase in the mean annual precipitation.

Channel size, morphology, and occurrence of abandoned channel lakes deposits change within the Ischigualasto Formation. These changes are related to the climate.

Axial channel frequency change is attributed to basin morphology, which is a direct consequence of fault activity.

Floral Preservation

Floral and faunal records in the strata are controlled by changes in patterns of preservation and/or extinction (Fig. A-10). Change in pattern of preservation can bias the fossil record, resulting in an apparent absence of flora and fauna. Paleosols have a higher potential for preservation of vertebrate fossil material than for preservation of plant material (Pickford, 1986) because plant remains are readily oxidized. Wetter conditions increase available plant material, which can increase the potential preservation of plant material. In addition, a higher water table provides a low-oxygen environment, which also increases the preservation potential for plant material (Retallack, 1990).

Lack of preserved wood and scarcity of plant material in the lower half of the Ischigualasto Formation is due to low sediment accumulation rates and an arid climate. The stratigraphically lowest occurrence of significant amounts of fossilized plant material corresponds to the disappearance of carbonate in the paleosols. Most of the plant remains are found in abandoned channel deposits in the upper half of the Ischigualasto Formation (appendices D, E, and F). These channel deposits were created during deposition of the upper portion of the Ischigualasto Formation, near section 1, where lakes were located near the active channels and on the floodplain.

CONCLUSION

Two different regional paleoenvironmental conditions existed during the deposition of the Ischigualasto Formation. (1) Dissected valleys with ephemeral streams dominated the landscape of the lower Ischigualasto Formation. The upper Ischigualasto Formation's depositional environment is dominated by wide braided channels over a undissected landscape with wide, expansive floodplains. These regional depositional environmental conditions changes in character along the axis of the basin. Interpretations considered both axial and regional depositional trends in order to develop an environmental reconstruction of the Ischigualasto Formation.

It is essential in any interpretation of basin paleoenvironments that basin morphology be considered in the context to regional trends in the alluvial architecture. This interpretation separates and addresses each of the different depositional signatures so as not to confuse their signals. (1) Secondary carbonate missing from paleosols indicates increase in the mean annual precipitation. (2) Landscape was less dissected in the upper half of the Ischigualasto Formation and better drained in the lower portions of the formation. (3) Toward the middle of the Ischigualasto Formation, lakes form lateral to the main axial channels. Abandoned channels become floodplain lakes form swamps lateral to the main channel facies. This coincides with increased preservation of plant material in the upper half of the Ischigualasto Formation. (4) Changes in the size of the channels laterally and temporally show a contemporaneous change in the drainage network within the rift basin.

Evidence from the paleoenvironmental reconstruction indicates an increase in the mean annual precipitation, which could relate to the reported intensification of the megamonsoon (Parrish *et al.*, 1996). This intensification may relate to the paleoenvironmental change to higher water tables, low-sinuosity channels, and increased in abandoned channels.

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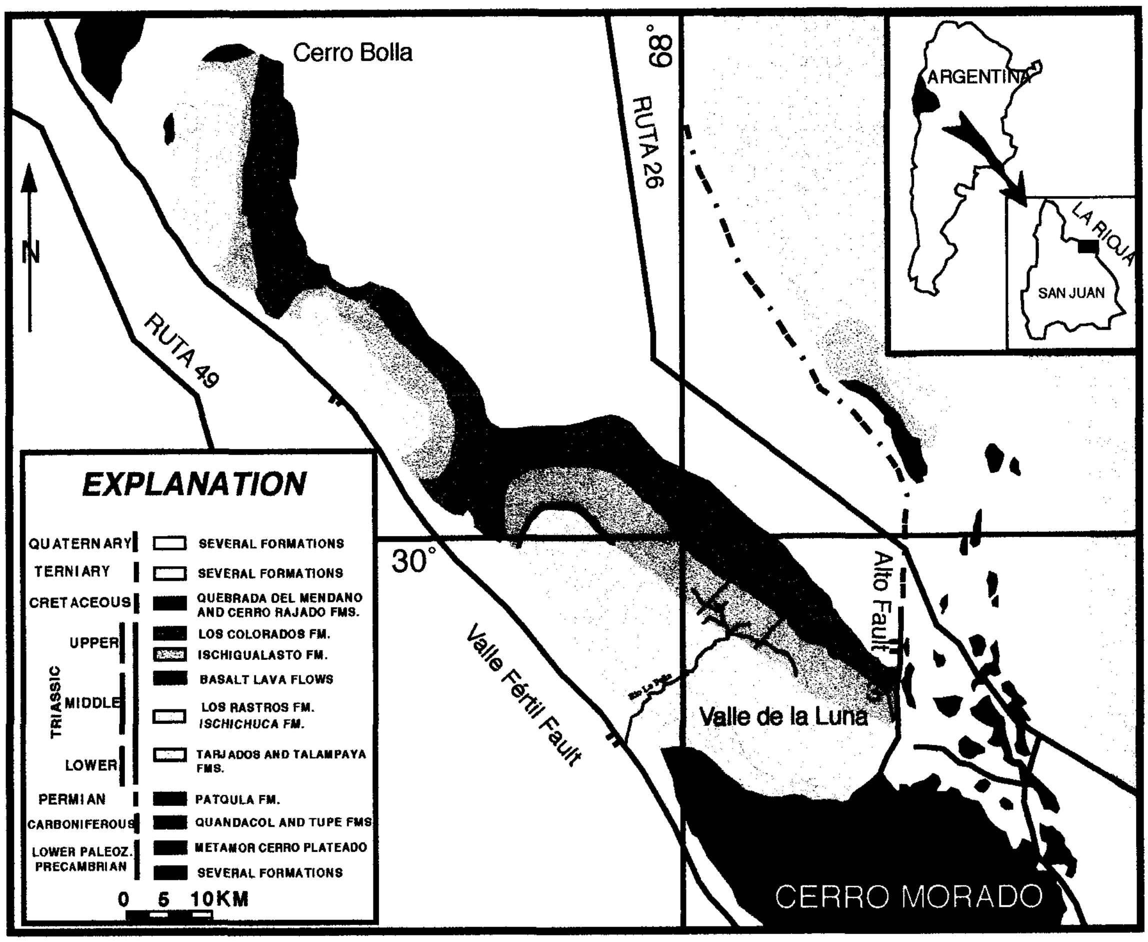


Figure A-1. This geologic map of the Ischigualasto Basin shows the entire extent of outcrops within the basin. Valle Fértil is the boundary fault that controls accommodation in the basin. Black lines and numbers represent the location of measured sections and their corresponding numbers. These sections were measured perpendicular to strike of the Ischigualasto Formation (map modified from Milana and Alcober, 1994)

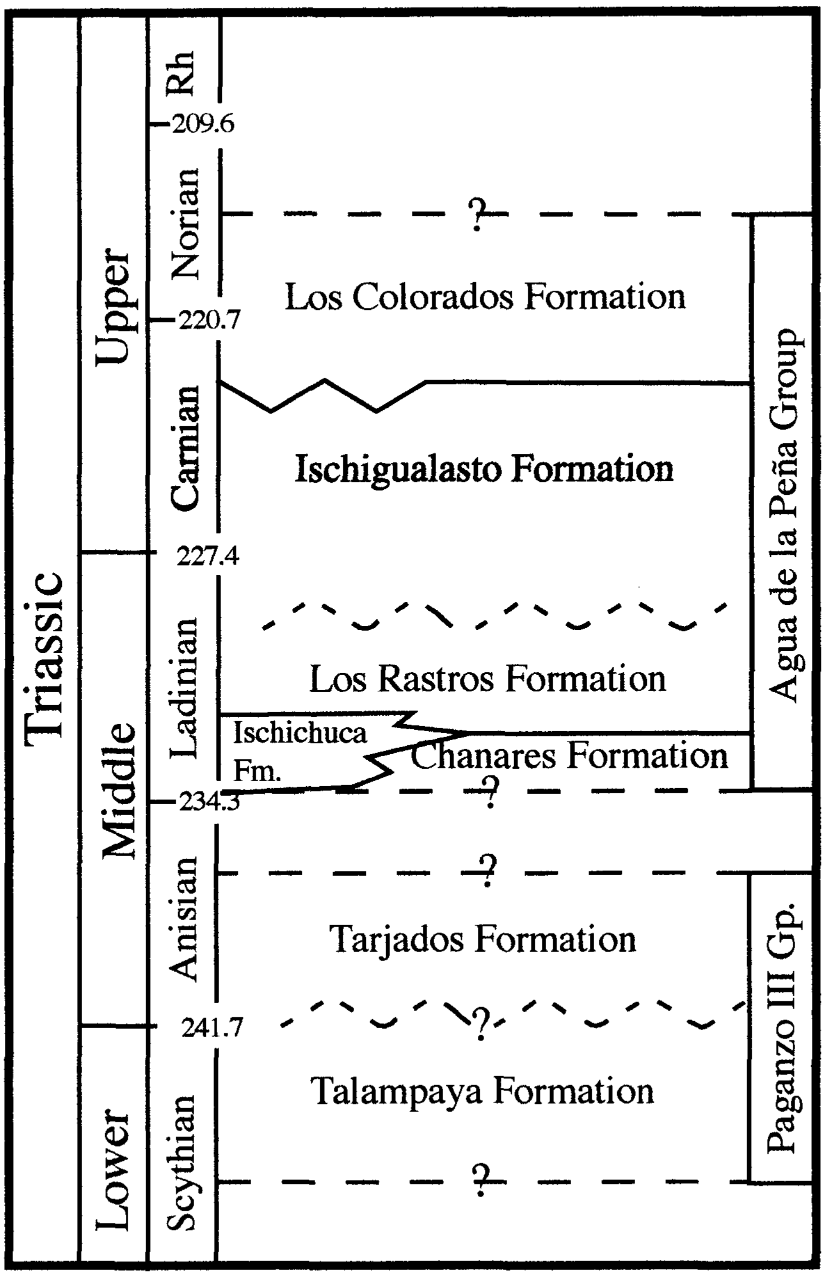


Figure A-2. The stratigraphy of Ischigualasto Basin fill sequence,deposited during the Triassic Period.

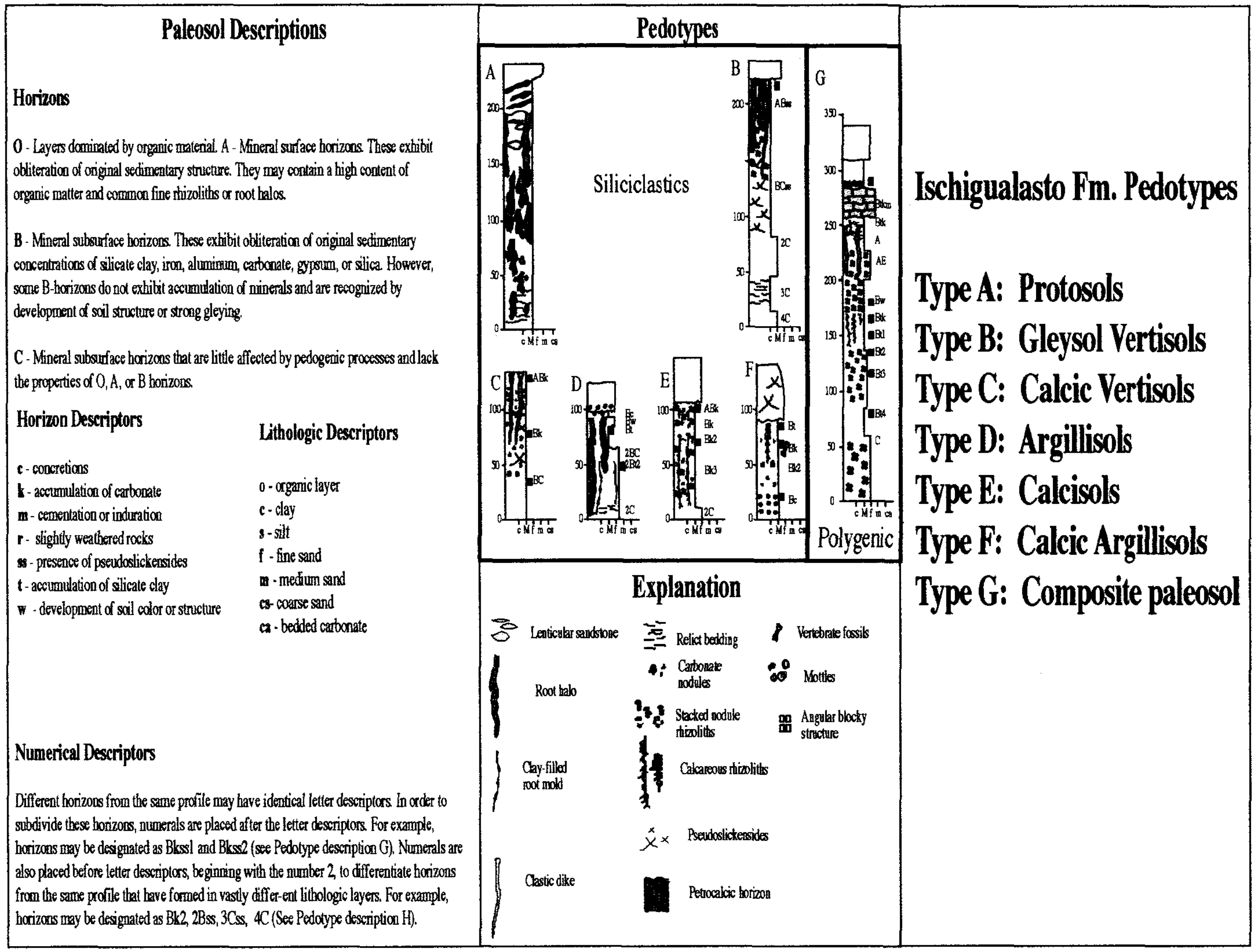


Figure A-3. Classification of the Ischigualasto Formation paleosols based on Mack *et al.* (1993)

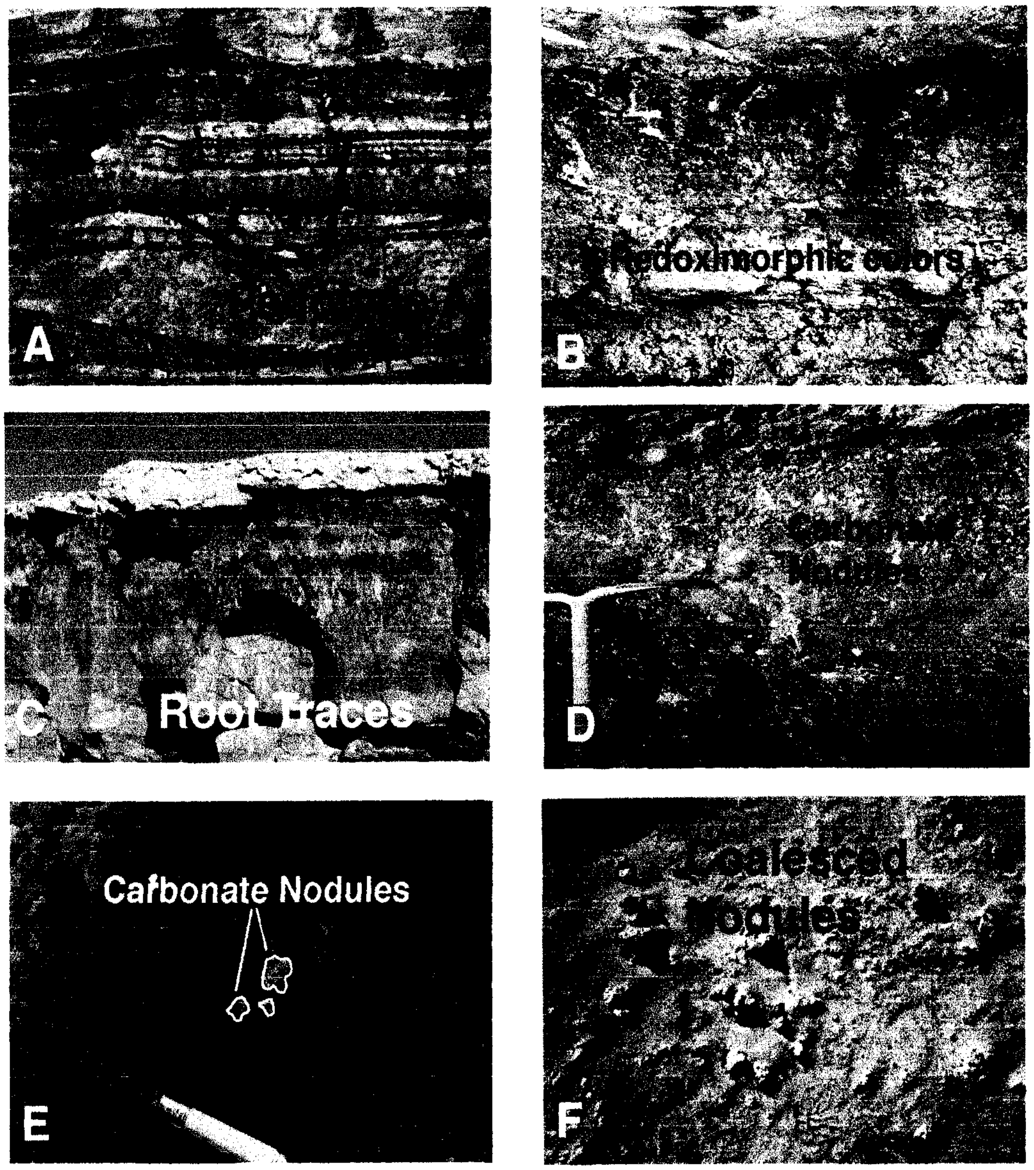
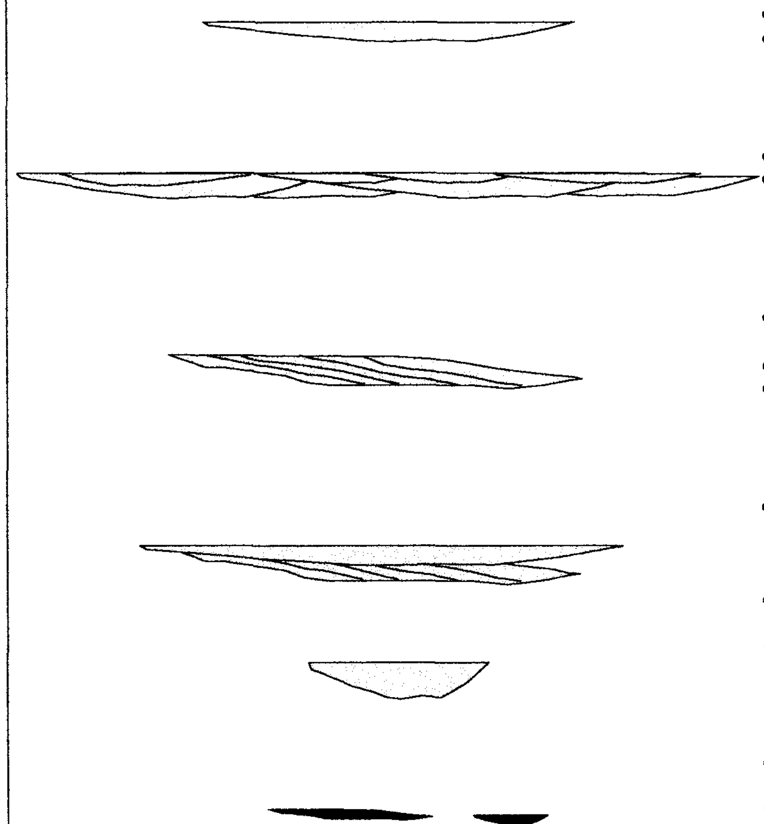


Figure A-4. Photographs of pedotypes in the Ischigualasto Formation
(A) Pedotype A is the most immature paleosol classified in the Ischigualasto Formation.
(B) Pedotype B is a gleyed paleosol with redoximorphic colors.
(C) Pedotype D has an illuviated clay horizon and abundant root traces.
(D) Pedotype C has represents the most immature of the carbonate-bearing paleosols and contains nodular carbonate.
(E) Pedotype F is the most mature soil type, with illuviated clay and coalesced carbonate nodules.
(F) Pedotype E is similar to pedotype C; however the secondary nodular carbonate is more developed.

Cross-Sectional Geometry



Sandstone Architecutral Elements

Type 1
Shallowly incised, broadly lenticular, sheet sandstone beds
- fill dominated by coarse-grained, trough cross-stratified sandstone
- 10s-100s m wide, 1-6 m thick

Interpretation: low-sinuosity, bar-dominated channels

Type 2
Amalgamated sheet sandstone beds
- vertically stacked, laterally coalesced, "Type 1" sandstones
- 100s-1000s m wide, 5-20 m thick

Interpretation: low-sinuosity, bar-dominated channels which amalgamate by avulsion or lateral migration of the channel.

Type 3
Laterally discontinuous, ribbon sandstone bodies
- fill dominated by inclined heterolithic strata consisting of coarse to fine, trough cross-stratified and ripple cross-laminated sandstone and interbedded mudstone
- associated with abundant thin splay sandstone beds and fine-grained overbank deposits
- 10s-100s m wide 1-8 m thick

Interpretation: high-sinuosity, point-bar dominated channels

Type 4
Composite ribbon/sheet sandstone beds
- "Type 3" sandstone beds overlain by "Type 1" and "Type 2" sandstone beds

Interpretation: High sinuosity channels that avulse and are overlain by a low sinuosity channel

Type 5
Solitary, lenticular sandstone beds
- moderately to steeply incised, coarse to fine, trough cross-stratified and ripple cross-laminated sandstones; may display lateral branching and evidence of contemporaneous "islands"
- 10-20 m wide and 1-3m thick

Interpretation: low sinuosity-"anastomosed" channels

Type 6
Thin, laterally discontinuous mudstone-dominated lenses and ribbons
- fill commonly consists of lenticular/inclined heterolithic strata consisting of mudstone and thin, ripple cross-laminated sandstones
- 5-15 m wide, 0.5-4.5 m thick

Interpretation: low-high sinuosity, mud-dominated channels

Figure A-5. Ischigualasto Formation sandstone architecture.

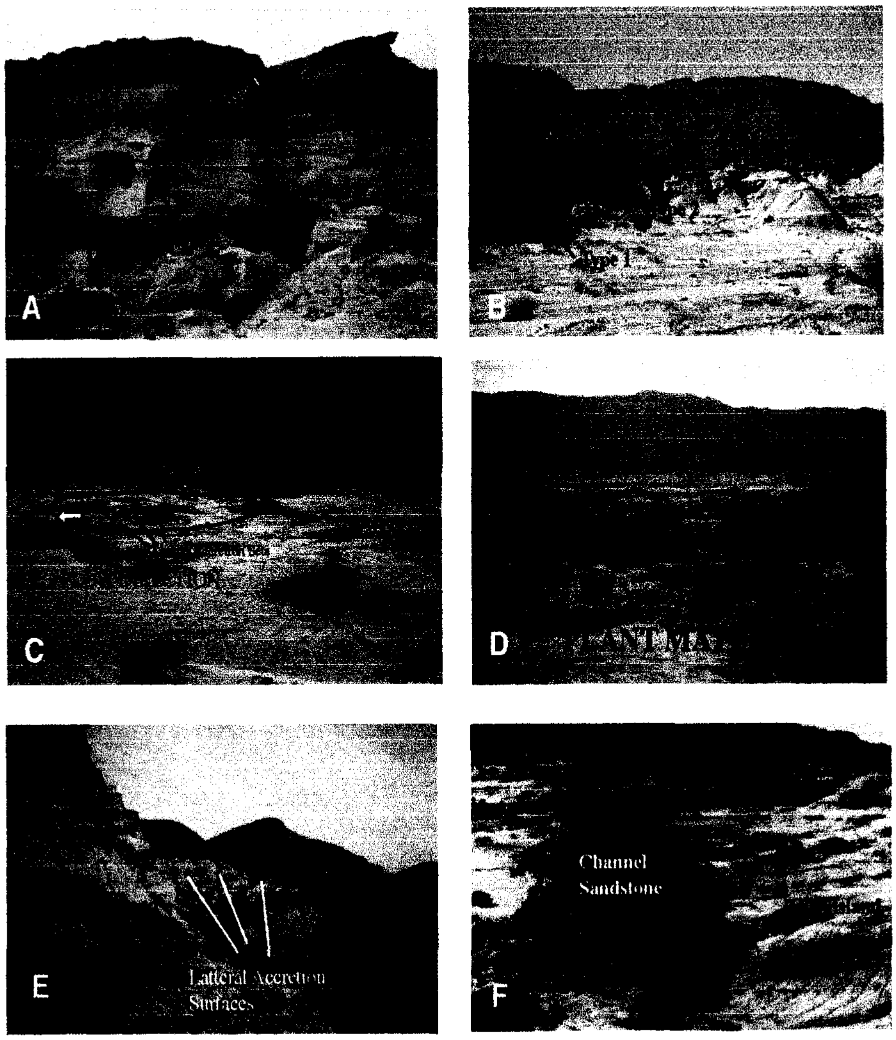


Figure A-6.
(A) Type 4 included a type 3 bed overlain by a type 1 or 2 bed. The bedded horizons in the type 3 channel sandstone are oblique views of lateral accretion set.
(B) Type 1 and 2 are deposited by similar channels; however the type 2 represents multi-story assemblage of type 1.
(C) Type 6 channel sandstones have high concentrations of mud and blend into the surrounding overbank deposits.
(D) Plant material is preserved within abandoned channel deposits, which formed lakes near active channels.
(E) Type 3 channel sandstone beds with pedogenic modification along the lateral accretion beds suggest an ephemeral nature to this channel.
(F) Type 5 channel sandstone beds are shown here branching on the paleofloodplain.

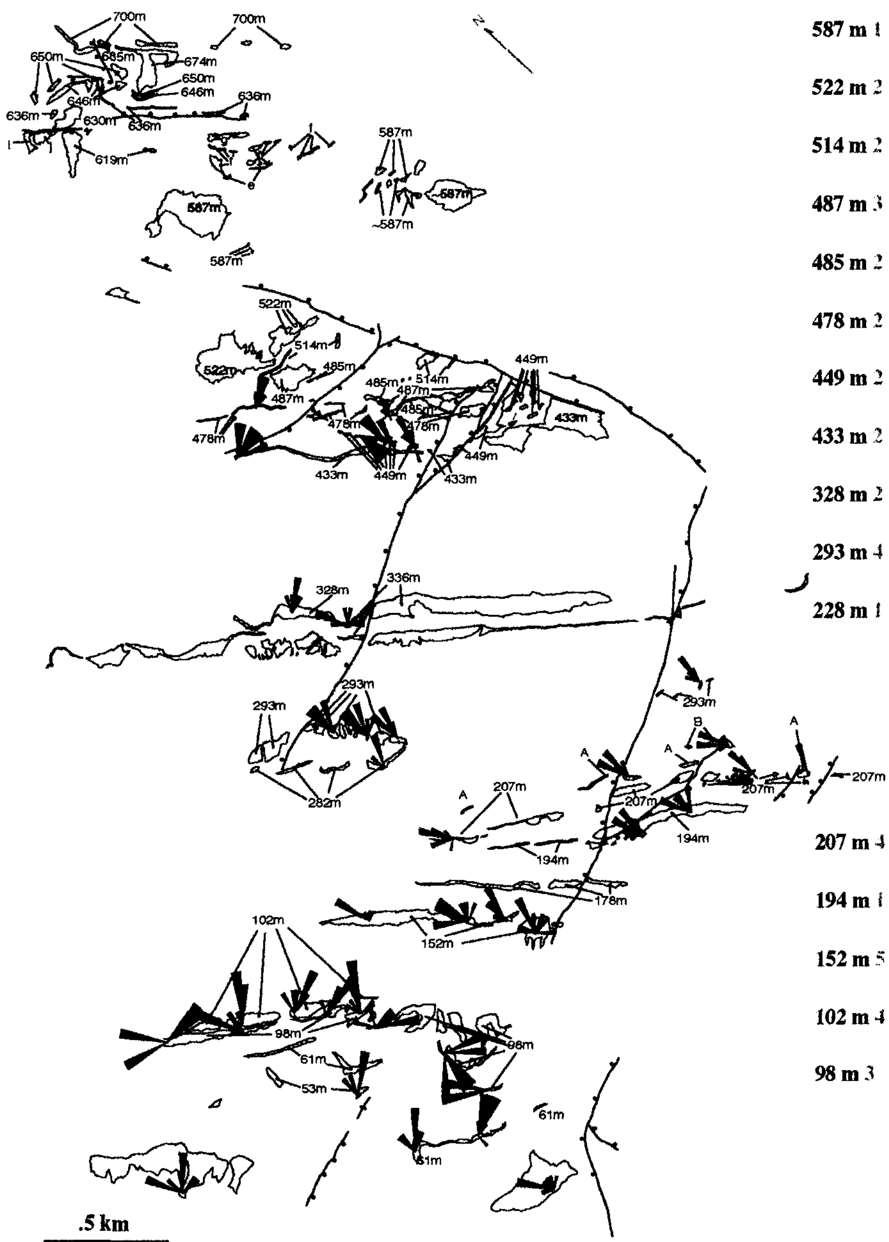


Figure A-7. Channel sandstone beds were mapped out in a 1.5 km wide swath adjacent to the location where section 1 was measured. Paleocurrent rose diagrams are placed at the locations where they were measured. Along the right side of the figure, numbers correspond to the stratigraphic location of mapped channel sandstones. Red numbers indicate the channel type catagory.

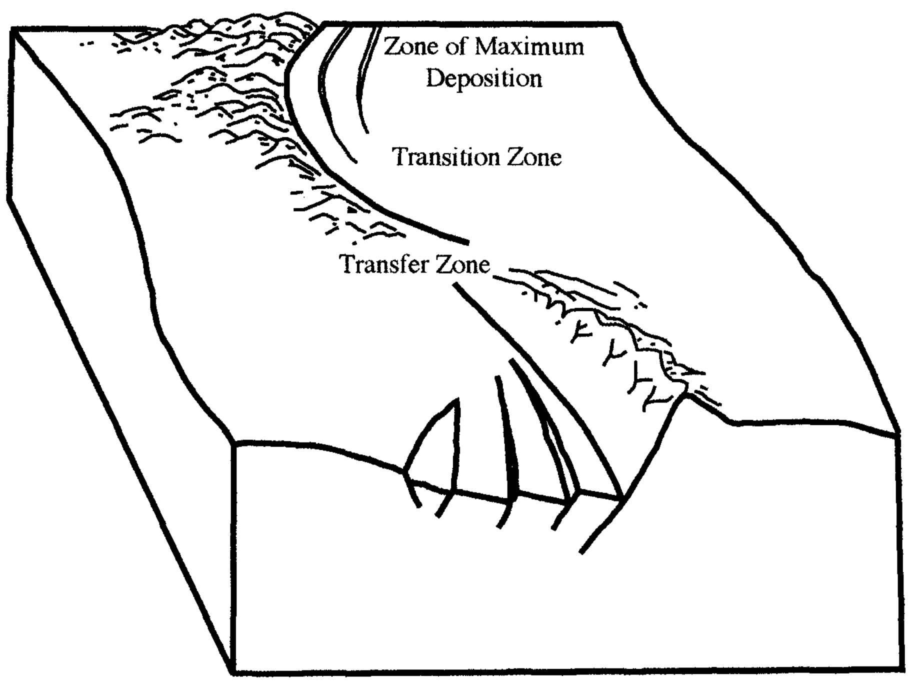


Figure A-8. Rift basins are commonly constructed as chains of reverse dipping half-graben faults. These individual half-graben basins can be divided by their relative accommodation; Transfer Zone, Transition Zone, and Zone of Maximum Deposition. Transition zones represents the areas between the Transfer Zone and the Zone of Maximum Deposition, which contains characteristics of both zones. Transfer zones have the least accommodation and the most mature paleosols. Zones of maximum deposition have the most accommodation and highest concentration of channel deposits. This figure is modified from Rosendahl *et al.* (1986).

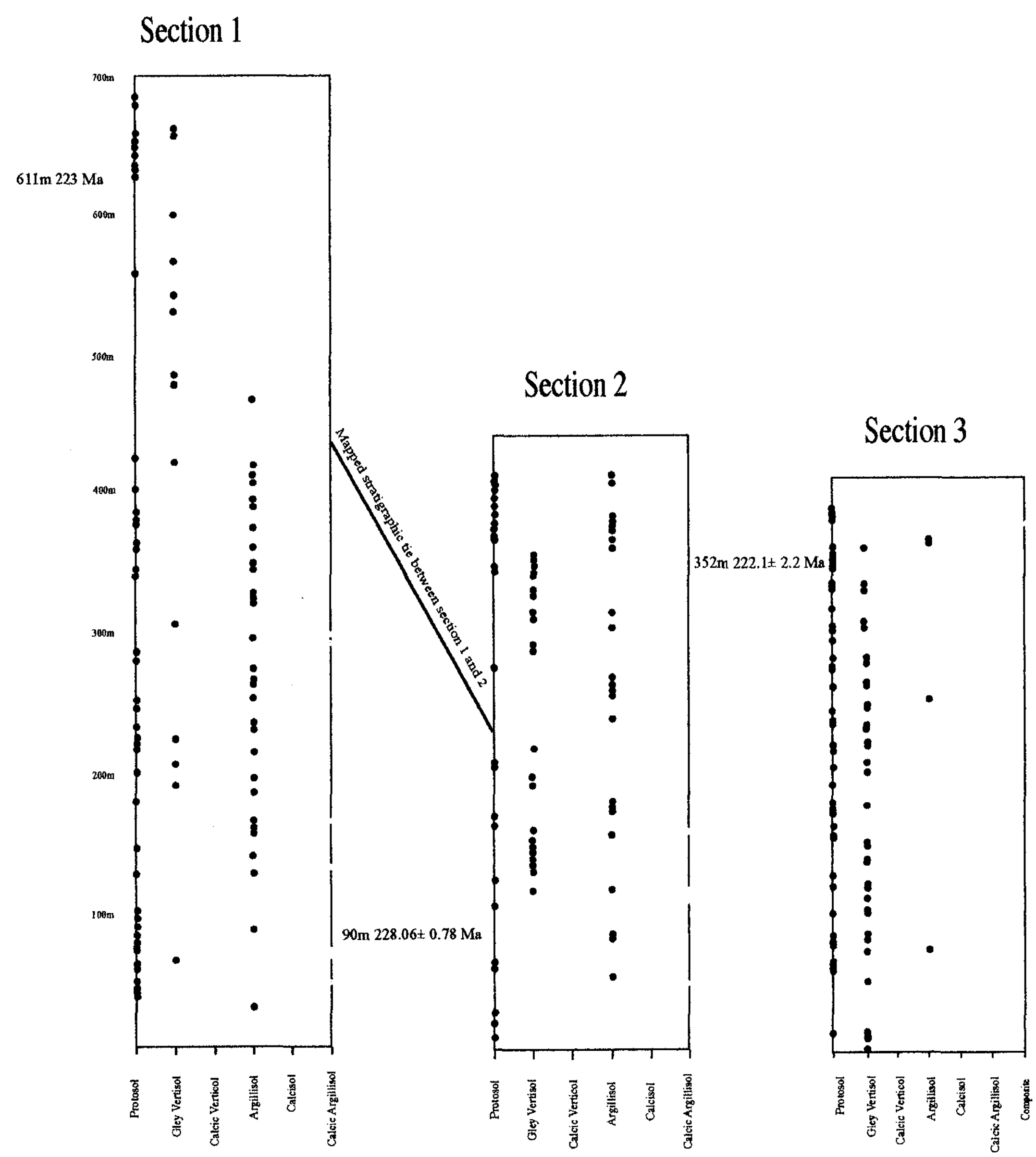


Figure A-9. Each column represents the stratigraphic thickness of each measured section, and soil types found in Ischigualasto Formation are listed across the bottom of each column. Yellow dots represent paleosols that contain secondary carbonate. Dots represent stratigraphic position of paleosols and type after Mack *et al.* (1993). Notice that paleosols bearing secondary carbonate are rare to absent in the upper portions of the Ischigualasto Formation.

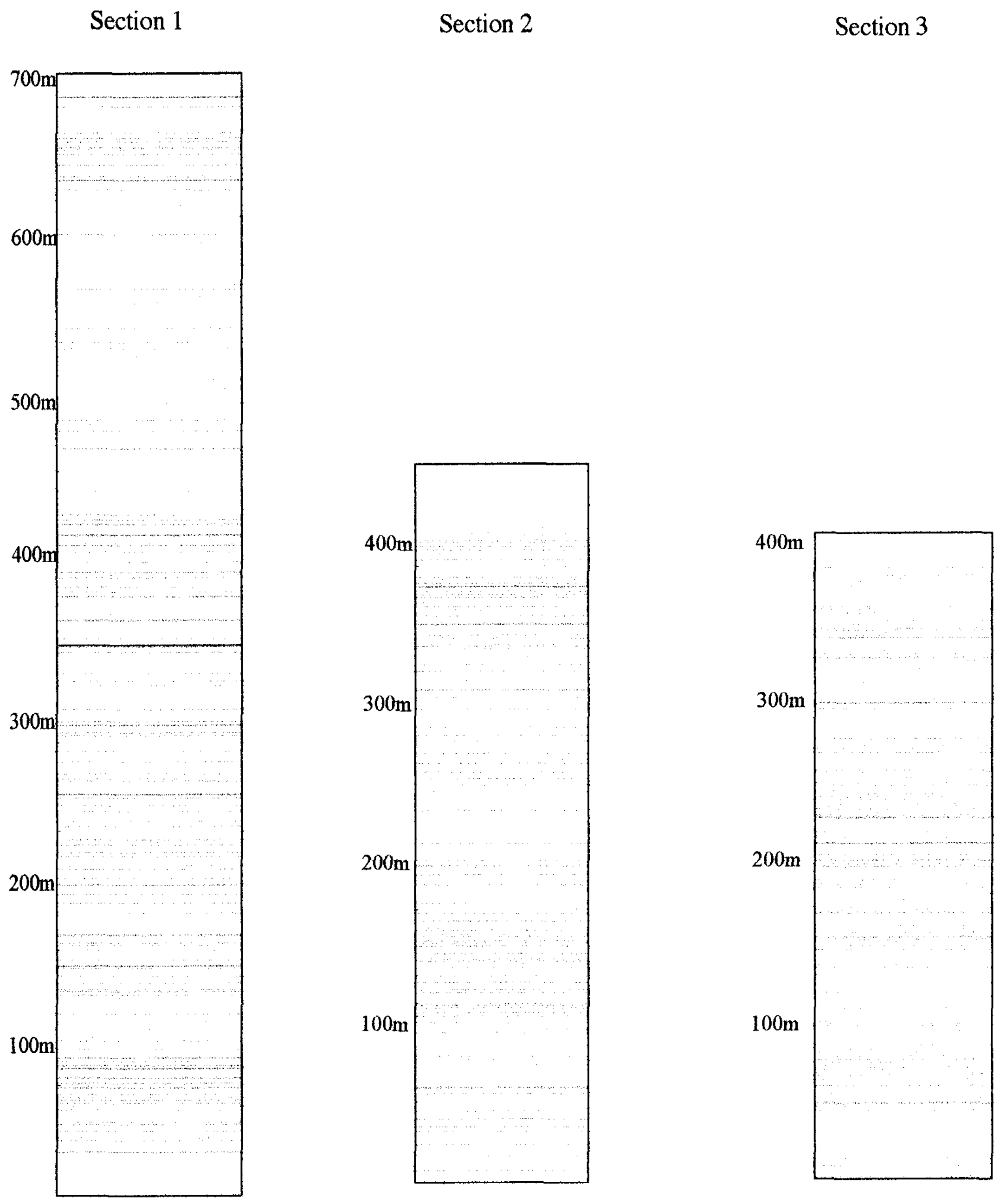


Figure A-10. All three sections are represented here with paleosol (green) and channel (red) stratigraphic locations. The density of paleosols is much greater in section 3 than section 1. Channels are more abundant in section 1 than in section 3.

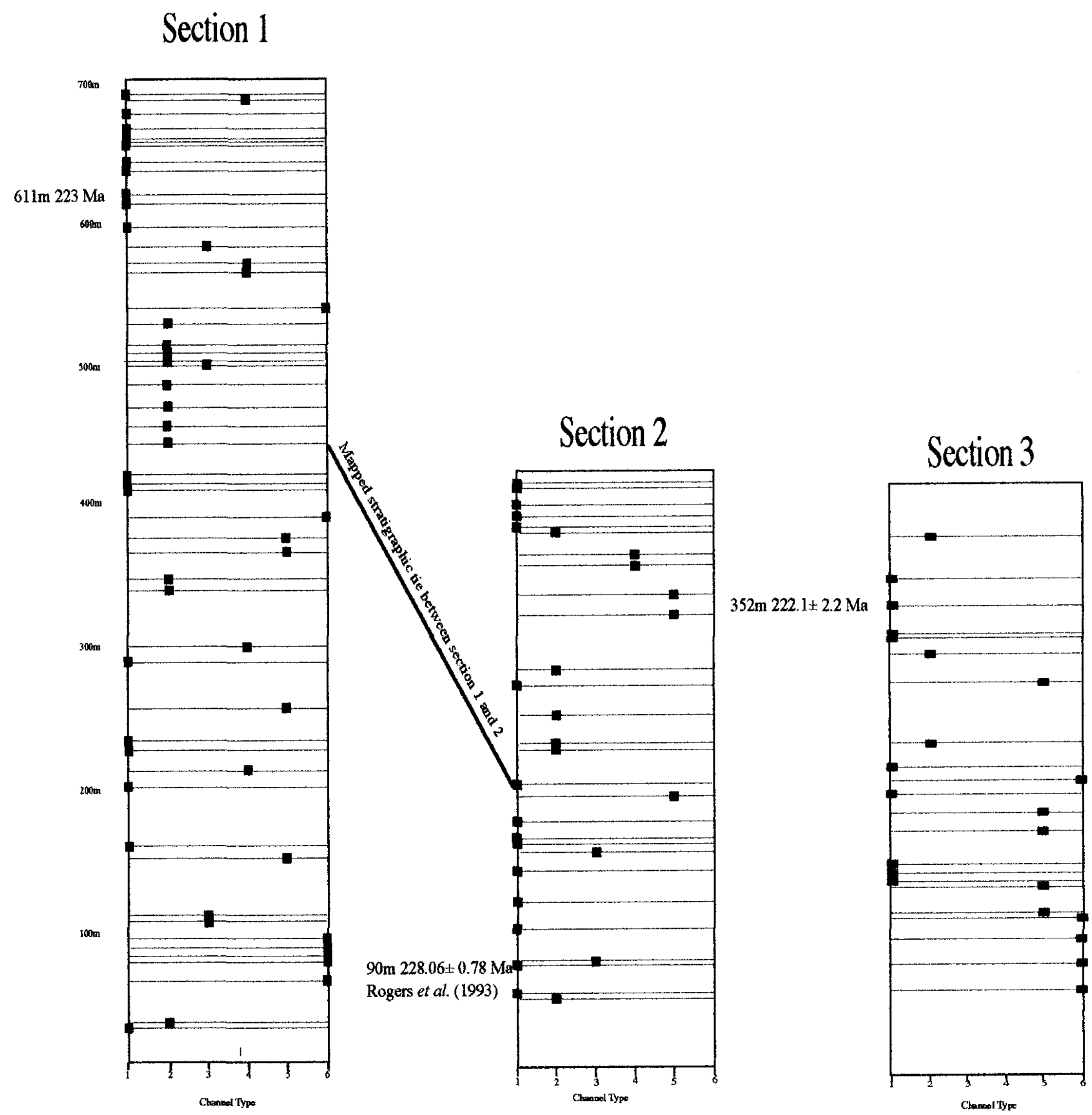


Figure A-11. Each column represents the stratigraphic thickness of each measured section. Squares represent the channel type, described on pages 39-41, and stratigraphic location of the channel.

APPENDIX B: SEDIMENTATION RATES AND THEIR EFFECTS ON FLUVIAL ARCHITECTURE AND PALEOSOL DEVELOPMENT WITHIN THE ISCHIGUALASTO BASIN

ABSTRACT

A model for the genesis of alluvial architecture in the Upper Triassic Ischigualasto Formation, northwestern Argentina, is based on data collected from volcanic ashes, channel sandstones, and paleosols, which were measured along the axis of the basin. $^{40}Ar/^{39}Ar$ dating of ash samples provided the chronostratigraphic framework. Channel interconnectedness increases upsection, and paleocurrents flowed to the west in the lower part and changed to flow parallel to the valley axis throughout the rest of the formation. Paleosols are interpreted to reflect an increase in the mean annual precipitation starting halfway through the Ischigualasto Formation. Paleosols also become thinner in the upper half of the formation. Channel avulsion frequency decreases upsection and is interpreted to represent a decrease in slip rates on the main half-graben fault. Increases in rainfall may be the cause for the increase in the sediment accumulation rates in the upper half of the Ischigualasto Formation.

INTRODUCTION

Geologists have long recognized a link between alluvial architecture and base-level, climate, and subsidence (Bridge and Leeder, 1979; Posamentier and Vail, 1988;

Write and Marriott, 1993; Mackey and Bridge, 1995; Heller and Paola, 1996; Currie, 1997; Ethridge *et al.*, 1998; Mack and Leeder, 1999). Major debates have risen about the specific driving processes of these controls, such as climate, base-level (eustacy), or tectonics (Miall, 1986; Blair and Bilodeau, 1988; Frostick and Reid, 1989a; Frostick and Reid, 1989b; Frostick *et al.*, 1992; Leeder *et al.*, 1996; Mack and Leeder, 1999). While meso-architecture in alluvial sediments is controlled by all three of these processes, it appears to be dominated by tectonics (accommodation) (Fig. B-1) (Leeder, 1993; Ethridge *et al.*, 1998). On the other hand, micro-architecture is potentially more diagnostic and can be controlled by a single dominant process. Models have established interpretive frameworks for alluvial architecture development (Allen, 1978; Leeder, 1978; Bridge and Leeder, 1979; Posamentier and Vail, 1988; Gawthorpe *et al.*, 1994; Heller and Paola, 1996; Ethridge *et al.*, 1998; Mack and Leeder, 1999) using parameters such as avulsion frequency, accommodation, subsidence rate, base-level, and sediment accumulation rates. Some of these parameters are not independent of each other making it difficult to ascribe a single cause for the changes seen in the rock record.

The magnitude and rates of sediment accumulation and accommodation creation exert strong controls on alluvial architectural development (Allen, 1978; Leeder, 1978; Bridge and Leeder, 1979; Posamentier and Vail, 1988; Gawthorpe *et al.*, 1994; Heller and Paola, 1996; Ethridge *et al.*, 1998; Mack and Leeder, 1999). The sediment accumulation rates depend on channel slope, sediment supply, and base-level effects (Currie, 1997). Although many of the developmental theories regarding alluvial architecture and basin formation are related to nearshore processes with respect to eustatic base-level change, many of these ideas can be applied to basins with no eustatic influence. The stratigraphic record contains ambiguous signatures related to sediment accumulation rates.

The Upper Triassic Ischigualasto Formation of northwestern Argentina provides an opportunity to evaluate changes in alluvial architecture within a well-constrained temporal and spatial context because the formation contains numerous dateable horizons and is exposed continuously over 10's of km^2 (Fig. B-2).

The Ischigualasto basin is interpreted as a continental rift basin related to back-arc extension (Stipanícic and Bonaparte, 1972; Uliana and Biddle, 1988; Milana and Alcober, 1994). The Ischigualasto Formation is composed of mudstone and sandstone deposited in an alluvial environment (Rogers *et al.*, 1993; Martínez, 1994; Milana and Alcober, 1994). Regional correlations, made in this study, are based on stratigraphic trends of significant climate, tectonic, and base-level indicators in three measured sections (Fig. B-2). Using measurements of paleosols and channel sandstones, relative sediment accumulation rates were derived. The paleosols and channel sandstones contained in the outcrops were divided and categorized on the basis of physical characteristics and compared across three stratigraphic sections. Dating of ash beds in the measured sections allows assessment of accommodation rates.

This paper's purpose is to describe the detailed stratigraphic record and analyze their implications for sediment accumulation rates and basin accommodation rates.

After first describing a model of the relationships between alluvial architecture and basin dynamics, I will apply this model to the regional architectural elements within the Upper Triassic Ischigualasto Formation. This will form the basis of my analysis of the sediment accumulation rates and accommodation rates. Whereas this 2-D model is limited to the axial portion of the rift valley deposit, this paper will apply the same stratigraphic principles to discern trends in the development of the entire basin.

Sedimentary Architectural Response to Accommodation and Sediment Supply Rates

In this section, the responses of stratigraphic alluvial architectural elements are compared to changes in sediment supply and accommodation rates (Table B-1). While changes are related to general shifts in sediment supply and accommodation rates, a regional or local interpretation is based upon the researcher's ability to correlate the depositional surface across the basin (Frostick and Reid, 1989a; Gawthorpe and Leeder, 2000).

An increase in accommodation results from subsidence and/or a rise of base-level (Posamentier and Vail, 1988; Schumm, 1993; Shanley and McCabe, 1994). Subsidence creates accommodation by lowering the depositional surface as base-level remains constant, as long as the basin is closed to the sea (Posamentier and Vail, 1988; Schumm, 1993). In continental basins, eustatic change generally does not control base-level; base-level change may be caused either by linkage between two previously isolated basins or a lake-level change related to climate (Gawthorpe and Leeder, 2000). Increased accommodation will initially increase stream energy. However, as channels reequilibrate, sediment supply will exceed transport capacity and aggradation will occur (Posamentier and Vail, 1988; Shanly and McCabe, 1994). Decreased stream power leads to increased channel sinuosity and stabilization of the floodplain (Schumm, 1981; Posamentier and Vail, 1988; Wright and Marriott, 1993). Individual channel deposits are commonly isolated within packages of such floodplain deposits (Leeder, 1978; Allen, 1978; Bridge and Leeder, 1979; Wright and Marriott, 1993). Paleosols may be thinner with higher sediment accumulation rates within the basin (Allen, 1989; Wright and Marriott, 1993; Kraus, 1999). During the highest rates of sediment accumulation, the basin reaches near capacity and fine-grained sediment will bypass the basin, creating sheet-like sandstone bodies (Blakey and Gubitosa, 1984; Posamentier and Vail, 1988; Wright and Marriott, 1993).

Accommodation decreases when there is a decrease or cessation of subsidence and/or a fall of base-level (Posamentier and Vail, 1988; Schumm, 1993; Shanly and McCabe, 1994). Decreased accommodation and a drop in base-level will cause incision and the reworking of floodplain material (Posamentier and Vail, 1988; Wright and Marriott, 1993). Stream power is magnified as channel slope is increased due to this incision toward the lowered base-level (Schumm, 1981; Schumm, 1993; Shanly and McCabe, 1994). Fine-grained sediment will bypass the basin as a result of increased stream power (Posamentier and Vail, 1988), limiting or decreasing the sediment supply to the basin (Shanly and McCabe, 1994). Channel morphology may exhibit lower sinuosity, which results from increased stream power, incision, and increased bed-load

(Schumm, 1981). Floodplains become confined and narrow as a result of increased stream power and incision, increasing the potential for reworking of the floodplain sediments (Bridge and Leeder, 1979; Mackey and Bridge, 1995) and amalgamating channel sandstone deposits (Wright and Marriott, 1993). Thicker paleosol profiles will develop as a result of decreased sediment accumulation rates and increased elevation above the floodplain (Allen, 1989; Wright and Marriott, 1993; Kraus, 1999).

Sediment accumulation rates are a function of climatic, tectonic, and base-level shifts. Climatic shifts can affect the amount of sediment transported through the drainage system, type of paleosols produced, flood magnitude and frequency, and abundance of plants on the floodplain (McCarthy *et al.*, 1992; Schumm, 1993; Mackey and Bridge, 1995; Ethridge *et al.*, 1998). Flood magnitude and frequency and plant abundance can affect the avulsion frequency, overbank deposit cohesiveness, and sandstone-body interconnectedness (Coleman, 1969; Ethridge *et al.*, 1998). Avulsion frequency and overbank deposit cohesiveness are contributing factors in sandstone-body interconnectedness (Bridge and Leeder, 1979). Tectonic activity will create accommodation, shifting topography below base-level, increasing avulsion frequency, directing drainage paths, and affecting the amount of sediment transported through the drainage system (Table B-1) (Bridge and Leeder, 1979; Frostick and Reid, 1989a). Increased avulsion frequency has been linked to active tilting of the floodplain, which directs break-out flood events toward the lowest point on the floodplain (Bridge and Leeder, 1979; Mackey and Bridge, 1995; Leeder *et al.*, 1996; Peakall, 1998; Mack and

Leeder, 1999; Peakall *et al.*, 2000). During periods of tectonic activity, flow direction can be drawn or diverted due to the resulting shifts in topography, which obstruct flow or tilt the floodplain (Frostick and Reid, 1989a; McCarthy *et al.*, 1993; Schumm, 1993). This activity will affect the percentage of fines/sand and the depositional environment. Base-level shifts will affect the creation of accommodation through incision and a change in stream power, which serve to control the amount of fine-grained sediments stored within a deposystem (Bridge and Leeder, 1979; Ethridge *et al.*, 1998). A change in stream power may affect the sediment supply in two ways: (1) erosion of the headlands, delivering more sediment to the deposystem or (2) increased stream power, allowing sediment to bypass the deposystem (Posamentier and Vail, 1988; Wright and Marriott, 1993; Mackey and Bridge, 1995; Currie, 1997). Multiple independent processes are involved in the rate of sediment accumulation in a basin (Table B-1). Using paleosol thickness, paleosol morphology, and channel sandstone morphology a qualitative model will be constructed for the alluvial architecture of the Ischigualasto Formation.

Alluvial indicators discussed above are combined into a model that compares shifts in the architecture with shifts in the sedimentation rates and accommodation (Fig. B-3). On the figure (stage 1), a base-level drop creates incised valleys with well-developed paleosols on the interfluves. Channel sandstones within the valley develop into sheets, due to a constricted floodplain. As this valley aggrades (stage 2), the floodplain expands in width and overbank facies preservation potential is increased (Fig.

B-3). Sediment accumulation rates increase and the paleosols profiles will decrease. Channel sandstones are isolated and avulsion frequencies are high, due to aggradation within the channels. As the basin fills, sediment accumulation rates will decrease and paleosol thicknesses will increase (Fig. B-3, stage 3). Channel sandstones will have a higher interconnectedness and avulsion frequencies will decrease. As the basin reaches capacity (stage 4), fine-grained sediment will bypass the basin and channel sandstones will increase in interconnectedness (Fig. B-3). This model of a basin fill represents a potential sequence of the alluvial architecture.

Rift Basin Application of this Model

Principles established in the previous sections can be applied to an analysis of the development of alluvial architecture within a continental rift basin (Fig. B-3, Table B-1). Continental rift basins may differ from other basins in their response to with eustacy and base-level shifts. Continental rift basin shapes are determined by the actual amount of throw along the strike of boundary faults and their associated rift systems. Half-graben faults develop as sets of opposing dipping plains that changing polarity along the length of basin development (Frostick and Reid, 1989a; Gabrielsen *et al.*, 1990; Morley *et al.*, 1999; Gawthorpe and Leeder, 2000). Normal fault slip decreases along the strike away from a point of maximum displacement (Cartwright *et al.*, 1995; Willemse *et al.*, 1996). Lateral change in displacement magnitude along the half-graben fault is the source of most accommodation variation within continental rift basins (Gawthorpe and Leeder, 2000). Eustacy is usually not a factor affecting base-level change in immature to moderately mature rift valleys because they drain internally (Frostick and Reid, 1989a). Base-level shifts are most likely created as the tectonic activity adjusts the deposition surface or as a linkage between two basins defines a new base-level (Frostick and Reid, 1989a; Gawthorpe and Leeder, 2000). Lake level can also control the base-level within a basin (Gawthrope and Leeder, 2000) which in turn, can be controlled by climatic or tectonic change.

Alluvial deposition in continental rifts is dominated by tectonic activity and climate. In internally drained basins (Frostick and Reid, 1989a) base-level is primarily controlled by structure (tectonic activity) (Table B-1). Because a basin's structure controls much of the creation of accommodation, the accommodation at any place in the basin depends on the position along strike of the boundary fault. Zones of sediment accumulation can be distinguished in terms of the amount of accommodation created along the strike (Gawthorpe *et al.*, 1994; Cohen, 1990; Gawthorpe and Hurst, 1993), the zone of maximum deposition, the transition zone, and the transfer zone (Fig. 4). Transition zones vary with the features identified in both maximum deposition and transfer zones.

The zone of maximum deposition is located at the point in the main half-graben adjacent to the portion of the fault that has the most slip. Here, basin fill is the thickest and paleosol frequency is the lowest (Allen, 1989; Wright, 1989; Wright and Marriott, 1993). Paleosols in this depozone are commonly immature to sub-mature and rarely polygenic (Wright and Marriott, 1993; Kraus, 1999). Channels with a higher areal density on a landscape are common in basin lows, which attract drainage (Frostick and Reid, 1989a; Mackey and Bridge, 1995; Ethridge *et al.*, 1998). Channel deposits should have been more abundant in the rock record in this portion of the basin, owing to the presence of the topographic low.

The transfer zone is located between two opposing normal faults and is the portion of the basin with the lowest rates of creation of accommodation (Frostick and Reid, 1989a; Gawthorpe and Leeder, 2000). Low rates of sediment accumulation may serve to allow mature and polygenic paleosols to develop (Atkinson, 1986; Allen, 1989; Wright and Marriott, 1993; Kraus, 1999). Topographically higher than other portions of the basin, the transfer zone will be drained by first-order streams, as defined by Strahler (1964). Channel sandstone bodies within this zone commonly are dominated by spatially dispersed isolated channels (Strahler, 1964; Frostick and Reid, 1989a).

The most important point to take from these specific depozone characteristics is that intrabasinal variability within alluvial architecture must not be confused with regional scale shifts related to base-level, tectonic (fault activity), or climatic shifts, which are caused by extrabasinal processes. Regional-scale trends should correlate across the basin.

METHODS AND DATA COLLECTION

Data collection focused on the aspects of the alluvial architecture that contain information about base-level, tectonic, and climatic change. The data collected include chronostratigraphic data (volcanic ashes), paleocurrent directions, interconnectedness which was derived from sandstone descriptions, paleosol thickness, paleosol type, and paleosol data from which the avulsion frequency was derived (Appendix A).

Chronostratigraphy

Ages were determined by $^{40}Ar/^{39}Ar$ incremental laser heating of fine-grained sanidine crystals extracted from ashes interbedded in the Ischigualasto Formation. All samples were sent to be analyzed at New Mexico Institute of Mining and Technology, Socorro.

Paleocurrents

Paleocurrent directions were collected from the top sets of trough cross-bedded channel sandstones (Fig. B-6). Mean vectors were calculated for each channel sandstone outcrop and corrections were made for the bed dip.

Bed Interconnectedness

Bed interconnectedness was determined using classification based on the lateral continuity of multi-story channel sandstone beds. Channel sandstone beds greater than 100 m wide with multiple stories are considered interconnected, and all others are classified as isolated

Avulsion Frequency

Avulsion frequency was determined by sequences of paleosols and their relationships to overlying channel sandstones. If the paleosol sequence below the sandstone indicates a progression from immature to mature then back to immature, then this suggests a channel migrating over the floodplain. However, if the paleosols indicate an immature to mature sequence below the channel sandstone, then this is interpreted as an avulsion. The avulsion inference is based on the principal of pedofacies defined by Bown and Kraus (1987), which defines the type of paleosol that will develop with the paleosol's proximity to a channel (Fig. B-7).

RESULTS

Chronostratigraphy

Fourteen ash samples were collected and analyzed, but only one sample produced a reliable age; the rest were too detritally contaminated and were demed to not yield accurate dates. The date we did obtain was from section 3 at 352 m and produced a date of 218 ± 1.7Ma.

Paleocurrents

Near the base of sections 1 and 2, paleocurrent data indicate a paleoflow direction to the east (Fig. B-7). Above the base, sections 1 and 2 are dominated by north and northeastward paleocurrent indicators. Section 3 has little variation in the paleocurrent directions and is dominated by flow directions to the north-northwest (Fig. B-8).

Bed Interconnectedness

Bed interconnectedness increases upsection across the basin (Fig. B-8), although there are examples of amalgamated channel sandstone beds (Fig. B-6) and isolated sandstone beds (Fig. B-8) in each section. Channel sandstone beds become more abundant near the tops of sections 1 and 2 (Fig. B-8).

Paleosols

Paleosol thicknesses decrease upsection across the basin (Fig. B-9). However, change seems to occur halfway through the Ischigualasto Formation. In section 1, profile thicknesses below 350 m average 0.85 m ± 0.57 m and above 350 m average 0.42 m ± 0.23 m, a significant difference ($p < 0.05$). In section 2, profile thicknesses below 200 m average 0.73 m ± 0.57 m and above 200 m average 0.40 m ± 0.23 m, a significant difference ($p < 0.05$). In section 3, profile thicknesses below 200 m average 0.81 m ± 0.41 m and above 200 m average 0.54 m ± 0.35 m, also a significant difference ($p < 0.05$).

Paleosol morphology changes halfway through all three sections. Paleosols containing carbonate are rare to absent in the upper halves of all three sections (Fig. B-10). All paleosols exhibit vertic features. However, mature soils contain secondary carbonate in the lower half of the Ischigualasto Formation, whereas mature soils exhibit clay horizons in the upper half. Two paleosol profiles in the upper half of the Ischigualasto Formation were found to contain secondary carbonate. A location in section 3 near the top contains a polygenic soil with secondary carbonate.

Avulsion Frequency

Avulsion frequency decreases upsection in the Ischigualasto Formation (Fig. B-11). This avulsion trend is seen in all three sections (Fig. B-11).

DISCUSSION

Some of the difficulty in establishing basin dynamics models from alluvial architectural data is that much of the data is ambiguous when observed on its own. This section will address aspects of the alluvial architecture and the possible implications that these features have for development of a basin model. Interpretations are based on merging of all architectural data.

Chronostratigraphy

The age-dated sample from the top of section 3 establishes the relationship of that section with section 1. Sections 1 and 2 were correlated with a continuous sandstone outcrops between them. The new date collected for this study, in conjunction with already-established dates, shows that the Ischigualasto Formation was deposited over a period of approximately 10 Ma (Fig. 5).

Paleocurrents

Paleocurrent directions of the Ischigualasto Formation are interpreted to indicate transverse flow directions in the lower portions and axial flow directions in the upper portions (Fig. 12). Drainage paths were controlled structurally, drawing the flow to topographic lows (Allen, 1979; Bridge and Leeder, 1979; Mackey and Bridge, 1995). Active movement on the main half-graben fault would have attracted drainage paths toward the fault and developed steep prograding fans off the footwall (Fig. 12) (Frostick and Reid, 1989a; Leeder *et al.*, 1996; Mack and Leeder, 1999). This is the most likely cause of transverse flow directions in the lower portions. Axial flow directions are common in actively subsiding basins; the change in flow direction from lower to upper halves is an indicator of some type of active change in the landscape (Bridge and Leeder, 1979; Frostick and Reid, 1989a). This change is most likely related to a decrease in the fault activity along the main half-graben fault. The paleocurrent directions collected in section 3 exhibit flow directions that do not change, which is indicative of less variation through time, as expected on the transfer zone.

Paleosols

Paleosols decrease in thickness upsection in the Ischigualasto Formation. The development of soils is a function of time of exposure, climate, parent material, relief, and biota. Paleosol types found in the lower half of the section are thicker than similar types found in the upper half (Fig. B-10). Parent material is the same throughout the formation (Stipanícic and Bonaparte, 1972; Milana and Alcober, 1994). Relief and maturity are commonly associated, because areas of low relief have higher rates of sediment accumulation (Atkinson, 1986; Bown and Kraus, 1987). Local relief is a factor in the development of individual soils; however regional trends would only respond to regional topography (Atkinson, 1986). Because change in the character of the paleosols is regionally expressed, we must assume that this is not a function of local topography. The flora was dominated by herbaceous plants and does not seem to change in character through the Ischigualasto Formation, thus excluding vegetation as a factor in soil formation (Spalletti *et al.*, 1999). Evidence of climatic change does exist and will be addressed later in this section. Time of exposure is commonly associated with sedimentation rates and relief; with thinner paleosol profiles we would expect shorter times of exposure and development (Bown and Kraus, 1987; Kraus and Gwinn, 1997). Thus, the upsection thinning of paleosols probably represents an increase in the sediment accumulation rates (Allen, 1989; Wright and Marriott, 1993; Kraus, 1999).

Secondary carbonate within the paleosols is absent in the upper half of the Ischigualasto Formation, which is interpreted to be the result of increased mean annual precipitation (Fig. B-10). Two possible processes can produce the absence of carbonate within a soil profile, (1) an absence of source or (2) the removal of Ca^+ from the profile by flow-through (Machette, 1985; Royer, 1999). Although secondary carbonate is rare in the upper portion of the Ischigualasto Formation, some was found (Fig. B-10). The presence of some secondary carbonate in the upper half of the Ischigualasto Formation is evidence of a source, therefore eliminating the first possible explanation for absence of source material. Removal of Ca^+ from the profile is most likely produced by an increase in the mean annual precipitation (Machette, 1985; Royer, 1999). Royer's (1999) studies of 1,481 modern soils show that secondary carbonate will not precipitate in climates with more than 760 mm of mean annual precipitation. Our data support an increase in the mean annual precipitation in the upper half of the Ischigualasto Formation. This increase, however, could not exceed 2100 mm of mean annual precipitation, since that amount is the upper boundary for the formation of vertisols and all the soils in the Ischigualasto Formation contain vertic structures (Gyllenhaal, 1990; Price and Sellwood, 1994). The vertic nature of the soils also supports an interpretation that periods of extreme climates occurred, during which it was alternately extremely dry or wet for months at a time (Retallack, 1990; Mack *et al.*, 1993). The mean annual precipitation for the Ischigualasto Formation changes from >760 mm to 760 to 2100 mm, with pronounced wet and dry periods.

Maturity of the paleosols could also affect the abundance of secondary carbonate. The paleosols in the upper half of section 1 are less mature overall than those in the lower half.. Paleosols such as pedotype D occur which is similar in maturities as pedotype C which contains secondary carbonate. This observation which precludes maturity as the agent for the absence of secondary carbonate.

Paleosol sequences beneath channel sandstones indicate a decrease in the avulsion frequency upsection within the Ischigualasto Formation (Fig. B-11). Data from the Ischigualasto Formation suggest that avulsion frequency decreases upsection (Fig. B-11). A decrease in avulsion frequency can be the result of four factors: (1) a decrease in the sediment accumulation rates (Bridge and Leeder, 1979), (2) plant abundance stabilizing the floodplains (McCarthy *et al.*, 1992), (3) a decrease in the flood magnitude or frequency (Mackey and Bridge, 1995), and (4) a decrease in the active tilting of the floodplain by the half-graben fault (Peakall *et al.*, 2000). Evidence collected from the paleosol thickness supports an increase in the sediment accumulation rate. The paleosols represent exposure time of the floodplain and thinner paleosols suggest an increased rate of burial, which is the result of increased sediment accumulation rates. Plant abundance was not a factor because it did not seem to change throughout the Ischigualasto Formation. If there was no change in the flora, it would not cause any change in the avulsion frequency. The decrease of secondary carbonate in paleosols suggest that the mean annual precipitation increased. An increase in the mean annual precipitation would support an increase in the flood magnitude or frequency. Because the avulsion frequency does not increase upward as it would with an increase in the flood magnitude and frequency, it will be disregarded as a factor controlling thinning of the paleosols. A decrease in tectonic activity would agree with the increased interconnectedness found upsection, as stated previously in this section. Thus the decrease in avulsion frequency is the result of a decrease in subsidence rates, which in turn decreased the tilting of the floodplain.

Bed Interconnectedness

The increase in channel sandstone interconnectedness in the upper half of the Ischigualasto Formation is due to several factors: overbank deposit cohesiveness, avulsion frequency, and subsidence rates (Bridge and Leeder, 1979; Blakey and Gubitosa, 1984; Wright and Marriott, 1993). Overbank deposit cohesiveness depends on the availability of fine sediment in the system and the abundance of plant matter in the region. The abundance of plants can increase the floodplain cohesiveness through consolidation by the root systems. Plants do not seem to change through the Ischigualasto Formation and were most likely not a factor for change in the interconnectedness. An increase in avulsion frequency would produce more interconnectedness in the channel sandstones (Bridge and Leeder, 1979; Wright and

Marriott, 1993; Mackey and Bridge, 1995); however the data show a decrease in the avulsion frequency space (Fig. B-11). Restriction of a source of fine-grained sediment will decrease overbank deposit cohesiveness.

The cessation of volcanism could be the cause for a change in the source of fine-grained material available for deposition. There is evidence that local volcanism is absent in the upper portions of the Ischigualasto Formation (Stipanícic and Bonaparte, 1972). Cessation of local volcanism may have caused the increase in the interconnectedness. Increased interconnectedness in the upper portion of the Ischigualasto is due to decreased fine-grained sediment input or decreased subsidence rates.

The alluvial architecture exhibits other characteristics, such as dominant isolated channels near the base of the Ischigualasto Formation. Isolated channels are interpreted as tributary channels to the main channel belt, which were isolated due to recent tectonic activity drawing flow toward the low point or increased slope. Increase stream power and minor incisions of the floodplain are conditions that help produce isolated channels sandstones (Bridge and Leeder, 1979; Wright and Marriott, 1993).

DISCUSSION OF BASE-LEVEL/CLIMATE/TECTONIC SHIFTS

Through the identification and analysis of alluvial architectural elements, it is possible to develop a model for the development of the Ischigualasto Formation using the constraints derived from the stratigraphic record. It is necessary distinguish between aspects of the alluvial architecture that developed due to intrabasinal controls versus extrabasinal controls. Basin development is controlled by the accommodation and sediment accumulation rates (Allen, 1978; Leeder, 1978; Bridge and Leeder, 1979; Posamentier and Vail, 1988; Gawthorpe *et al.*, 1994; Heller and Paola, 1996; Ethridge *et al.*, 1998; Mack and Leeder, 1999). The amount of accommodation within the alluvial portion of a rift basin is primarily controlled by subsidence (Ethridge *et al.*, 1998). Sediment accumulation rates are controlled by base-level, tectonic, and climatic shifts. Each of these factors controlling basin accommodation and sediment accumulation rates is addressed with respect to the evidence that supports the interpretation of its impact.

Potential base-level change, in the absence of a lake, could be due to the linkage of basins, which is not likely in the later stages of a rift basin (Gawthorpe and Leeder, 2000). The Ischigualasto Formation comprises the upper portions of the rift basin fill and was deposited in an axial alluvial deposystem (Stipanícic and Bonaparte, 1972). Rift basins begin as isolated half-grabens, which link into a single basin as the magnitude of the extension increases. Initially each isolated half-graben will most likely be internally draining and have a different base-level (Frostick and Reid, 1989a). As the basin developed through time, base-level change due to sub-basin linkage decreased, especially near the last stages of the rift basin fill. Base-level change was most likely not a factor in the formation of the Ischigualasto Formation (Stipanícic and Bonaparte, 1972). Eustatic base-level controls are unlikely a product of tectonic subsidence since it has been established that this basin was not directly connected to the ocean basin (Uliana and Biddle, 1988). The sediment cycles in the basin do not match with sea-level curves for the period of deposition (Uliana and Biddle, 1988). Paleocurrent directions show flow to the northwest; however any basin outlet to the north has been subsequently eroded by uplift (Veevers *et al.*, 1994). If base-level drops, incision and increased erosion would have created an unconformity as indicated in the basin model (Fig. B-3). However, no major unconformities were found to lie within the Ischigualasto Formation in this portion of the basin (Stipanícic and Bonaparte, 1972). Base-level was most likely constant and subsidence created the accommodation found in this basin (Ethridge *et al.*, 1998).

Tectonic activity in rift basins has been found to control the preservation (accommodation) of alluvial sediment on the macro-scale (Ethridge *et al.*, 1998, Gawthorpe and Leeder, 2000). However, the interconnectedness of channel sandstones increases upsection in the Ischigualasto, which supports a decrease in the subsidence rates (Fig. B-8). The thinning paleosol profiles found upsection could have been created by increased subsidence rates, which serves to increase stream power and produces higher rates of sediment accumulation (Allen, 1989; Wright and Marriott, 1993). However, the avulsion frequency decreases upsection, which contradicts increased sediment accumulation rates induced by increased channel slope (Peakall, 1998; Peakall *et al.*, 2000). As a result, increased sediment accumulation rates were most likely not caused by tectonic activity.

Our paleosol data support the existence of an increase in the mean annual precipitation in the Ischigualasto Formation from 760 mm or less in the lower half to 760-2100 mm in the upper half. The vertic features within all the paleosols define a climate containing both dry and wet extremes that may be characterized as seasonal. Thin paleosol profiles suggest an increase in the sediment accumulation rate, which could have been caused by increased mean annual precipitation which eroded the material at a higher than normal rate (Schumm, 1993; Ethridge *et al.*, 1998). The paleosol data suggest that the climate shifted from arid to semi-arid, which increased the erosion rates and filled the basin.

The climate of the Triassic Pangea was dominated by a "megamonsoon," which induced dramatic swings in the amount of precipitation over short periods of time (Kutzbach and Gallimore, 1989). The size of Pangea, its topography, and the geographical proximity of the continent to the equator explains the existence of the megamonsoon and the wide spread aridity of the region due to the large landmass, the cool global temperatures, and the relative lack of vegetation (Hay and Wold, 1998). Parrish *et al.* (1996) interpret a shift at the beginning of the Carnian stage to a more humid climate from deposits located in Australia, as compared to the shift we see in the middle to late Carnian. The deposits in Australia have poor age constraints and could be representative of the climatic shift interpreted in the Ischigualasto Formation.

Comparison of the initial proposed model (Fig. B-3) for continental alluvial fill is very similar to what is seen in the Ischigualasto Formation (Fig. B-13). The column of the Ischigualasto Formation (Fig. B-13) was developed from mapping of a 1.5 km wide zone that was centered on section 1. Sandstone beds are depicted as they appeared laterally and vertically correlated to section 1. Paleosols are depicted as cartoons of the associated dominate pedofacies. The predicted (Fig. B-3) thickness trends of the paleosols are different from the data. Paleosols thin upwards in the rock record, and predictions suggest that reduction of the accommodation will slow sediment accumulation rates and thicker soil profiles will develop (Fig. B-3). In the rock record, paleosol profiles decrease upsection as a result of increased sediment accumulation rates. The basin was under-filled as a result of subsidence in a dry climate with low sediment accumulation rates. As climate grew wetter the sediment accumulations rates increased, effectively increasing the channel interconnectedness. Channel interconnectedness was similarly affected by the reduction in the fines introduced to the basin. As the basin overfilled, channel sandstone interconnectedness increased as fines bypassed the system and channels comb the floodplain.

CONCLUSIONS

(1) Increase in the mean annual precipitation increased the sediment accumulation rates in the Ischigualasto basin. The increase in the rainfall is demonstrated by paleosol data in the transition of the carbonate bearing paleosols to non-carbonate bearing paleosols. This transition in the paleosols corresponds to the change in the paleosols' thickness throughout the basin. The link between the paleosol types and their thicknesses is interpreted as an increase in the sediment accumulation rates due

to an increased mean annual precipitation.

(2) Avulsion frequency decreases upsection, indicating that tectonic activity most likely slowed down or stopped near the base of the Ischigualasto Formation. The work by Peakall *et al.* (2000) supports the idea that tectonic activity within a half-graben rift valley will increase the avulsion frequency as the channel flow is drawn toward the lowest spot in the valley. Paleosol evidence suggests an increase in the sediment accumulation rates, which would correspond to an increase in the tectonic activity within the basin. Increased tectonic activity should be indicated by an increase in the avulsion frequency.

(3) Mean annual precipitation of 760 mm or less to 760 mm to 2100 mm. This trend matches climatic indicator trends found in the Carnian to Norian transition in Australia (Parrish *et al.*, 1996). This could potentially represent a global shift in the Carnian to Norian period to a wetter climate.

(4) Climate directly influenced the development of the alluvial architecture of the Ischigualasto Formation. Shifts in the climate correlated with shift in the sediment accumulation rates and channel interconnectedness. Although accommodation was available for potential accumulation, precipitation controlled the rate.

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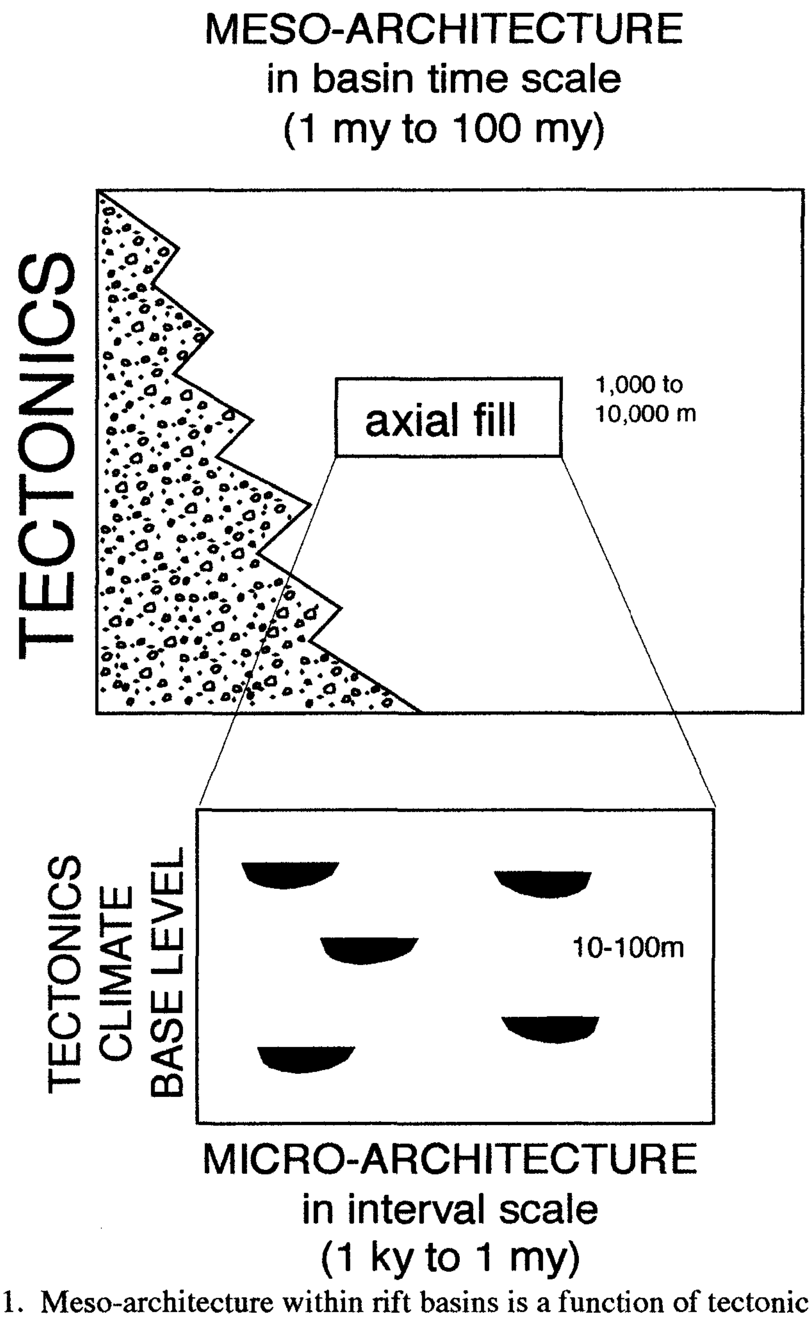


Figure B-1. Meso-architecture within rift basins is a function of tectonic related accommodation. However, micro-architecture is controlled by multiple factors which can often overlap or compound each effect (Ethridge *et al.*, 1998).

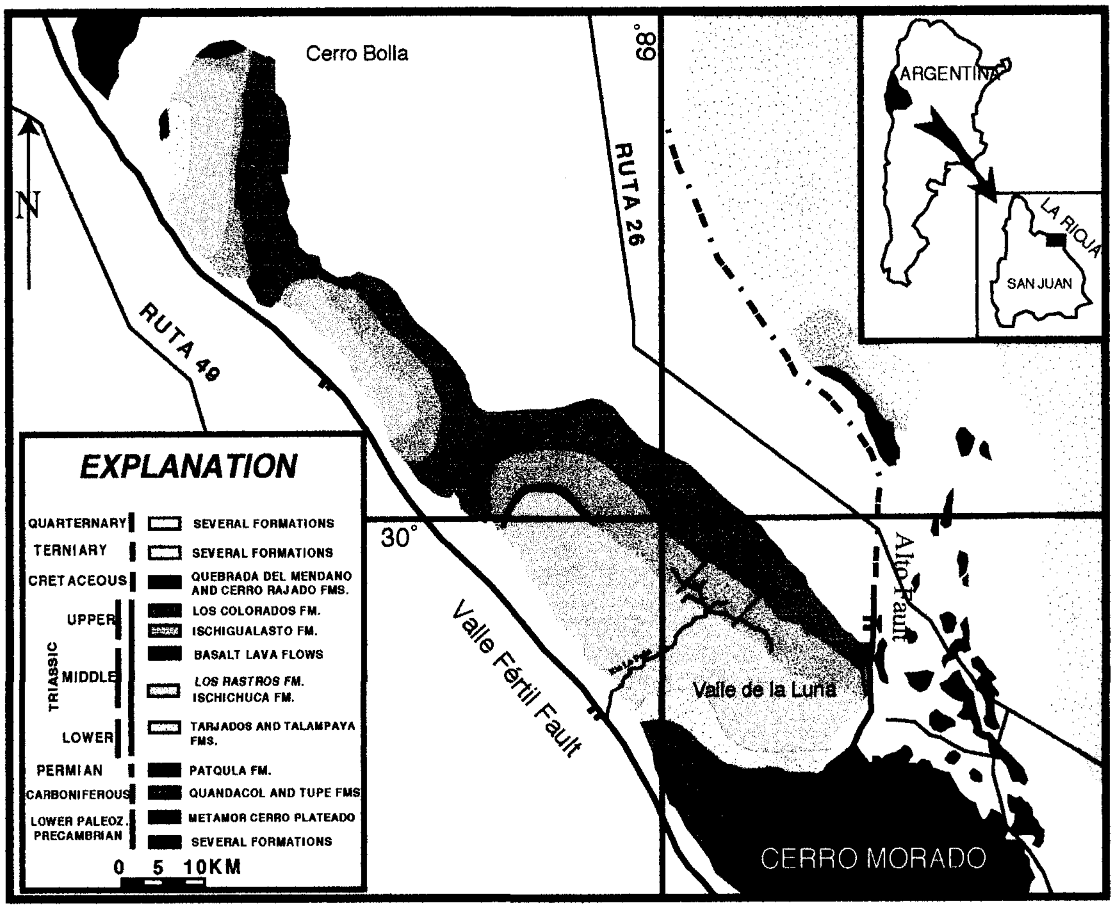


Figure B-2. This geologic map of the Ischigualasto Basin shows the entire extent of the basin outcrops. Valle Fértil fault is the boundary fault that controls the creation of most of the accommodation space in the basin, with a splay fault named Alto Fault. Black lines with corresponding numbers represent the location of measured sections and their corresponding numbers. These sections were measured perpendicular to the strike of the Ischigualasto Formation (modified from Milana and Alcober, 1994).

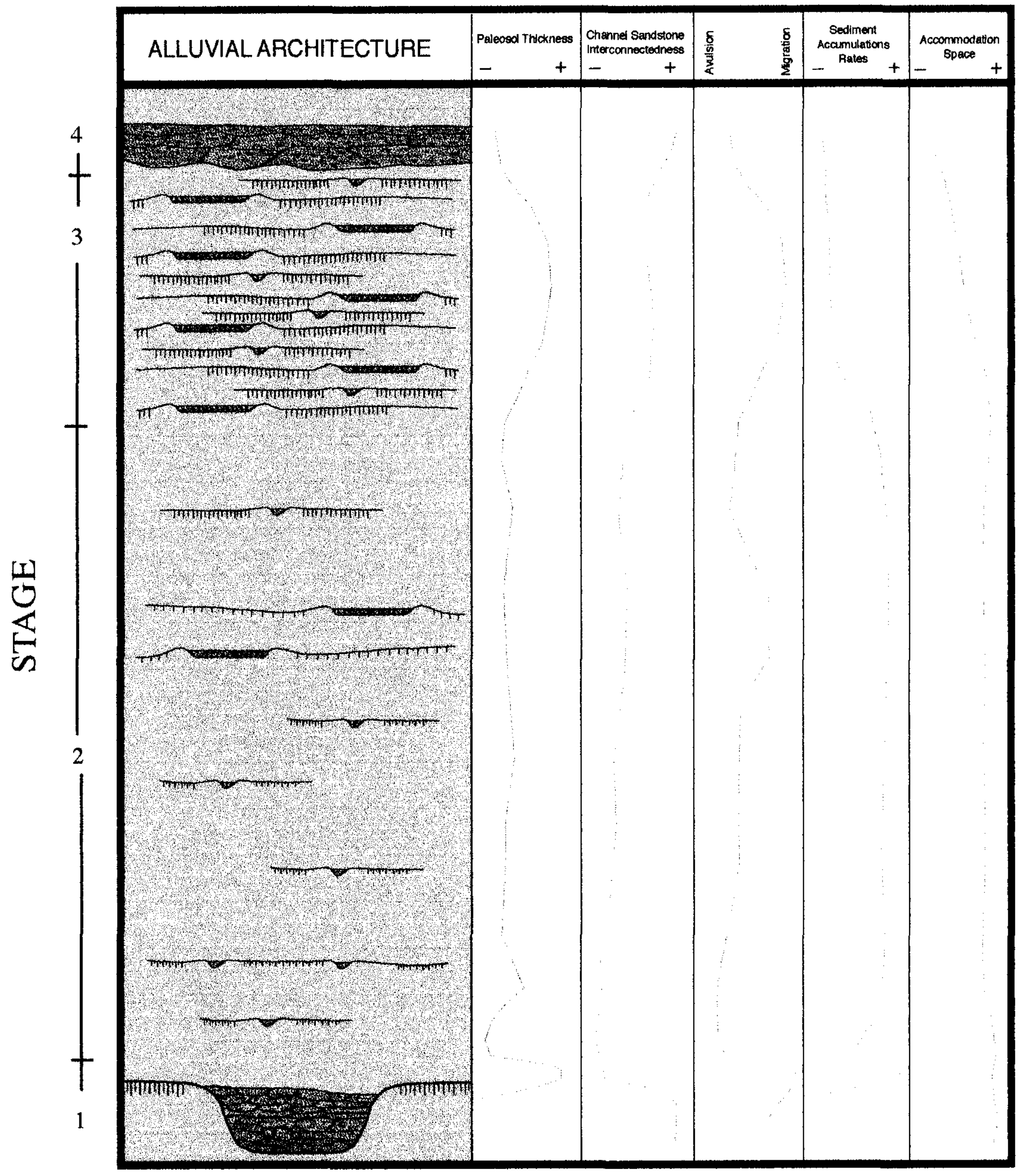


Figure B-3. The vertical column represents a model of the alluvial architecture that will develop with variations in the sediment accumulation rates and basin morphology. Vertical lines represent the increase or decrease of various factors in the basin. Yellow represents the sandstone beds, vertical hatch marks represent the paleosols, and pink represents fine-grained sediments.

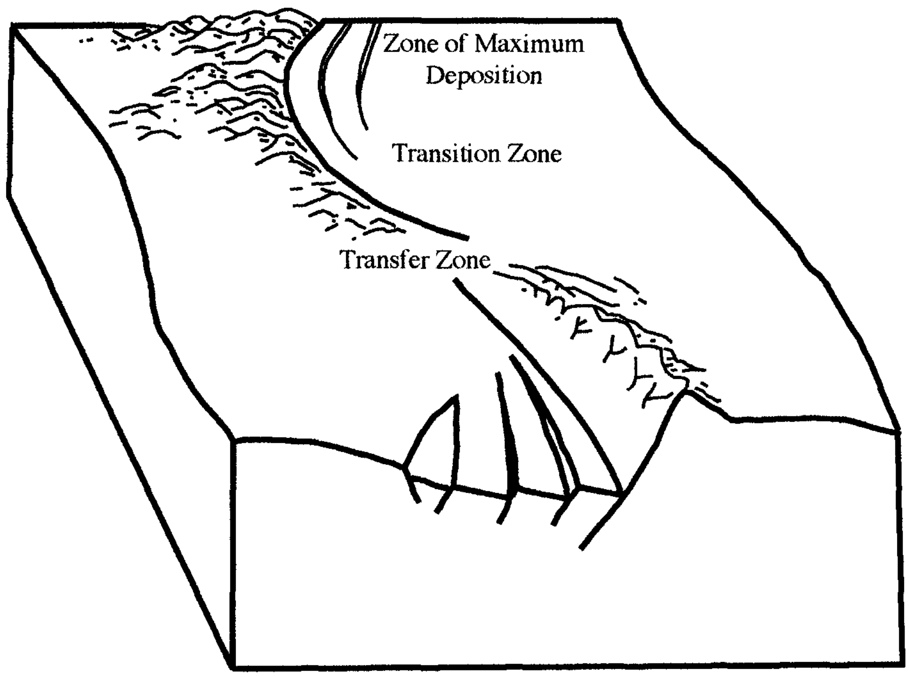


Figure B-4. Schematic diagram of a rift basin system. Rift basins that are composed of opposing faults have transition zones in the accommodation. The transition zones affect the alluvial architecture of the rift basin. Transition zones have the least accommodation and the most mature paleosols. Zones of Maximum Deposition have the most accommodation and high concentrations of channel deposits. This figure is modfied from Rosendahl *et al.* (1986).

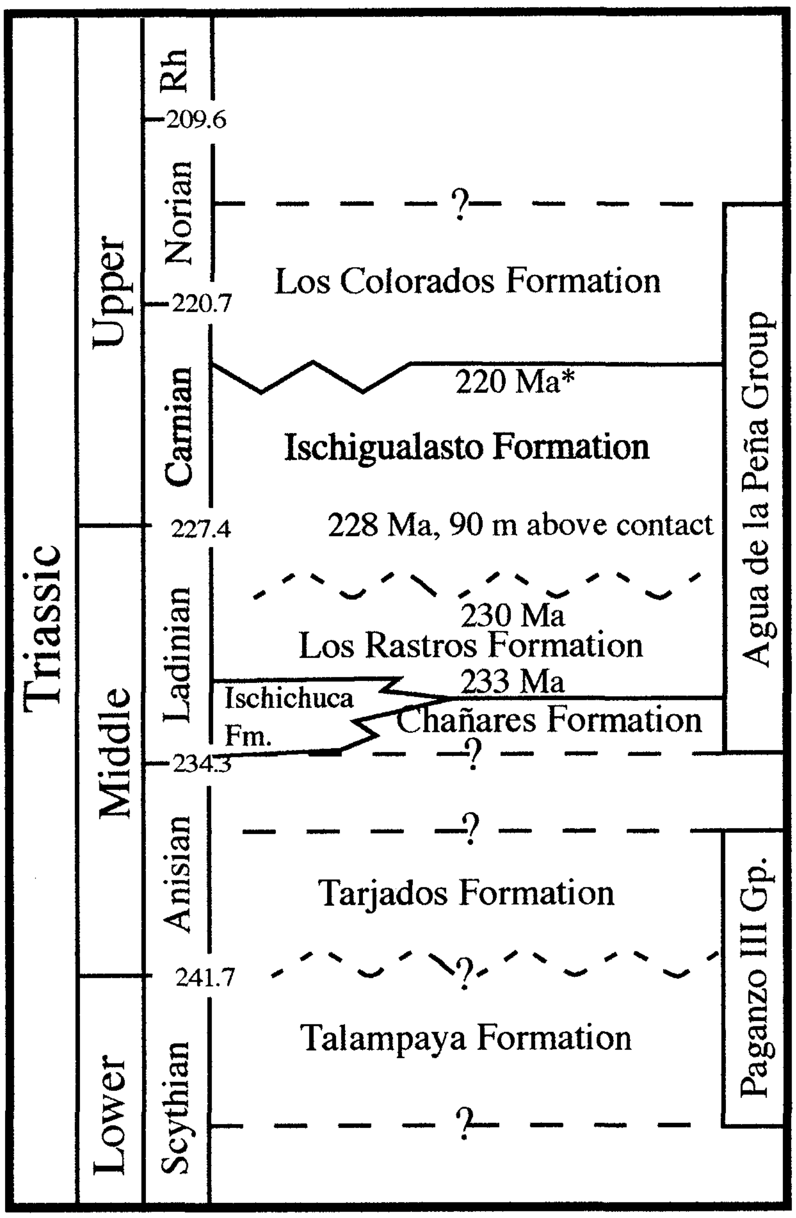


Figure B-5. Chronostratigraphy based on biostratigraphic work established by earlier research and radiogenic dating. Date with an asterisk (*) is a date collected for this study. The 230 Ma date is taken from the diabase near the contact between the Ischigualasto and Los Rastros Formation (Odin and Létolle, 1982).

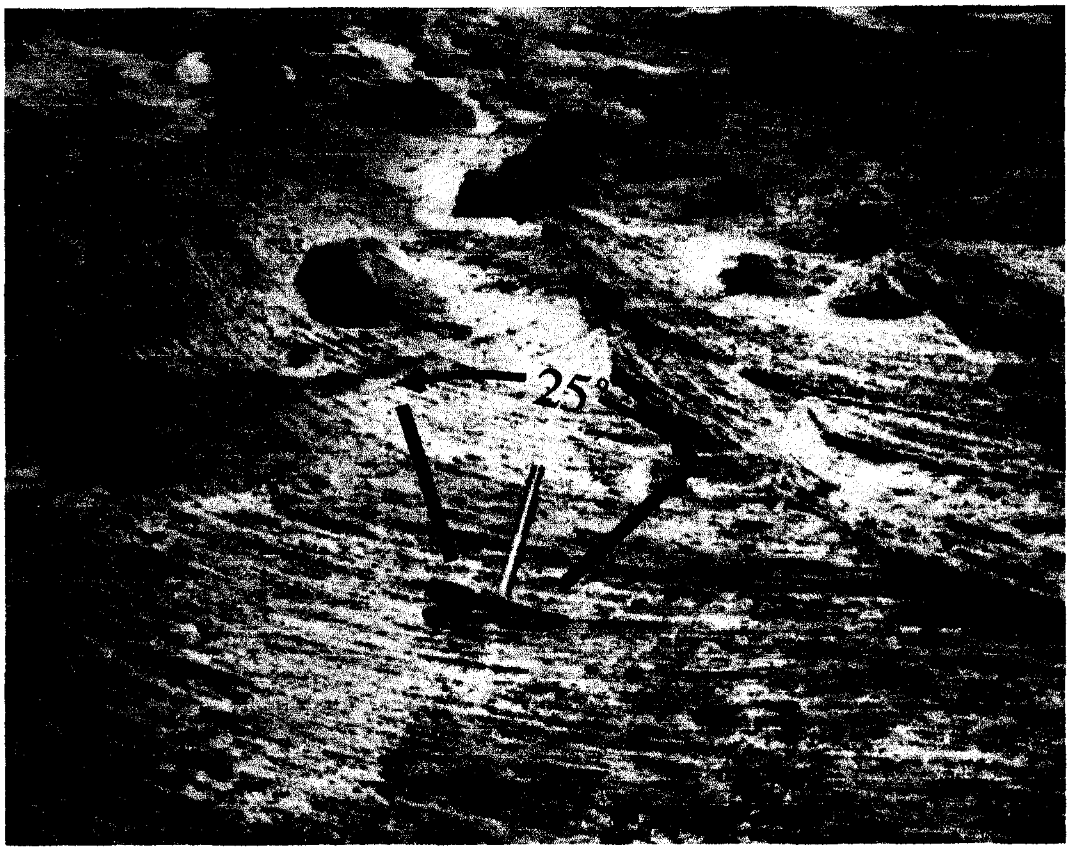
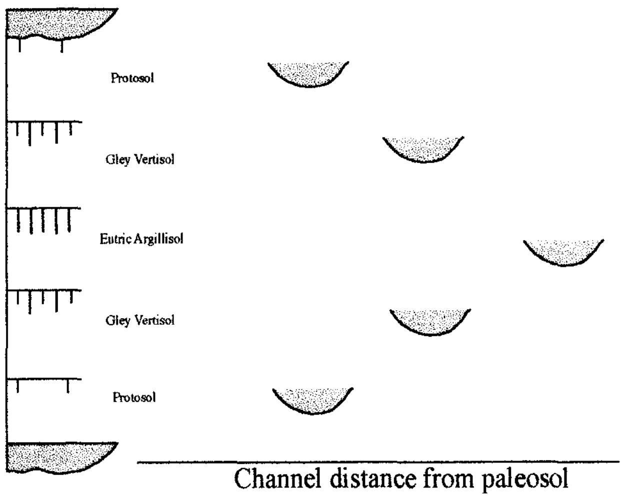


Figure B-6. Topsets of trough cross-stratified channel sandstones were used to collect paleocurrent directions. Field pick is .5 m in length and pointing in the paleocurrent direction, as indicated from the tops of the trough cross-stratified sandstones.

Migration of a channel over the floodplain



Avulsion of channel over the floodplain

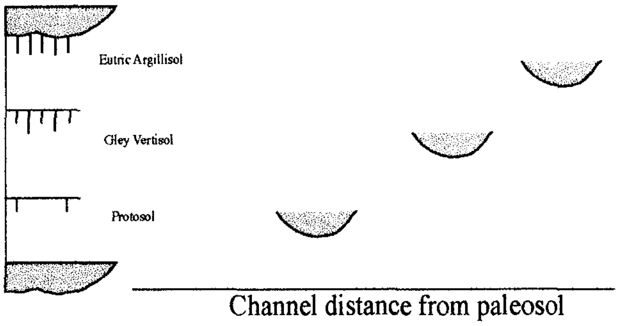


Figure B-7. Avulsion frequency was calculated by paleosol packages between channel sandstones. This system is based on the development of soils with respect to their distance from the channels. If stacked paleosols show a gradation from young to mature back to young, this is recorded as channel migration. If paleosols are stacked from young to mature with a channel on top, this is recorded as an avulsion (Wright, 1989).

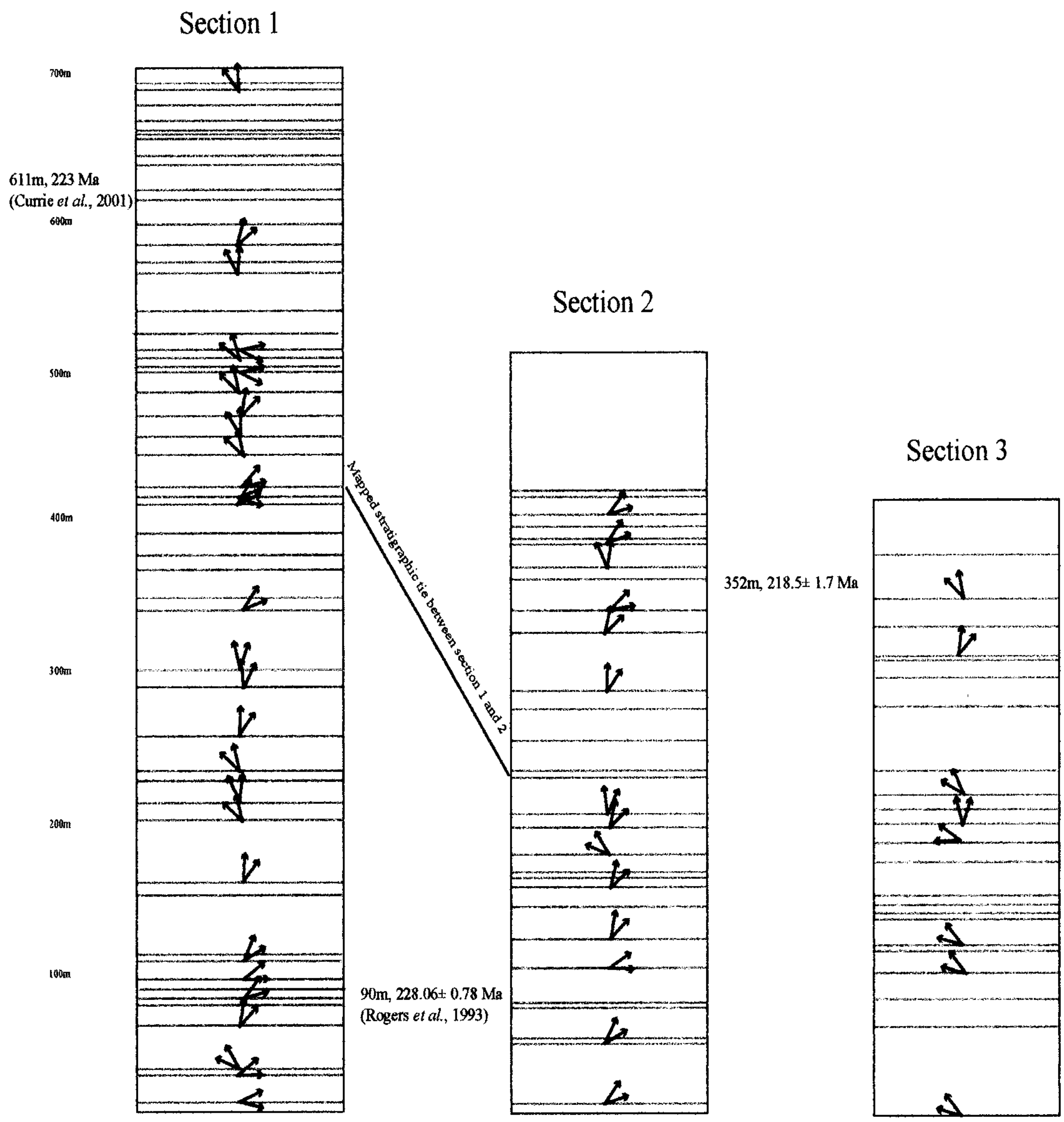


Figure B-8. Each column represents the stratigraphic thickness of each measured section. Lines in these sections define the location of channel deposits: red lines are isolated channels and green lines are laterally continuous interconnected channels. Notice the increase in interconnected channels near the tops of the sections. Arrows located on the channel sandstone beds represent the the average paleocurrent direction collected for each bed, with north at the top of the page. Each arrow represents a minimum of 30 paleocurrent measurements.

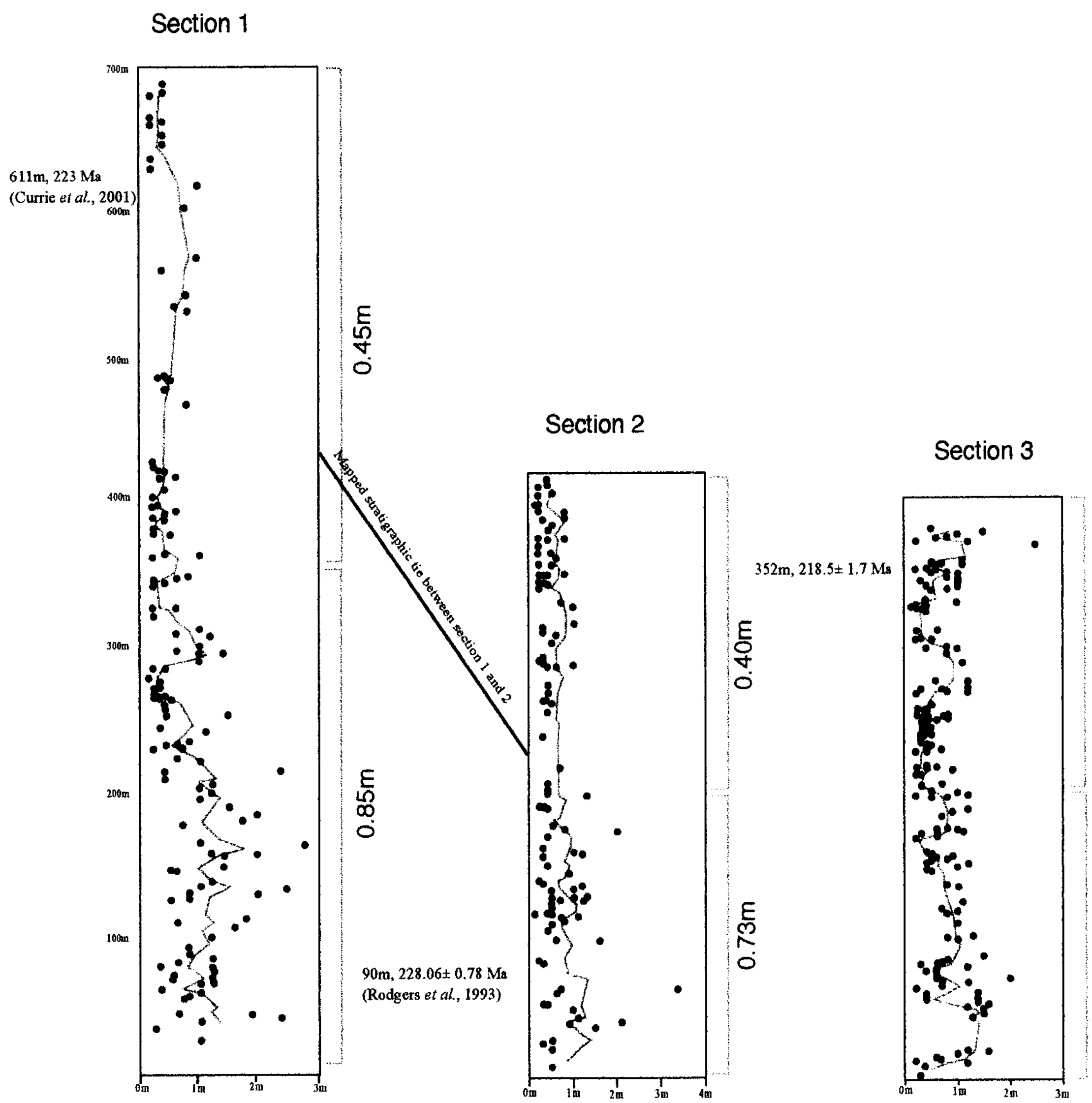


Figure B-9. Each column represents the stratigraphic thickness of each measured section. Dots indicate stratigraphic position and thickness of each paleosol identified in the sections. Red lines indicate running average of paleosol thicknesses. The orange lines and corresponding numbers represent the averages of the paleosol thicknesses in the upper and lower portions of the Ischigualasto Formation. Paleosols become thinner in the upper half of the Ischigualasto Formation.

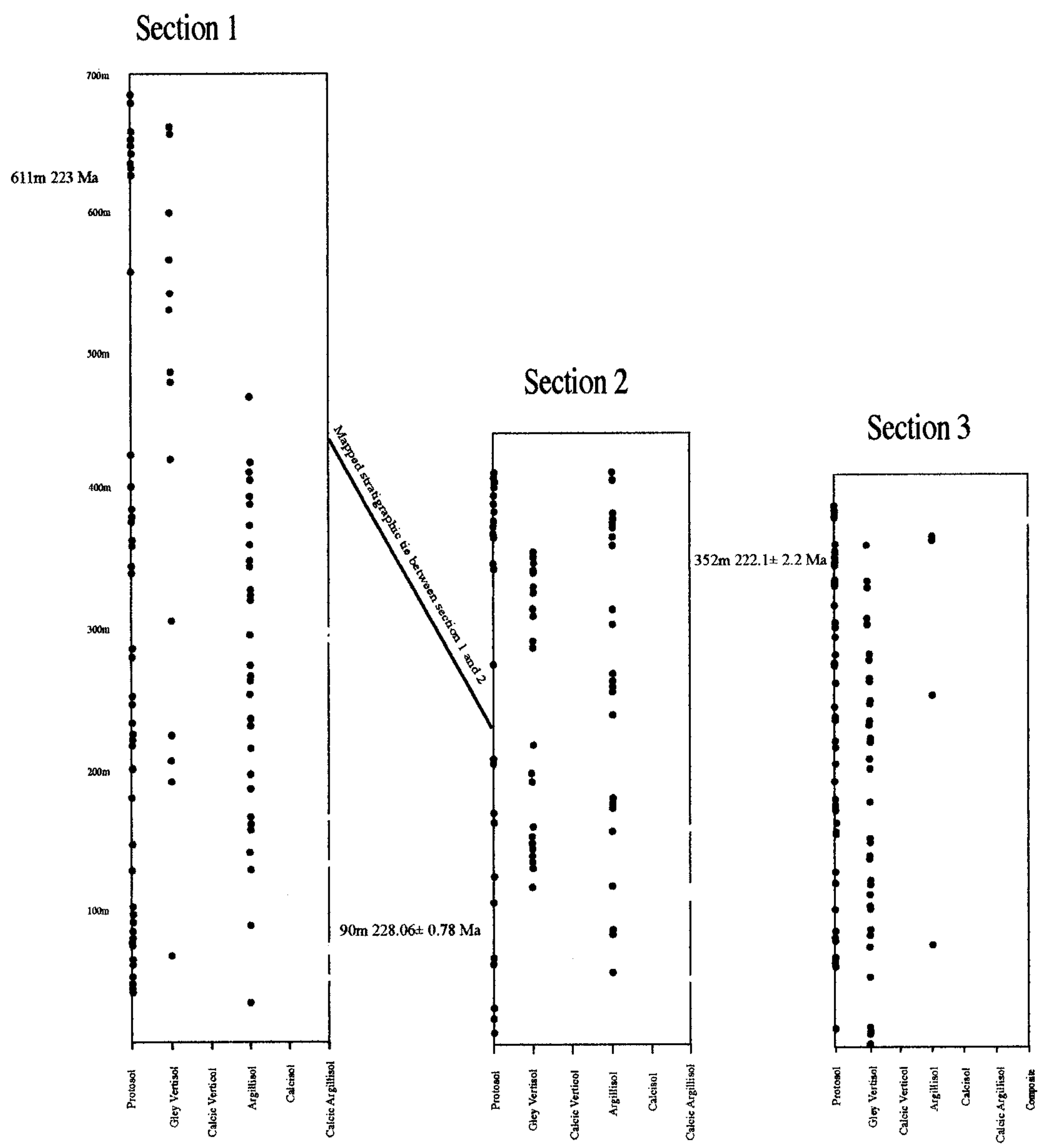


Figure B-10. Each column represents the stratigraphic thickness of each measured section, and soil types found in Ischigualasto Formation are listed across the bottom of each column. Yellow dots represent paleosols that contain secondary carbonate. Dots represent stratigraphic position of paleosols and type after Mack *et al.* (1993). Notice that paleosols bearing secondary carbonate are rare to absent in the upper portions of the Ischigualasto Formation.

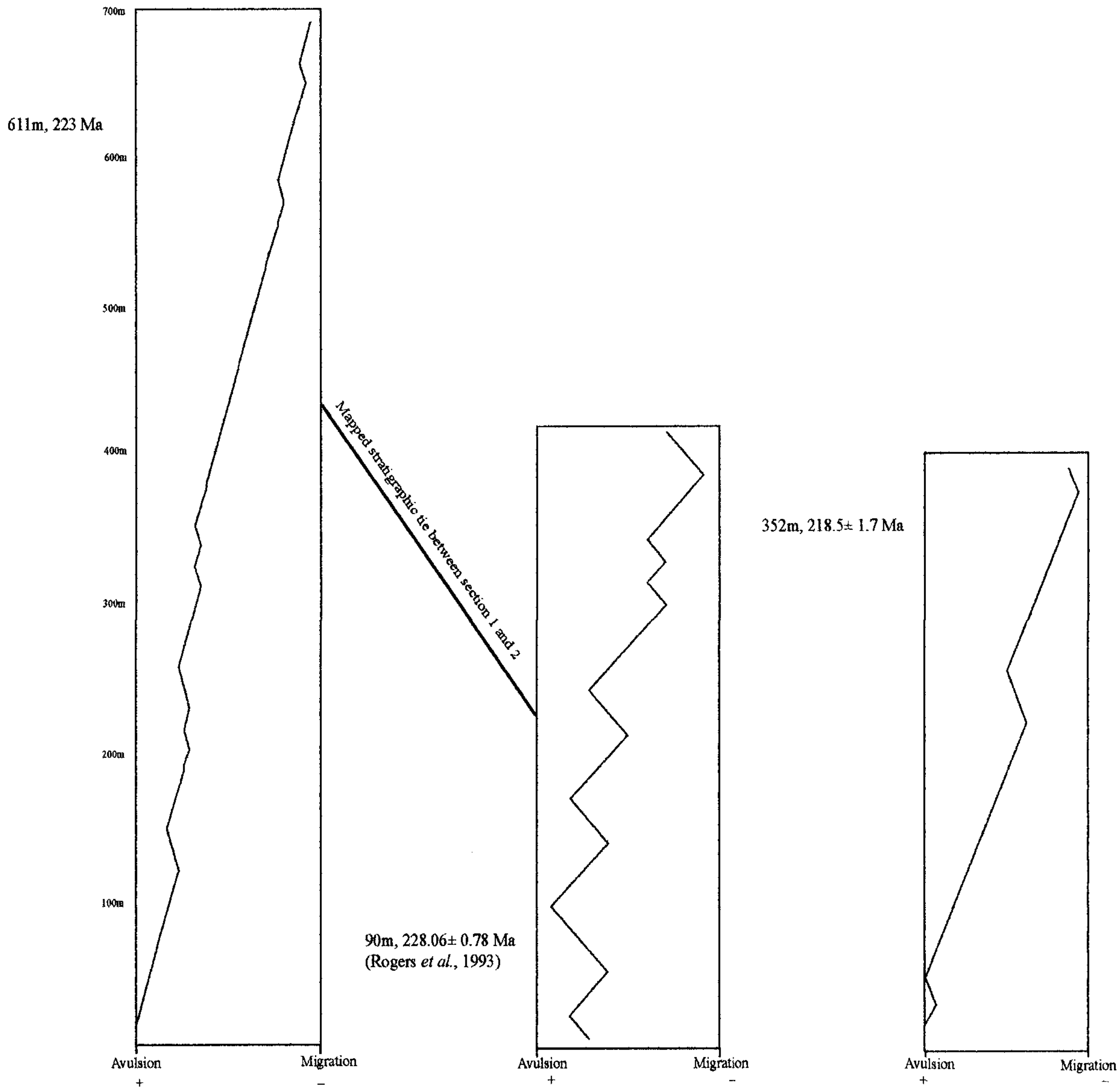


Figure B-11. Each column represents stratigraphic thickness of each measured section. Red lines represent the data collected from paleosol sequences beneath channels, as cumulative curves of avulsion versus migration. Lines start at zero, with an avulsion adding one step and a migration subtracting one. Sections exhibit decreases in the avulsion frequency. Frequent avulsion would drive the curve to the left.

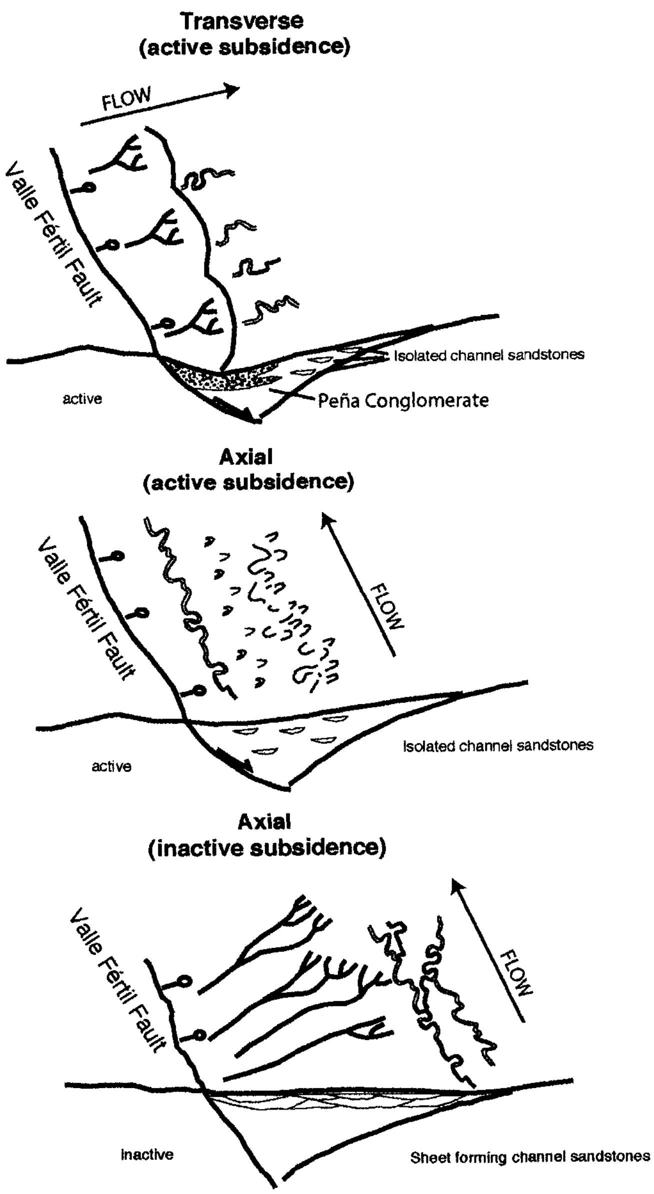
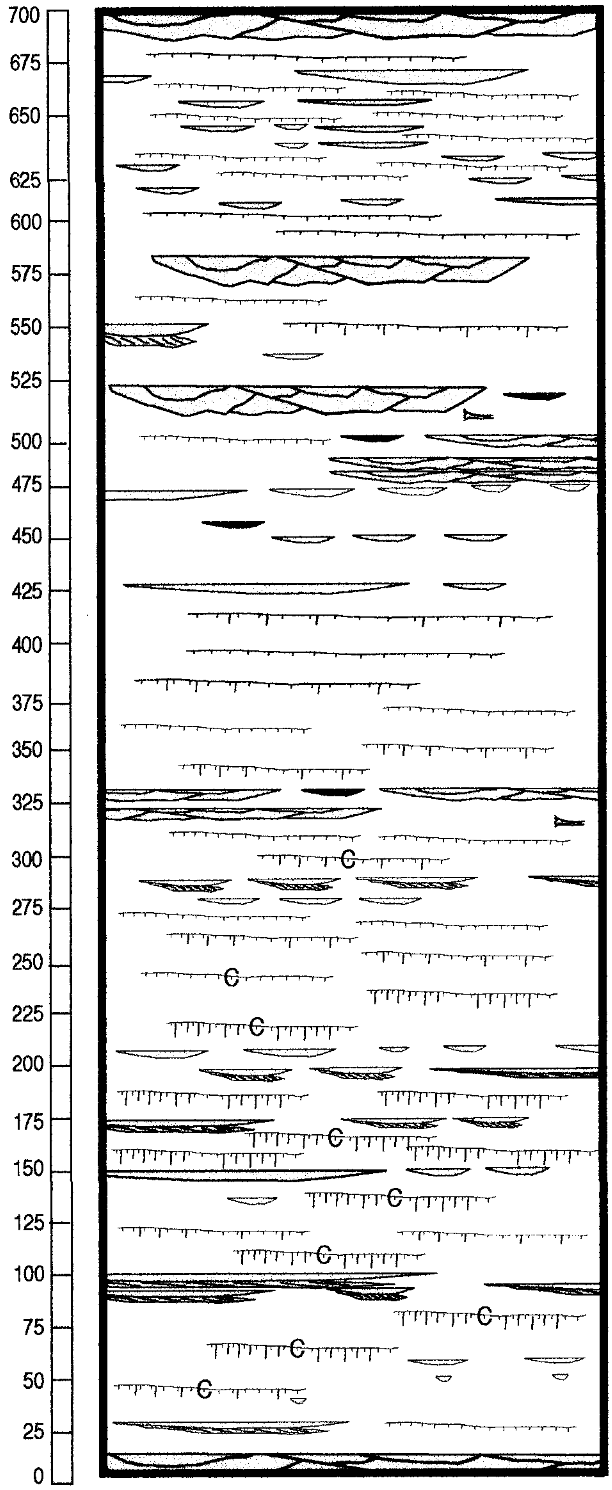
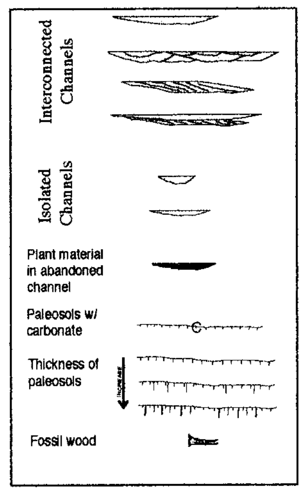


Figure B-12. Paleocurrent directions relate to the relative accommodation within the basin. Movement on the fault precipitated a discontinuity with a fan conglomerate off the footwall. Flow directed away from the fault during this phase. As the rate of movement decreases on the fault, axial flow dominates with isolated channel sandstones. In the final phases of deposition, axial flow is maintained with little accommodation, producing sheet sandstone bodies.





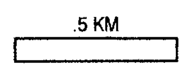


Figure B-13. Information for this panel diagram was collected for mapping while correlating to the measured section 1. This can be compared to the model (Fig. B-3) and has many of the predicted sequences, yet architectural features are dissimilar with respect to the soil thickness.

		PALEOSOLS	CHANNEL INTERCONNECTEDNESS	AVULSION FREQUENCY	STREAM POWER	CHANNEL TYPE	PALEOCURRENT
SEDIMENT ACCUMULATION	BASE-LEVEL	If base-level drops then entrenchment will leave topographically isolated interfluves that will develop mature paleosols. If base-level rises valleys will fill with sediment and paleosols may become less mature as sediment accumulation rates increase.	If base-level drops, entrenchment of the channel will create a narrow channel floodplain, which will increase the channel interconnectedness. If base-level rises, valley fill will create a wide floodplain, which decreases the interconnectedness of the channels.	If base-level drops, avulsion frequency will decrease. If base-level rises, avulsion frequency will increase.	If base-level drops, stream power will increase. If base-level rises, stream power will decrease.	If base-level drops, sinuosity will decrease (braided channels). If base-level rises, sinuosity will increase (meandering channels).	N/A
	TECTONICS	Increase of topographic slope by tectonic activity will increase erosion rates which will decrease the paleosol thickness Decrease in erosion rates may increase the paleosol thickness.	Increased subsidence will cause base-level to rise and increase the accommodation space which disperses channel deposits. Decreased subsidence will change base-level to reequilibrate and decreases the accommodation space which concentrates channel deposits.	Increase in slope may increase erosion rates, which may increase the inter-channel deposition and increase avulsion rates. Movement on a half-graben fault may increase avulsion frequency. Tilting of the floodplain will induce the avulsion toward the basin topographic low.	Increased activity will increase the slope of the channels, which increases stream power. Orographic effects may tie into particular climatic affects on the stream power.	Increase in the slope will increase the erosion rates and affect the drainage system sediment load. Increased sediment load will decrease the sinuosity. Decrease in the drainage systems sediment load may increase the sinuosity of the channels	Increased subsidence will direct flow toward the basinal low.
	CLIMATE	Climate may dictate the type of paleosol that forms. In wet climates, secondary carbonate formation is unlikley.	Increased flood magnitude and frequency will increase the avulsion frequency and channels may become interconnected. Decreased flood magnitude and frequency will decreased the avulsion frequency and channels may be isolated.	Increase the avulsion frequency and increase channel *interconnectedness*. Decrease the avulsion frequency and decrease channel interconnectedness.	Increase in the flood magnitude and frequency will increase the stream power.	Change in the water may affect the ratio of sediment to water, which will affect the sinuosity. Increase in the ratio will decrease the sinuosity and decrease in the ratio will increase the sinuosity.	N/A

		CLIMATE	TECTONICS	EUSTACY
ACCOMMODATION	SUBSIDENCE	Climates may remove topographic loads which affect the flexural load and reduce subsidence.	Increased tectonic activity may increase the amount of accommodation space	Shoreline changes produce sediment bypass of the basin, may reduce loading and reduce subsidence.
	BASE-LEVEL	Lake levels can drop during arid periods, affecting base-level	Linkage of sub-basins may affect base-level if the one of the linked sub-basins base-level is different.	Change in the sea-level will rise or lower base-level directly connected to the ocean.

Table B-1. Factors controling sediment accumulation and accommodation space, with the expected features of alluvial architecture under different conditions. Accommodation space is controled by base-level and subsidence, and is further impacted by their relationships with climate, tectonics, and eustacy. Sediment accumulation rate are impacted by climate, tectonics, and base-level.

APPENDIX C: MODEL FOR THE TECTONOSEDIMENTARY BASIN FILL OF THE TRIASSIC ISCHIGUALASTO BASIN, NORTHWESTERN ARGENTINA

ABSTRACT

The Ischigualasto basin is a Triassic extensional basin located in northwestern Argentina. This study uses previous studies, field investigations, and isotopic dating to develop a model for the basin. Our tectonostratigraphic model will incorporate new research that links basin development to fault length and displacement.

The Ischigualasto basin developed in three stages that were controlled by extension: isolated sub-basins, single basin, and underfilled basin. Our tectonostratigraphic model suggests that these stages are related to Talampaya and Tarjados Formations (isolated sub-basins), Chañares/Ischichuca and Los Rastros Formations (single basin), and Ischigualasto and Los Colorados Formations (underfilled basin). Basalt flows are absent in the upper portion of the Ischigualasto and Los Colorados Formations, which indicates the possible onset of thermal contraction within the basin. A siliceous layer at the contact of the Chañares and Tarjados Formation is reinterpreted as a welded tuff, which represents a contemporaneous surface that shows simultaneous deposition and erosion along that surface within the basin. $^{40}Ar/^{39}Ar$ dates indicate that the Ischigualasto Formation (800 m) was deposited over 10 million years and the Los Rastros Formation (1000 m) was deposited in 3 million years. Sedimentation

rates calculated from the $^{40}Ar/^{39}Ar$ dates agree with the model developed from the tectonostratigraphic framework.

INTRODUCTION

The most recent tectonostratigraphic model for the Ischigualasto basin was constructed by Stipanícic and Bonaparte (1979) and was later improved upon by Milana and Alcober (1994) (Fig. C-1). In their model, Stipanícic and Bonaparte (1979) described the basin fill sequence as one cycle that included climate and accommodation (subsidence) as controlling factors in the basin fill. The climate was hot and the cycle shifted from dry to humid and back to dry, which included a phase of extension that created the basin. Stipanícic and Bonaparte (1979) emphasized early on the importance of an evaluation of the climate and tectonics in the creation of sediment supply, which they incorporated in their model. The red sandstones of the Talampaya and Tarjados Formations represent a hot and dry phase early in the formation of Ischigualasto basin. Lacustrine deposits of the Ischichuca and Los Rastros Formations represent the humid phase of the basin fill and alluvial deposits of the Ischigualasto and Los Colorados Formations would then represent the return to dry conditions. Later, Milana and Alcober (1994) further developed the model by integrating seismic data, geophysical data, and data from the measured sections throughout the basin. Milana and Alcober (1994) also incorporated periods of synrift and post-rift (sag phases) in their model to account for changes in the accommodation rate and tectonostratigraphy (Fig. C-1). The synrift phases are identified by basalt flows interbedded with fine-grained sediments. Coarse-grained sediments are also identified to be the product of a reactivation of the synrift phase (active extension). All sediment not associated with these features were considered to be post-rift periods.

Recent advances in the understanding of extensional basins and fieldwork that was completed over the summers of 2000 and 2001 have supplied evidence for a reevaluation of the Milana and Alcober (1994) Ischigualasto basin model (Fig. C-1). Rift basins develop in stages (Gawthorpe and Leeder, 2000). The different stages of rift basin development control the type of deposits found in the basin fill (Denys *et al.*, 1986; Gawthorpe and Leeder, 2000). These different stages of rift basin development are controlled by the degree of extension, which can be directly linked with creation of accommodation. Recent research has better established the relationship between the normal fault length and slip ratio (Cartwright *et al.*, 1995; Willemse *et al.*, 1996), which regulates the development of rift basins (Gawthorpe and Leeder, 2000). This paper evaluates the relationship of stratigraphic sequences, measurement of accommodation, relative slip along the normal fault, and the means of sediment delivery to the development of the basin.

The Milana and Alcober (1994) model does not address the aspects of basin dynamics that this study addresses. (1) The Talampaya and Tarjados Formations were interpreted as being deposited during dry climatic conditions (Stipanícic and Bonaparte, 1979; Milana and Alcober, 1994), yet there has been no determination of the geographical extent of this dryness and no evaluation of whether the dryness was due to orographic effects caused by local topographic doming or an aspect of regional climatic conditions (Denys *et al.*, 1986). (2) The transition between the Tarjados Formation and the Ischichuca/Chañares Formations has not previously been addressed in detail. The transition between the two formations changes in character away from Valle Fértil fault (Romer and Jensen, 1966; Rogers *et al.*, 2001; Curtin, 2001). The nature of this transition is linked to the basin model and its extensional activity. (3) The presence of basalt flows was used by Milana and Alcober (1994) to indicate synrift activity in their model (Fig. C-1). Volcanism does not always indicate rifting activity, yet it does indicate that the crust is not thermally subsiding (Morley *et al.*, 1999). If the crust is hot enough to melt and produce lavas it is will not thermally subside. As a part of this study new dates have been collected from the Ischigualasto and Los Rastros Formations in order to resolve sediment accumulation rates that are associated with rift phases, and to develop a basin model.

The creation of a basin model linking the stratigraphy and the basin development is important for understanding and reconstructing the tectonostratigraphy of this basin. This study also uses the general model recently proposed by Gawthorpe and Leeder (2000) for rift basin development. In early stages, rift basins contain multiple half-grabens whose boundary faults switch polarity on either side of areas of low subsidence called "transfer zones" (Frostick and Reid, 1989; Gabrielsen *et al.*, 1990; Morley *et al.*, 1999; Gawthorpe and Leeder, 2000). In early stages of extension, these transfer zones block axial drainage and linkage between basins. During the early stages of rifting, a basin's internal drainage is minimal and the surrounding drainage is deflected away from the basin due to the characteristic doming created by the high heat flow associated with rifts (Denys *et al.*, 1986; Frostick and Reid, 1989). In later stages of development, the rift sub-basins coalesce into a single basin proportional to the accommodation created by the slip along the boundary half-graben fault (Gawthorpe and Leeder, 2000). When the tectonic activity is reduced in the late stages of development, accommodation is created by the isostatic effect of the sediment load and the thermal contraction of the crust (Morley *et al.*, 1999; Gawthorpe and Leeder, 2000). The latest stage of basin fill produces a reduction of accommodation during deposition within an underfilled basin (Frostick and Steel, 1993; Morley *et al.*, 1999; Gawthorpe and Leeder, 2000).

This study uses existing general models combined with new data to develop a specific detailed model of accommodation, climate, base-level change, and tectonic activity of the Ischigualasto basin fill stratigraphic sequence. We intend to explain the tectonic significance of the contacts and their relationships to lithology and volcanic activity. Using data collected from literature and our recent fieldwork, a tectonostratigraphic model will be developed for the Ischigualasto basin.

Basin Fill Sequence

The Ischigualasto basin extends northwest from the Valle de la Luna Provincial Park to Cerro Bolla and is about 120 km long and 50 km wide (Fig. C-3). The deposits that fill the Ischigualasto basin have been divided into seven formations, which comprise two groups: (1) the Early Triassic Paganzo III Group (containing the Talampaya

Formation and the Tarjados Formation) and (2) the Middle to Late Triassic Agua de la Peña Group (containing the Chañares/Ischichuca Formations, the Los Rastros Formation, the Ischigualasto Formation, and the Los Colorados Formation (Romer and Jenson, 1966; Frenguelli, 1948; Grober and Stipanícic, 1953) (Fig. C-4). Each of these formations thickens toward the Valle Fértil fault (Fig. C-3) and thins toward the basin southern edge (Georgieff, 1992; Milana and Alcober, 1994). Sedimentary facies change along strike and toward the Valle Fértil fault (Milana and Alcober, 1994; Currie *et al.*, 2001). At six sites in the Ischigualasto basin fill sequence, basalt flows are found near the base of and stratigraphically below the Ischigualasto Formation (Fig. -1) (Stipanícic and Bonaparte, 1979; Milana and Alcober, 1994).

The Talampaya Formation is up to 400 m thick and is composed of conglomerate, amygdaloidal basalt flows, and red sandstone that is poorly sorted and medium to coarse grained (Romer and Jensen, 1966; Stipanícic, 1983). The conglomerate is composed of clasts of Precambrian crystalline granite with diameters measuring from 8 to 30 cm (Romer and Jensen, 1996). Sedimentary structures in this formation include planar beds and poorly defined trough cross-beds. Although fine-grained sediment is absent, mudstone rip-ups are present as clasts within the conglomerate. Conglomerate is found at the base and middle of this formation. Basalt flows are found at various levels within the Talampaya Formation (Milana and Alcober, 1994). At the top of the Talampaya Formation is a layer of eolian sandstone 10-15 m thick. Above this sandstone is an unconformity with the basal conglomerate of the Tarjados Formation, which has a maximum thickness of 2 to 3 m (Romer and Jensen, 1966). The direction of the paleocurrents is to the northeast and east (Alcober, 1996).

The Tarjados Formation measures up to 250 m thick and is composed of fine to coarse sandstone and mudstone (Groeber and Stipanícic, 1953; Romer and Jensen, 1966; Stipanícic, 1983; Rogers *et al.*, 2001). The sandstone beds display tabular geometries and contain small- to large-scale trough cross-beds. The intraformational conglomerate clasts are composed of cobbles of chert, silicified wood, and mudstone rip-ups (Romer and Jensen, 1966; Rogers *et al.*, 2001). Mudcracks and silicified rhizocretions are preserved within the mudstones, which also contain septarian carbonate nodules (Rogers *et al.*, 2001). Near the top of the formation, basalt flows are present (Milana and Alcober, 1994). The top of the Tarjados Formation contains a conglomerate in which portions of the cobbles are covered with a silica coating derived from a silica-rich bed located above the conglomerate. The top of the Tarjados Formation is identified as a "silcrete" horizon with 2 m of relief (Romer and Jensen, 1966). The silcrete is bioturbated and contains sub-horizontal silicified root traces (Romer and Jensen, 1966; Rogers *et al.*, 2001). The top of the Tarjados Formation is capped unconformably by a matrix-supported conglomerate or a pedogenically modified ash (this study). The transition between the two styles of unconformities depend on the proximity to the boundary fault. This modified ash is a 5 to 50 cm thick silica-dominated bed with tubules that are 5 cm in diameter. Thin sections taken from the "silcrete" show remnant bubble wall shards (Fig. C-5) (Scholle, 1979), and thus probably represents zones of the ash that have undergone diagenesis. The Tarjados Formation paleocurrents vary laterally with mean direction of 333° (Milana and Alcober, 1994; Rogers *et al.*, 2001).

The Chañares Formation interfingers laterally with the Ischichuca and Los Rastros Formations and is up to 190 m thick (Romer and Jensen, 1966; Stipanícic, 1983; Curtin, 2001; Rogers *et al.*, 2001). The Chañares Formation is composed of volcanogenic, calcareous sandstone, mudstone with abundant pedogenic development, and volcanogenic debris flow deposits. The sandstone beds in this formation display small to large trough cross-beds and ripple cross-lamination. Concretions, which are generally oblate in the z-axis, occur throughout the formation. These concretions are dominated by silica in the upper portions of the formation and dominated by calcium carbonate in the lower 10 m (Rogers *et al.*, 2001). Nearer to the Valle Fértil fault, the rocks become dominated by channel sandstone and mudstone (Curtin, 2001). The Chañares Formation has a gradational relationship to both the Ischichuca and Los Rastros Formations (Fig. C-4). Near the Valle Fértil fault, the Chañares Formation grades into the Ischichuca Formation (Curtin, 2001), and closer to the eastern edge of the basin the Chañares Formation grades into the Los Rastros Formation (Roger *et al.*, 2001). Paleocurrent measurements from the lower and upper sandstone beds yield mean paleoflow directions of 199° and 183°; however, within the middle of the formation paleoflow directions average 344° (Rogers *et al.*, 2001).

The Ischichuca Formation is 200 to 405 m thick and is composed of clinoform deltaic sandstone and siltstone deposits (Stipanícic and Bonaparte, 1979). Coarsening upward cycles have been identified throughout the Ischichuca Formation (Milana and Mozetic, 1995; Curtin, 2001). These cycles begin with a coarse-grained sandstone clinoform, whose angle slowly decreases upsection (Fig. C-6). As the angle nears horizontal, sediments become finer grained and horizontally bedded. Also, organic material becomes abundant, and lignite coals are present near the top of this sequence (Curtin, 2001). The Ischichuca Formation has a gradational contact with the superjacent Los Rastros Formation. Paleocurrent data indicate a north to northeast direction of flow (Milana and Alcober, 1994).

The Los Rastros Formation is 470 to 1000 m thick and is composed of basalt flows, thinly bedded mudstones, and siltstone beds interbedded with lenticular sandstone bodies and bentonites (Romer and Jensen, 1966; Rogers *et al.*, 2001). The deposits are arranged into distinct depositional packages of coarsening upward sequences that are 10 to 25 m thick (Romer and Jensen, 1966; Rodgers *et al.*, 2001). Siltstone and sandstone beds that have planar, ripple laminated, and trough cross-bedded structures are found within the lenticular sandstone (Romer and Jensen, 1966; Rogers *et al.*, 2001). Plant material and carbonized wood are abundant throughout the Los Rastros Formation, as well as rare fossilized fish parts (*Estheria*, fresh water fish) (Stipanícic, 1983; Gallego, 1997). Tan to yellow bentonite beds and orange ironstone beds are present within the formation (Romer and Jensen, 1966; Rogers *et al.*, 2001). The Los Rastros Formation is capped by an erosional unconformity, which is associated with Peña Conglomerate that represent the basal conglomerate of the Ischigualasto Formation (Stipanícic and

Bonaparte, 1979; Rogers *et al.*, 1993; Milana and Alcober, 1994; Rogers *et al.*, 2001). Paleocurrent data indicate flow of northeast to north (Curtin, 2001).

The Ischigualasto Formation is 400 to 900m thick and is composed of channelized to sheet sandstone encased within mudstone and interbedded bentonite (Romer and Jensen, 1966; Stipanícic, 1983; Milana and Alcober, 1994; Alcober, 1996; Alcober and Parrish, 1997). The Peña Conglomerate is thickest near the Agua de la Peña canyon mouth and thinnest near the entrance to the Valle de la Luna provincial park, San Juan, Argentina (B.S. Currie, personal communication). Near the base of the Ischigualasto Formation, several basalt flows are interbedded with the alluvial sedimentary rocks (Page *et al.*, 1997). It is common for the mudstone to be pedogenically modified and to contain thin tabular sandstone beds with ripple cross-lamination (Stipanícic and Bonaparte, 1979; Rogers *et al.*, 1993; Alcober and Parrish, 1997). The paleosols here all contain vertic features, and in the lower half of the formation, contain secondary carbonates (Currie *et al.*, 2001). The channel sandstone beds become more interconnected near the top of the formation, and this feature continues into the overlying Los Colorados Formation (Alcober *et al.*, 1997). The Ischigualasto Formation is conformable to the southeast and unconformable to the northwest (Stipanícic and Bonaparte, 1979). Paleocurrent direction is dominantly eastward in the Peña Conglomerate and the units immediately above, with flow directions toward the north to northeast throughout the rest of the formation (Milana and Alcober, 1994; this study).

The Los Colorados Formation is greater than 650 m thick and is composed of red, laterally continuous, thin sandstone sheets with thin mudstone and siltstone interbeds (Yrigoyen and Stover, 1970; Stipanícic and Bonaparte, 1979; López-Gamundí *et al.*, 1989; Milana and Alcober, 1994). The sandstone is coarse to medium-grained and contains some conglomerate lenses (Stipanícic and Bonaparte, 1979; López-Gamundí *et al.*, 1989). The thin tabular sandstone beds in this formation are commonly amalgamated, and contain some interbeds of eolian-sandstone channel infills (López-Gamundí *et al.*, 1989). The sandstone beds have trough cross-bedded to ripple-laminated sedimentary structures. Near Cerro Bola, the northernmost extent of the Ischigualasto basin deposits, the Los Colorados Formation contain beds of gypsum as well as gypsum crystal molds (J.T. Parrish, personal communication). Large root traces and rare fossilized wood are also present in the Los Colorados Formation (Stipanícic, 1983). The mudstone beds show little to no pedogenic development. The paleocurrent evidence indicates flow to the northeast and southeast (Milana and Alcober, 1994). Currently there are no radiometric dates for the Los Colorados Formation; however, a Norian age can be inferred from the biostratigraphy (Stipanícic and Bonaparte, 1979; Milana and Alcober, 1994).

Regional tectonics and volcanism

The Ischigualasto basin developed during extension along the Panthalassan margin of Gondwana during the Early Triassic period (Stipanícic and Bonaparte, 1979; Milana and Alcober, 1994; Rogers *et al.*, 2001). Bimodal volcanism is associated with deposits dated from the Triassic Period found in northwestern Argentina (Ramos and Kay, 1991; Martin *et al.*, 1999). Although volcanism has been linked to the extension, the mechanisms involved in the rifting of this basin are unclear (Uliana and Biddle, 1988; Ramos and Kay, 1991). Extensional basins in this region are found from 25-53° S, with continental deposits in the southern basins and a progression to marine deposits in the northernmost basins (Fig. 2) (Uliana and Biddle, 1988).

There are two main theories for the development of the extension on the western margin of Gondwana: (1) back-arc spreading (Storey and Alabaster, 1991) and (2) gravity collapse of over-thickened continental crust (Uliana and Biddle, 1988).

The back-arc spreading model suggests that extension was generated from an over-steepening of a westward-dipping slab angle caused by a reduction of the subduction rate slowed due to a decrease in the slab's age (Stelkov and Alvarez, 1984; Storey and Alabaster, 1991). Igneous activity associated with subduction is found in the Amazon Basin at 220 to 140 Ma (diabase sills), in the Thurston Island Block at 230 Ma (Mt. Bramhall granitic intrusions) (Veevers *et al.*, 1994), in the Cuyo Basin at approximately 235 Ma (basalt flows; Ramos and Kay, 1991), and in the Ischigualasto basin at 224±5 Ma (diabase sills; Valencio *et al.*, 1975). Basins near the center of the Pangean craton (the Parana Basin and Karoo Basin) have also been identified as evidence for subduction off the west coast (Veevers *et al.*, 1994).

The gravity collapse model is the result of the crustal heating in response to the thermal insulation from a supercontinent and stresses within the continent that result in extension (Gurnis, 1988; Martin *et al.*, 1999). Gravity collapse of the over-thickened crust of southern Pangea in the vicinity of Ischigualasto has been proposed due to the lack of evidence of the existence of any single volcanic chain parallel to the extensional basin trends (Charrier, 1979; Uliana and Biddle, 1988).

The rift basins in this study are unusual for their relationship with igneous activity (Kay *et al.*, 1989). The Red Sea Rift was more than 250 km wide before dike intrusion occurred (Coleman and McGuire, 1988). Incontrast, the Cuyo and Ischigualasto basins were only 47 km wide before intrusions were emplaced (Valencio *et al.*, 1975; Ramos and Kay, 1991; Page *et al.*, 1997). The intrusive igneous history of western Argentina includes Early Permian (280-270 Ma) biotite granites, Early to Middle Triassic (242-238 Ma) silica-rich leucocratic granites and rhyolite porphyries, and earlier Late Triassic to Early Jurassic (221-200 Ma) intrusive rhyolitic porphyries, extrusive domes, and mafic intrusions (Martin *et al.*, 1999). Paleomagnetic data (Valencio *et al.*, 1975, 1983) indicate the slow motion of the supercontinent in relation to the magnetic poles (Kay *et al.*, 1989). Kay *et al.* (1989) proposed that this slow motion of the supercontinent allowed for heat to build up in the mantle, which created the necessary conditions for gravity collapse. Kay *et al.* (1989) proposed that this data indicates the similarities of these basins to the silicic magmatism in Gondwana and the middle Proterozoic in North America.

Local Triassic tectonics and volcanism

Two major faults are apparent in the geologic record of the Triassic extension of northwest Argentina, the Alto fault and Valle Fértil fault (Georgieff, 1992; Milana and Alcober, 1994). The main half-graben fault in this region is thought to be the Valle Fértil fault, which lies to the west of the thickest portions of the Ischigualasto basin stratigraphic sequence and has been seismically imaged and shown to be dipping 40° (Bossi, 1971; Stipanícic and Bonaparte, 1979; Georgieff, 1992; Milana and Alcober, 1994). The Valle Fértil fault is a compressive Paleozoic structure that was reactivated during the Triassic as a result of tensional forces (Milana and Alcober, 1994).

The Alto fault is most likely a synthetic sub-basin, high-angle normal fault that linked to the Valle Fértil fault (Currie *et al.*, 2001; Gawthorpe and Leeder, 2000). Smaller trans-axial normal faults have been located adjacent to the Valle Fértil fault through detailed stratigraphic work and seismic imaging (Georgieff, 1992; Currie *et al.*, 2001). Volcanic deposits such as reworked tuffs, basalt flows, and mafic dikes have also been identified within the Ischigualasto basin stratigraphic sequence (Valencio *et al.*, 1975; Alcober, 1996; Page *et al.*, 1997). Basalt flows once thought to be sills were found to have well-developed paleosols and associated channel sandstones with basalt lithics (Alcober, 1996; Currie *et al.*, 2001). Page *et al*'s. (1997) study of the basalts suggests that "flows were extruded through fracture-related vents and/or monogenetic volcanoes constructed of piles of thick viscous lavas."

Regional paleogeography and paleoclimate

Paleomagnetic data collected from basalt flows within the upper Chañares Formation near the base of the Ischigualasto Formation place the basin at 30°S (Veevers *et al.*, 1994; Valencio *et al.*, 1975; López Gamndí *et al.*, 1994), in a zone that should have been influenced by subtropical temperatures and climate. The climate of the Triassic Pangea was dominated by a "megamonsoon", which created dramatic swings in the amount of precipitation over much of the continent over short periods of time (Kutzbach and Gallimore, 1989). The size of Pangea, its topography, and the symmetrical disposition of the continent on either side of the equator explains the existence of the megamonsoon, the widespread aridity in the continental interior, the warm global temperatures, and the relative lack of vegetation (Curtin, 2001; Hay and Wold, 1998). Strong seasonality during periods of overall aridity has been identified and interpreted through analysis of the Ischigualasto basin sedimentary fill sequence, flora, and fauna (Volkheimer, 1969; Bossi, 1970; Stipanícic and Bonaparte, 1979; Rogers *et al.*, 1993; Martínez, 1994; Curtin, 2001).

Volkheimer (1969) suggested warm to hot temperatures with seasonal precipitation (local aridity), mostly based on floral data during deposition of the Ischigualasto basin fill. Stipanícic and Bonaparte (1979) suggested that the Ischigualasto basin sediment sequence represents a single climate cycle, from relatively dry and seasonal to more humid and back again, with temperatures mild to hot and with a low mean annual precipitation that may have varied through time. Stipanícic and Bonaparte's

(1979) reconstruction primarily relied upon rock evidence in the Talampaya and the Tarjados Formations and rock and flora/faunal evidence in the Chañares/Ischichuca Formations, the Los Rastros Formation, the Ischigualasto Formation, and the Los Colorados Formation. They also considered the possibility that some of the changes in the rock record were the result of tectonic influences and that the climate was relatively uniform. Spalletti *et al.* (1999) suggested a shift from mixed forest to an herbaceous and shrub-like paleocommunity in the Ischichuca and Ischigualasto Formations and from a mixed forest to a mesoxerophytic forest in the Los Colorados Formation, based on paleofloristic biozonation interpreted from pollen. Spalletti *et al.*'s (1999) interpretation supports the previous interpretations of the paleoenvironment, that this phase of the basin fill was deposited during a dry period.

<u>Dates/biostratigraphy</u>

The Paganzo III and Agua de la Peña Group have both been investigated using biostratigraphy and radiogenic isotopic dating techniques (Fig. C-7) (Romer and Jensen, 1966; Yrigoyen and Stover, 1970; Valencio *et al.*, 1975; Stipanícic, 1983; Rogers *et al.*, 1993; Spalletti *et al.*, 1999; Rogers *et al.*, 2001).

Chirotherium-type footprints have been used to date the Talampaya Formation in the Early Triassic epoch (Stipanícic, 1983). *Kannemeyerid*-type dicynodont fragments have been found within beds of the Tarjados Formation and have also been used to place it in the Early Triassic (Groeber and Stipanícic, 1953; Romer and Jensen, 1966). Tetrapod fauna found within the Chañares Formation indicate an age of Middle Triassic

(Ladinian) (Rogers *et al.*, 2001). The Ischichuca Formation has no dates at present but has abundant biostratigraphic data suggesting the Middle Triassic (Stipanícic, 1983). The Los Colorados Formation contains fossil wood, thecodonts (*Riojasuchus*), saurischians (*Riojasaurus*), and crocodilians (*Hemiprotosuchus*), which places it in the Late Triassic (Stipanícic, 1983).

There are few dates in the literature. Basalts between the Los Rastros and Ischigualasto Formations have been dated at 229 Ma ± 5, using K/Ar techniques (Odin and Létolle, 1982). Rogers *et al.* (1993) dated a tuff 90 m above the contact between the Los Rastros and Ischigualasto Formations at 227.78 Ma ± .3 using $^{40}Ar/^{39}Ar$.

Our study also produced new dates from interbedded bentonite beds. Dates were determined by the $^{40}Ar/^{39}Ar$ incremental laser heating of samples of fine-grained sanidine crystals extracted from the ashes interbedded in the Ischigualasto Formation. Nineteen ash samples were collected and analyzed at New Mexico Institute of Mining and Technology, but only three samples produced dates.

Near the base of the Los Rastros Formation, a date of 233 Ma was obtained from a bentonite sample (this study). Two ashes near the top of the Ischigualasto Formation have been dated at 223 and 218.5±1.5 Ma (this study). The top boundary of the Ischigualasto Formation's age, established by Gradstein *et al.* (1995), is between the Carnian and Norian stages.

DISCUSSION

This portion of the paper will discuss the tectonic significance of the sedimentary sequences found in the Triassic Ischigualasto basin. The interpretation will incorporate modern basin models, climatic indicators, and the temporal distribution of volcanic activity, all based on a tectonostratigraphic framework.

Tectonostratigraphic Framework

The Ischigualasto basin stratigraphic sequence can be broken down into three phases of deposition: (1) the isolated sub-basins phase; (2) the large, single half-graben fault phase; and (3) the passive underfilled phase (Frostick and Steel, 1993; Gawthorpe and Leeder, 2000). Although the Milana and Alcober (1994) model calls for episodic periods of extension and thermal contraction, extension is most likely a continuous process punctuated by changes in the rate of extension (Morley *et al.*, 1999; Gawthorpe and Leeder, 2000). Evidence that we collected from the basin fill morphology, stratigraphic sequence, paleocurrent directions, and geochronology support three phases of basin development that fit into the Gawthorpe and Leeder (2000) model.

Initial stages of rifting are exhibited as multiple sub-basins (Fig. C-8) (Gawthorpe and Leeder, 2000). Early phases of extension tend to be internally draining and are commonly arid due to orographic effects. The wider distribution of the older rift sediments with respect to the younger rift sediments is detailed in the east African rift deposits (Morley *et al.*, 1999). As rift systems mature, the focus of extension will concentrate into the narrow, elongate basins (Gawthorpe and Leeder, 2000). Sediments within the basin, in turn, reflect the change in the focus of extension through changes in their environment of deposition and direction of fluvial transport (Frostick and Reid, 1989). An increase in the extension will direct flow into the graben basin and will draw nearby streams toward the basin (Peakall *et al.*, 2000). The Talampaya and Tarjados Formations represent alluvial fan deposits that were formed during the initial stages of rifting (Milana and Alcober, 1994; Alcober, 1996). Paganzo III deposits are more dispersed than earlier deposits identified within the same basin (Romer and Jensen, 1966; Rogers *et al.*, 2001). The steep margins of the footwall at the sub-basin margins create an environment that produces alluvial fans and debris flows (Frostick and Steel, 1993). Gawthorpe and Leeder (2000) suggested that eolianites, such as the ones found in the Talampaya Formation, are common in the initial stages of sub-basin development due to arid conditions brought about by orographic effects. A conglomerate marking the boundary between the Talampaya and Tarjados Formations marks an unconformity, which is the product of tectonic activity affecting the base-level within these basins. Changes in the paleocurrent direction found in the Talampaya and Tarjados Formations could indicate that the drainage direction was affected by tectonic activity during their deposition. Extension increased within the crust, which in turn increased the throw on the main boundary fault, coalescing the isolated sub-basins into one large basin (Frostick and Reid, 1989; Gawthorpe and Leeder, 2000).

The upper contact between the Tarjados and Chañares Formations is marked by a matrix-supported conglomerate and "silcrete". New evidence taken from photomicrograph (Fig. C-5) supports a reinterpreting of the "silcrete" as a welded tuff. While this is clearly a pedogenically modified tuff at the contact between the Tarjados and Chañares Formations near the basin margins, the same deposit located proximal to the boundary fault is not pedogenically modified.

The silcrete represents a period of depositional quiescence (Romer and Jensen, 1966; Milana and Alcober, 1994; Alcober, 1996) and a surface of transportation that is preserved in the ash bed. Deposition and erosion occur at the same time at this contact. Matrix-supported conglomerate represents deposits proximal to the main boundary fault and the "silcrete" represents a depositional hiatus, which was punctuated by an ash fall event that is recorded throughout the basin. Matrix-supported conglomerates were the product of mass wasting produced by increased subsidence. Deposits similar to this are found in the Salton Trough extensional basin (Winker, 1987). In the Salton Sea Basin, these deposits are considered to represent rapid subsidence. Closer to the Valle Fértil fault this "silcrete" is located 40 m above the contact point between the Chañares and the Tarjados Formations. The ash was deposited near the basin edge where sediment accumulation rates were low and the ash was pedogenically modified.

The tuff near the boundary fault is located above the Chañares and the Tarjados Formation unconformity, which implies higher sediment accumulation rates in this portion of the basin. The transition between the Chañares and Tarjados Formations represents the presence of a tremendous amount of accommodation, which is suggested by the matrix-supported conglomerate (deposited during a mass wasting event) and the subsequent change in the depositional environment. This transition initiated a linkage of the sub-basins and fault networks concentrating the regional drainage which developed into a lake.

As extension focused on the Valle Fértil fault, the sub-basins were incorporated into a single basin (Fig. C-8) (Frostick and Reid, 1989; Frostick and Steel, 1993; Gawthorpe and Leeder, 2000). This resulted in drainage being focused into a single basin, forming a lake. All paleocurrents point to the existence of an outlet in the northern portion of the basin that has not been preserved (Fig. C-1) (Milana and Alcober, 1994). The Chañares Formation represents the initial stages of the basin's increase in accommodation. Near the Valle Fértil fault, the Chañares Formation grades into the Ischichuca Formation; however, 20 km away from the fault within the basin, the Ischichuca Formation is absent (Romer and Jensen, 1966; Rogers *et al.*, 2001). The Ischichuca Formation's absence relates to the lack of accommodation near the basin hinge (Fig. C-8). The thickest portions of the Ischichuca Formation are located near the Valle Fértil fault, which is the location of the thickest accumulation (maximum accommodation) and the focus for drainage (Frostick and Reid, 1989; Milana and Alcober, 1994). The lake level of this basin became shallow during the deposition of the Los Rastros Formation, which contains both lacustrine and fluvial deposits (Stipanícic and Bonaparte, 1979; Milana and Alcober, 1994; Milana, 1998). Accumulation rates decreased from the Chañares to Los Rastros Formations.

A phase of active accommodation creation occurred during the transition between the Los Rastros and the Ischigualasto Formations (Fig. C-8). This activity is marked by the Agua de la Peña conglomerate, which overlies a regionally correlatable unconformity (Stipanícic and Bonaparte, 1979; Milana and Alcober, 1994). Paleocurrents within and above the Agua de la Peña conglomerate indicate eastward flow toward the Valle Fértil fault (Fig. C-1) (Currie *et al.*, 2001). The eastward flow was most likely due to active subsidence on the Valle Fértil fault. Paleocurrent flow throughout the rest of the Ischigualasto Formation is axial to the basin (Stipanícic and Bonaparte, 1979; Milana and Alcober, 1994; Currie *et al.*, 2001). The contact between the Ischigualasto and overlying Los Colorados Formations is gradational in the south and erosional in the north (Stipanícic and Bonaparte, 1979). Since all of the flow is to the north and there is no evidence of large accumulations of salt, it is reasonable to assume that this basin had an outlet to the north. The local erosional unconformity in the north portion of the basin is most likely the result of a base-level change caused by accommodation in the outlet to the north. The gradational contact in the south is marked by a change in the color of the rocks (greenish grays to reddish browns) and an increase in the presence of sheet sandstone beds (Bossi, 1971; Stipanícic and Bonaparte, 1979; Milana and Alcober, 1994; Alcober and Parrish, 1997). This change has been interpreted to be a decrease in the accommodation and a general lack of fine-grained input. At the base of the Ischigualasto Formation, paleocurrent directions shift dramatically toward the boundary fault, which suggest that the basin was actively subsiding; there is no evidence of this type of activity in the Los Colorados Formation, which caps the basin fill. The relative sediment accumulation rates decrease upsection from 1000 m in 3 Ma (Los Rastros Formation) to 700 m in 10 Ma (Ischigualasto Formation) (Fig. C-7).

The Ischigualasto basin's stratigraphic sequence represents three stages of basin development: (1) the initial sub-basins, (2) the maximum accommodation period, with lacustrine deposition, and (3) the axial fluvial deposition in the under-filled, passively subsiding basin. Isolated sub-basins are dominated by the presence of alluvial fan deposition that is represented by the Talampaya and Tarjados Formations. As extension increased, the sub-basins developed into a single rift half-graben. When the sub-basin faults linked, the movement was focused onto the Valle Fértil fault. This increase in accommodation produced a large lake with alluvial margins, which is represented in the Chañares, Ischichuca, and Los Rastros Formations. Accommodation decrease and thermal subsidence is dominant during the deposition of the alluvial deposits within the Ischigualasto and Los Colorados Formations.

Climate

During the Triassic period the climate was dominated by the existence of the super-continent Pangea, which created a "megamonsoon." Extreme swings in the amount of precipitation were common and have been interpreted as seasonality during the Late Triassic of North America (Dubiel *et al.*, 1991). Each formation's climatic indicators within the Ischigualasto basin were used to estimate the mean annual precipitation. This range in mean annual precipitation is correlated to an interpretation of the tectonostratigraphy of the formation and derived from paleoclimatic indicators such as paleosols, eolianites, and flora.

It is not clear whether the arid climatic conditions indicated in the Tarjados Formation were local or regional. Doming, caused by rifting, may have created topography that produced an orographic effect that shielded the basin from rainfall (Denys *et al.*, 1986). Topographic relief within rift basins can cause local aridity (Parrish, 1998). The Talampaya Formation has an eolian unit that is indicative of an arid environment (Parrish, 1998). The Tarjados Formation contains abundant evidence of arid conditions, such as secondary soil carbonates and mudcracks, which indicate arid conditions. The Chañares Formation paleosols were identified as vertisols (Curtin, 2001), which suggests the existence of a mean annual precipitation of 250 mm-1500 mm MAP (Gyllenhaal, 1990). Paleosol evidence in the Ischichuca and Los Rastros Formations is sparse due to the nature of their depositional environments, but the ones that exist are vertic in nature (Milana, 1998; Curtin, 2001). Previous workers have interpreted the Ischichuca Formation to have represented a wet climatic period (Stipanícic and Bonaparte, 1979; Curtin, 2001); the mean annual precipitation most likely did not exceed 1500 mm MAP because of the precipitation associated with the formation of vertisols. The Ischigualasto Formation's paleosols are all vertisols that only contain secondary carbonates in the lower half of the formation. The mean annual precipitation in the Ischigualasto Formation based on the vertisols was between 250 to 1500 mm. The mean annual precipitation is interpreted to have changed from 250 to 760 mm in the lower part of the formation (where the carbonates occur) and 760 to 1500 mm in the upper part (where the carbonates are absent to rare) (Royer, 1999). The Los Colorados Formation contains evidence of gypsum deposition, which translates into a maximum mean annual precipitation as high as 1500 mm with high temperatures (Gyllenhaal, 1991).

Evidence for the climate change described above are apparent within the Ischigualasto basin stratigraphic sequence, with shifts that indicate a climatic range of arid to semi-arid. In the Early Triassic, the climate was arid with a mean annual precipitation of less than 760 mm. In the Middle Triassic, the climate shifted to semi-arid with a mean annual precipitation of 250-1500 mm. In the Late Triassic, the mean annual precipitation shifted to arid (early Carnian) and then back to semi-arid (late Carnian). The climate then shifted back to arid in the Norian time. The relationships between the climate and the tectonostratigraphic framework are very similar. During the periods of alluvial fan and axial fluvial deposition, arid climate dominated. During the periods of lacustrine deposition, semi-arid climate dominated. This correlation may also depend on several other variables addressed elsewhere such as base-level, parent material, and accommodation availability.

Temporal distribution of volcanic activity

Basalt flows are found interbedded from the base of the Ischigualasto basin stratigraphic sequence to the base of the Ischigualasto Formation. Although there are ashes located throughout the remainder of the Ischigualasto Formation, no evidence of local volcanism has been found (Stipanícic and Bonaparte, 1979; Milana and Alcober, 1994). A cessation of volcanism and possibly a continuation of subsidence through the process of thermal contraction are common phases near the last stages of extension (Alverez and Ramos, 1999). The tectonostratigraphic framework suggests a general decrease in accommodation that could be explained by the shift from active extension to passive thermal contraction in the basin. From the Early Triassic epoch to the early Carnian age, the Ischigualasto basin was actively extending. This activity shifted to passive thermal contraction during and after the late Carnian age.

CONCLUSION

(1) The Ischigualasto basin developed in three phases: (1) initial isolated sub-basins (Talampaya and Tarjados Formations), (2) single large half-graben (Chañares/Ischichuca and Los Rastros Formations), and (3) passively subsiding underfilled basin (Ischigualasto and Los Colorados Formations). These phases are interpreted from the basin fill, morphology, and chronostratigraphy.

(2) Absence of basalt flows in the Ischigualasto Formation's upper portion and Los Colorados Formations implies that thermal contraction of the crust did not dominate until their deposition. Comparing the stratigraphic location of basalts and chronostratigraphic data, sedimentation rates decrease as basalts become absent from the basin fill, which would be expected as the basin thermally contracted after the secession active extension.

(3) The "silcrete" is actually a weathered welded tuff. This surface represents a transportation surface where deposition (near the Valle Fértil fault) and erosion (away from the Valle Fértil fault) occurred at the same time. Deposition rate slowed near the margins and was higher near the boundary fault, which represents erosion and deposition within the basin at the same time.

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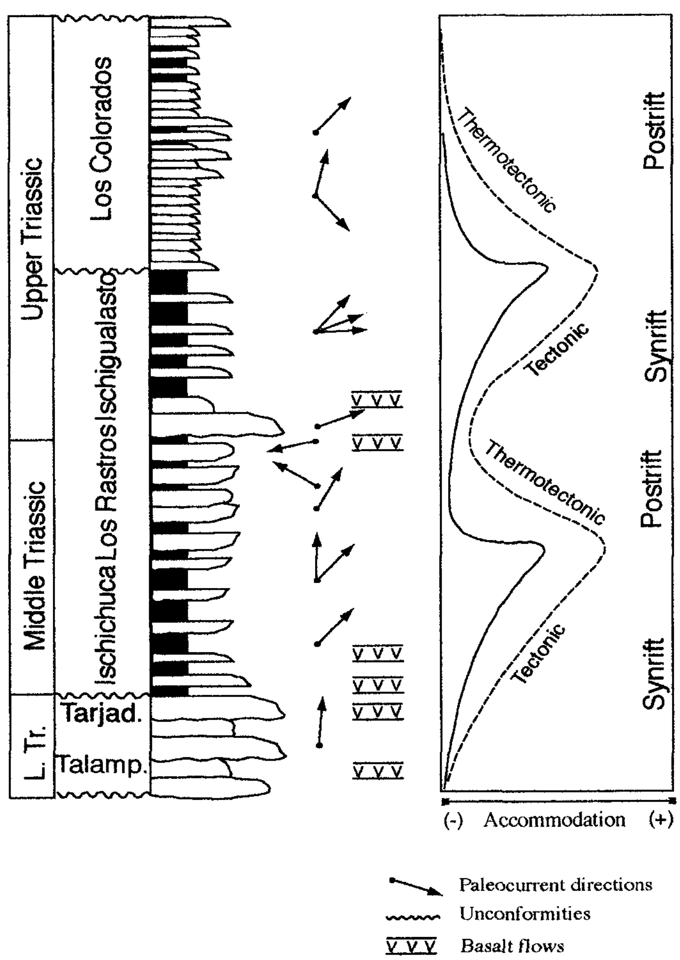


Figure C-1. Milana and Alcober's (1994) model suggests multiple phases of rifting with subsequent thermal subsidence.

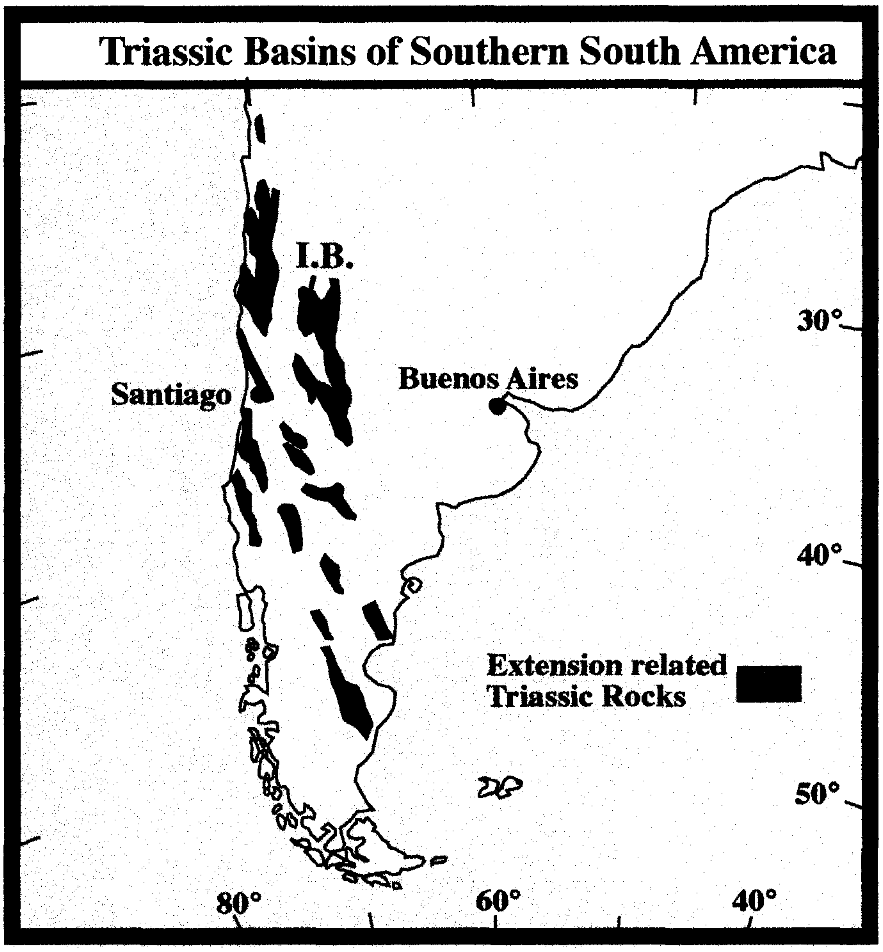


Figure C-2. Extensional basins are present through Chile and Argentina. The Ischigualasto Basinis located northeast of Santiago, Chile, designated as I.B. (Uliana and Biddle, 1988).

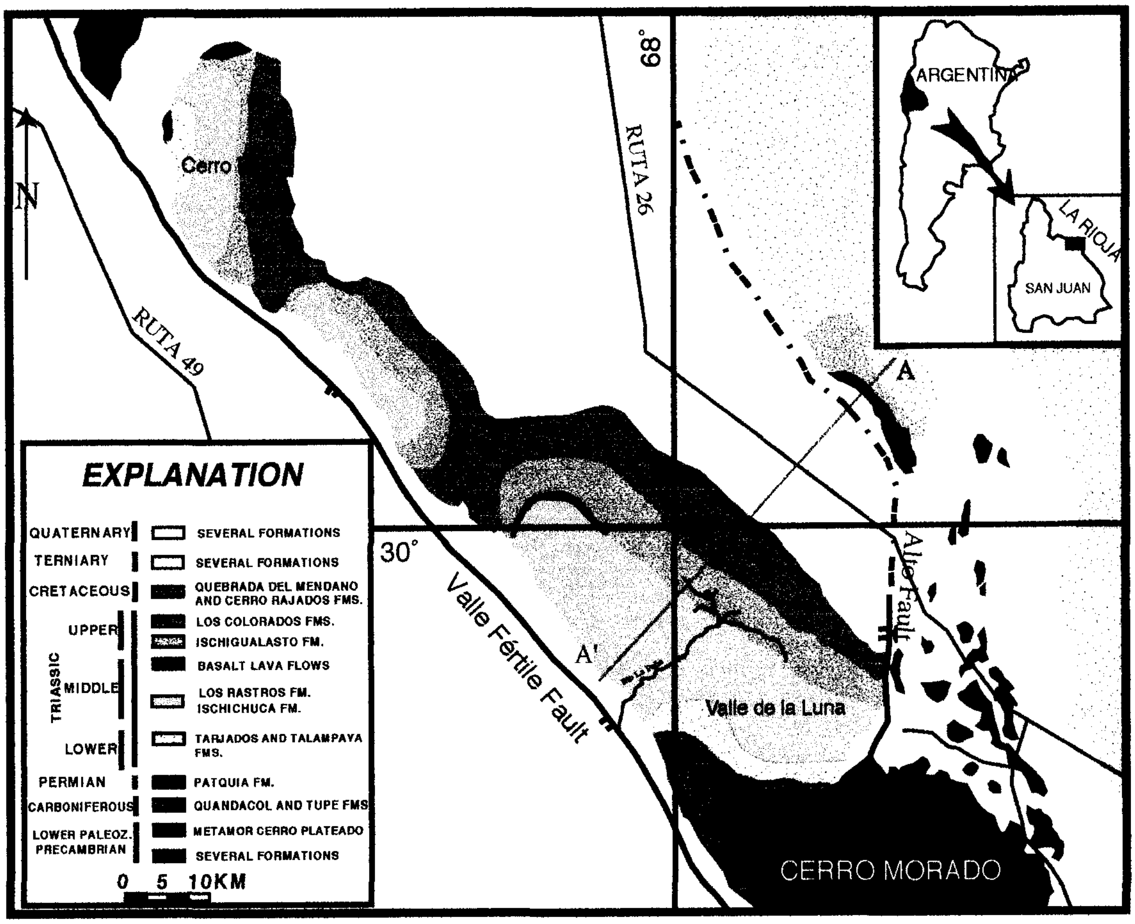


Figure C-3. This geologic map of the Ischigualasto basin represents the boundaries of the basin deposits. Older deposits have a wider distribution than the younger deposits. The red line shows the position of Figure 4's cross-section of the stratigraphic package.

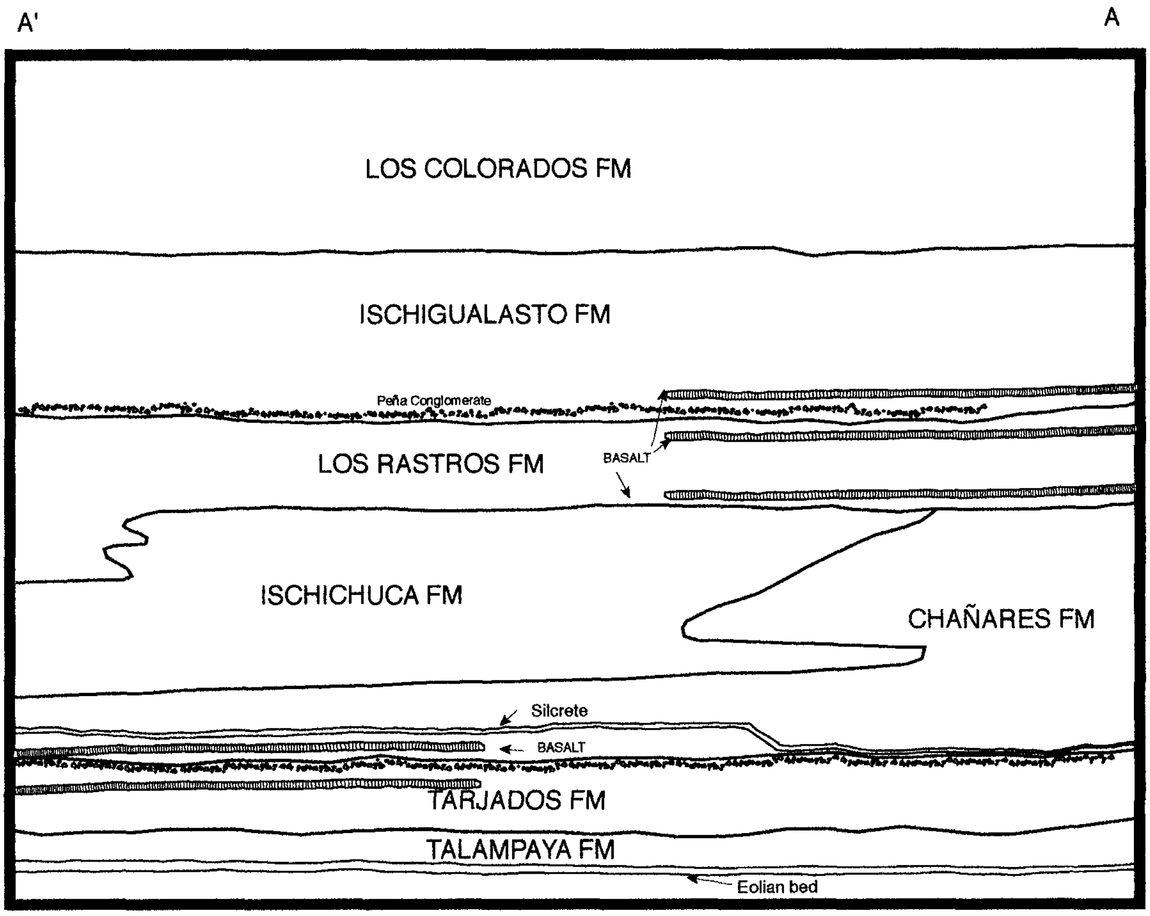


Figure C-4. This schematic of the stratigraphy of the Ischigualasto basin was used to develop a tectonostratigraphic model.

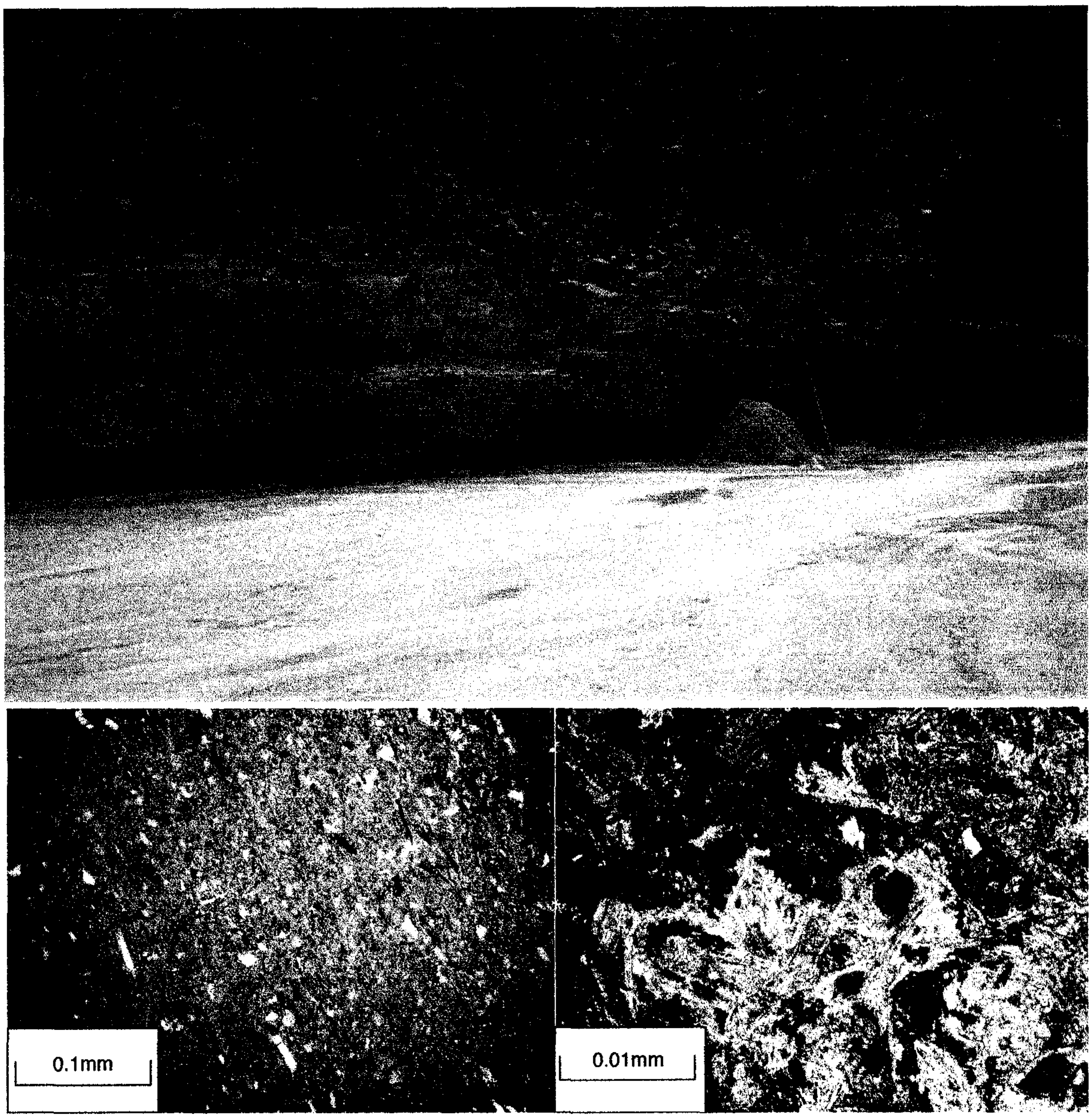
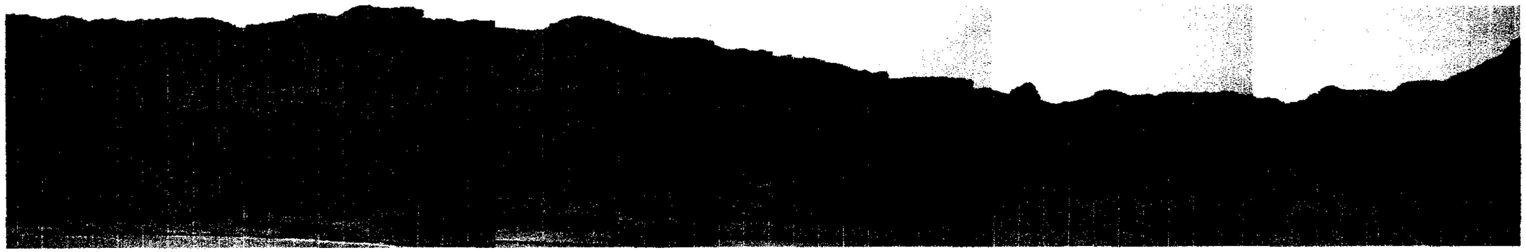


Figure C-5. Thin sections collected from the "silcrete" show glass shards, which idenify this rock as a silicified ash. The right photomicrograph is an enlargement of a portion of the right photomicrograph. The top photograph is the outcrop from which the sample was taken. Jacob staff is 1.5 m long.



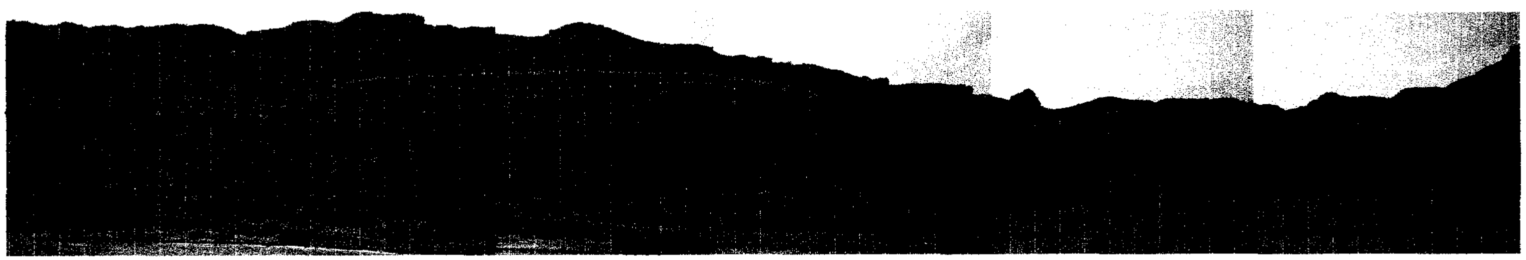


Figure C-6. Multiple clinoform sets are found along outcrops within the Agua de la Peña canyon. Red outlines fan sets, yellow represents a lateral fan lobe overlapping the toe of the clinoform, and blue represents the shallow lacustrine swamp facies.

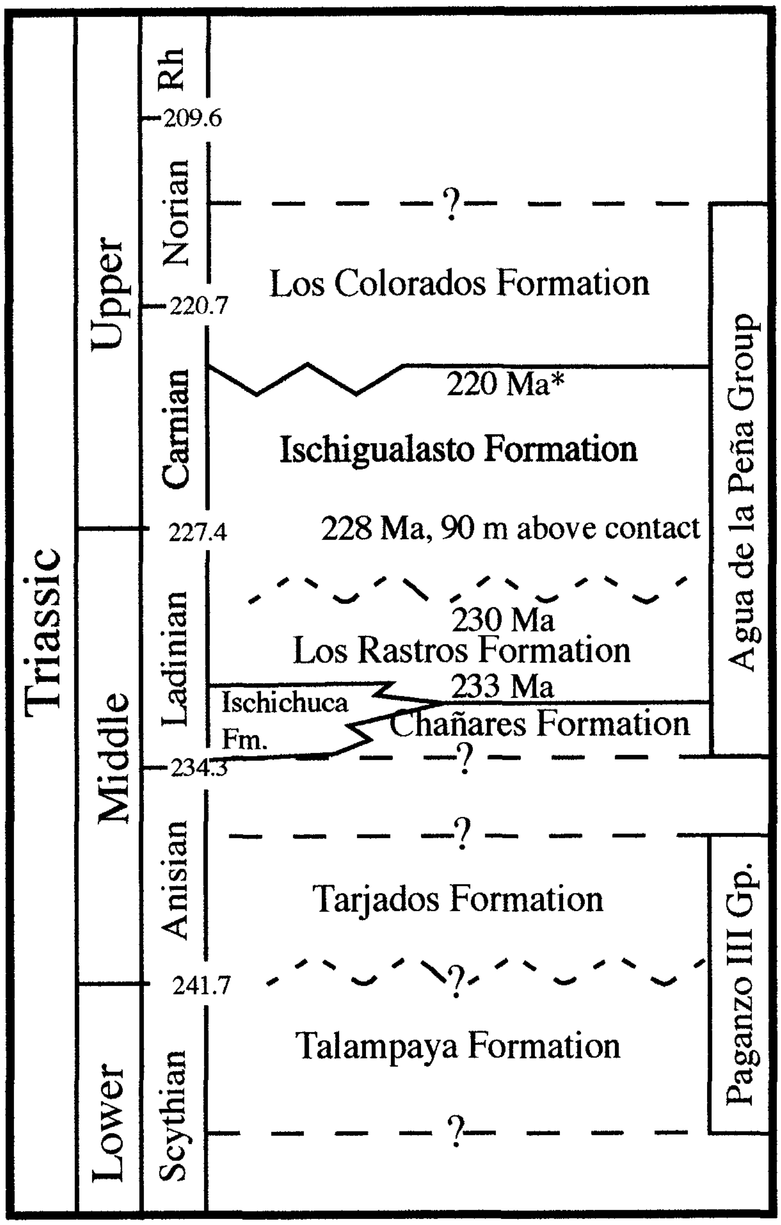
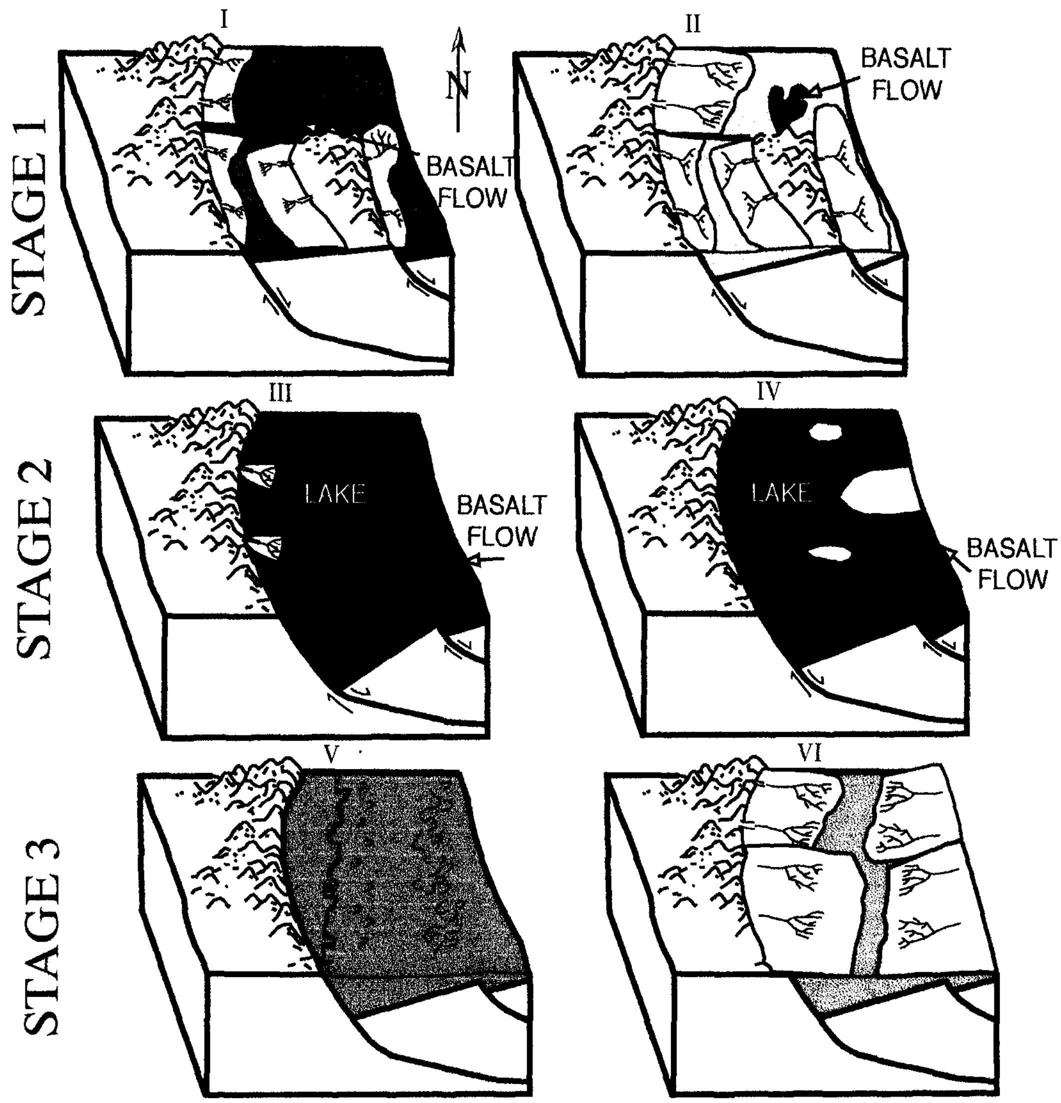


Figure C-7. Chronostratigraphy based on biostratigraphic work established by earlier research and radiogenic dating. Date with an asterisk (*) is the date collected for this study. The 230 Ma date is taken from the diabase near the contact between the Ischigualasto and Los Rastros Formation (Odin and Létolle, 1982).



Talampaya Fm	Block I Sub-basin morphology shown eolian component and basalt flows
Tarjados Fm.	Block II Sub-basins persist; however drainage is more concentrated
Chañares/Ischichuca Fm.	Block III Subsidence is focused on boundary fault, forming a lake
Los Rastros Fm.	Block IV Lake basin becomes more shallow with fluvial interaction
Ischigualasto Fm.	Block V Basalt flows are absent and alluvial basin fill begins
Los Colorados Fm.	Block VI Alluvial fans nearly reach accross the basin

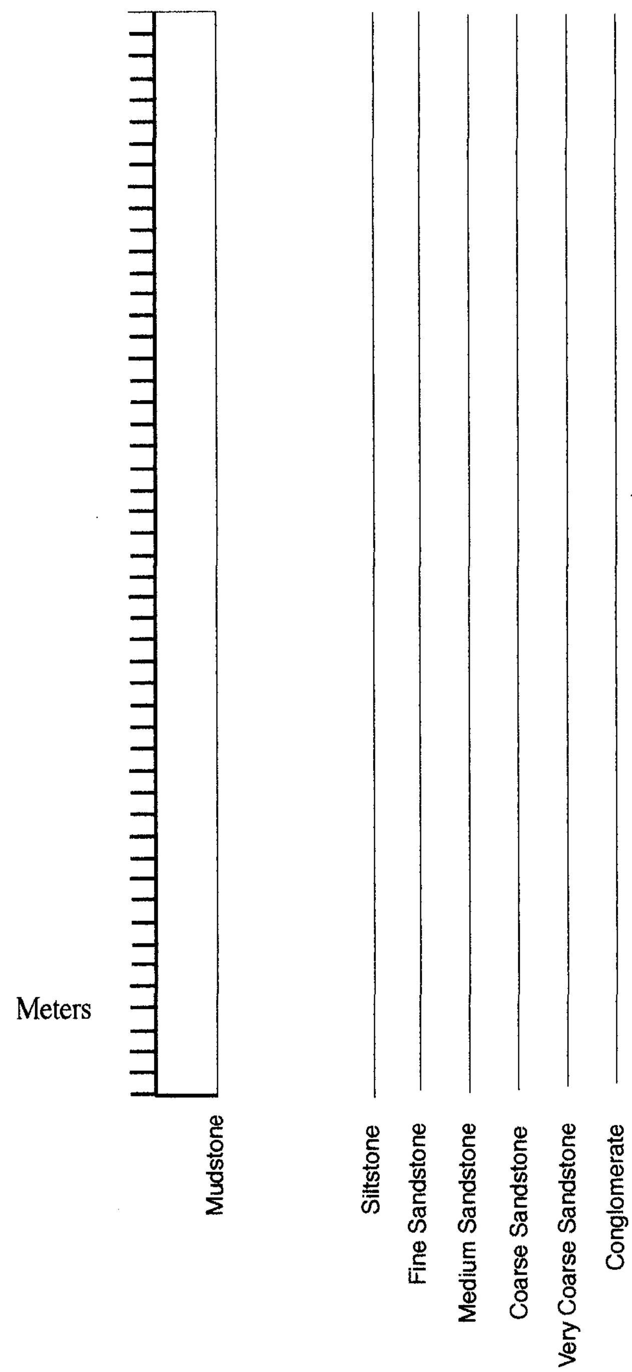
Figure C-8. The six block diagrams represent the three stages of basin development. Stage 1 represents isolated sub-basins, with multiple graben faults. Stage 2 represents the development of a single basin which fills with water. Stage 3 represents the last stage of development that results as an underfilled basin is filled.

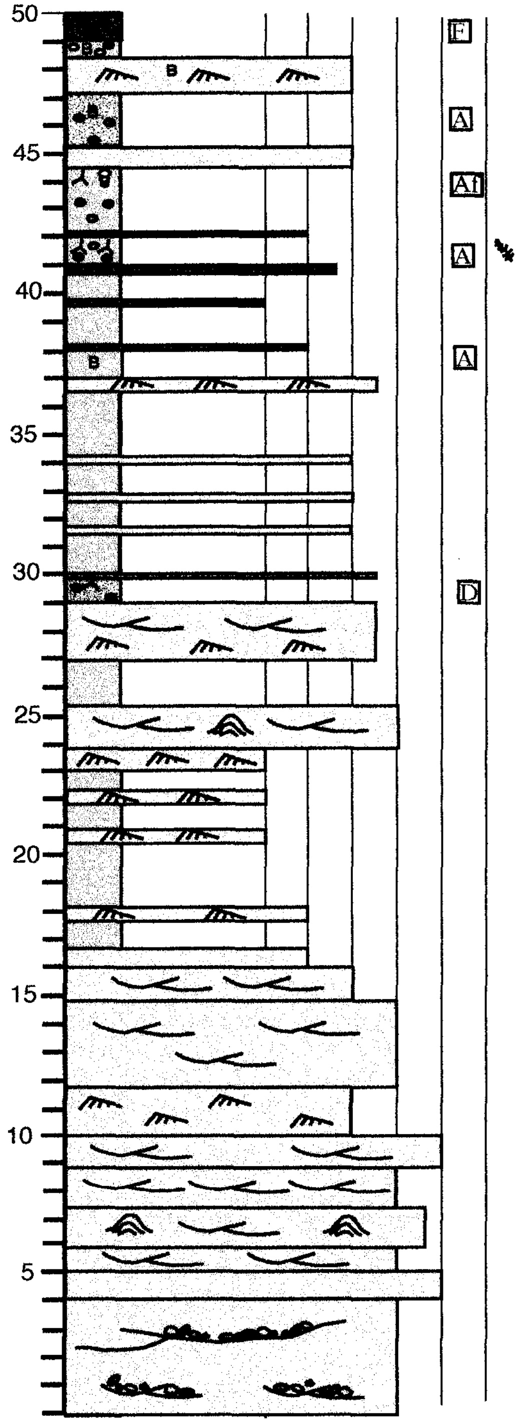
APPENDIX-D

SECTION 1

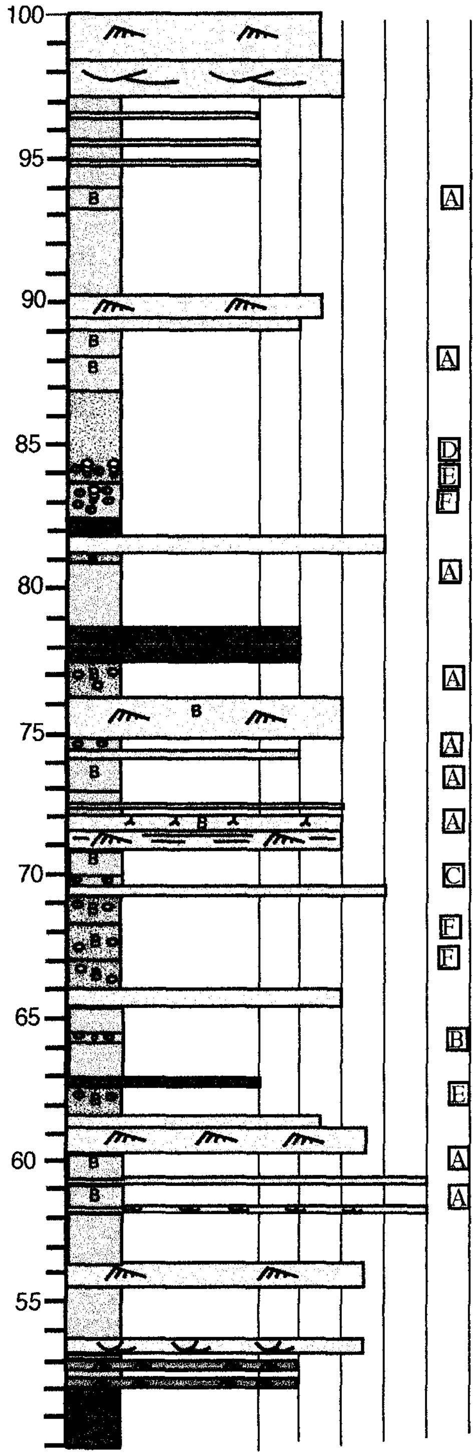
Key to stratigraphic columns

Mottles
Pedotype
Sand pocket
Soft sediment deformation
Trough cross-stratified
Petrocalcic horizon
Ripple cross-laminated
Rip-up Clasts
Root trace
Clasts
Fe nodules
Mn nodules
Rhizocrete
Plant material
Bioturbation
Carbonate nodule
Clastic dike
Basalt
Spheroidal-weathered basalt
Planar beds
Fossil wood





Top of the Peña Conglomerate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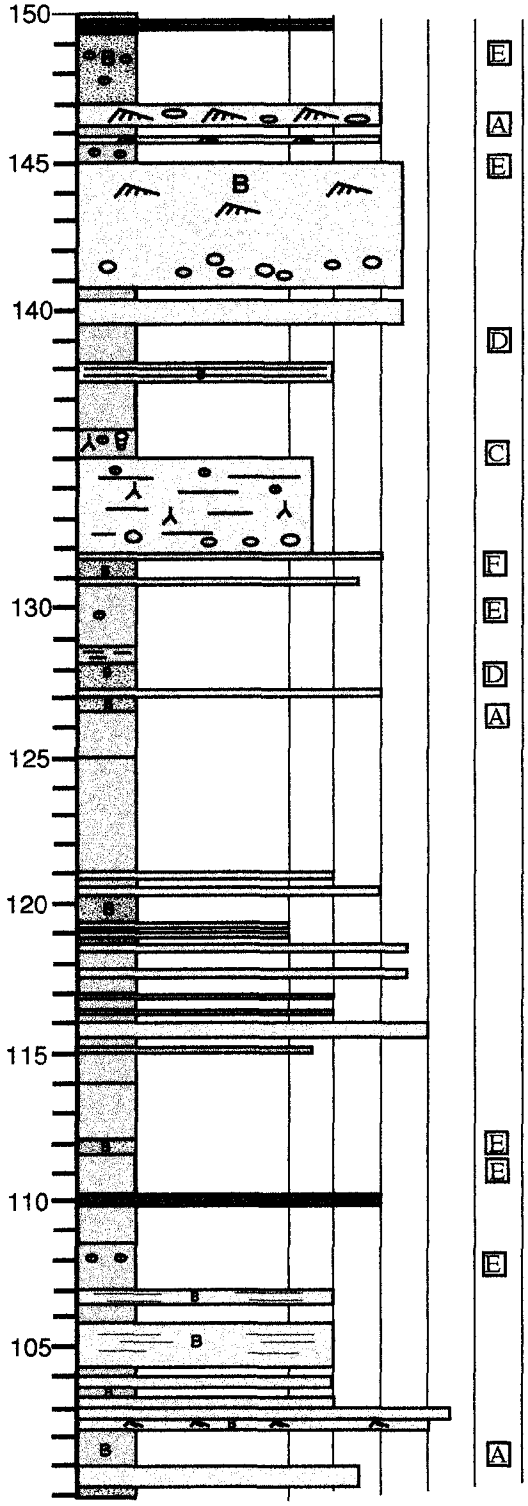
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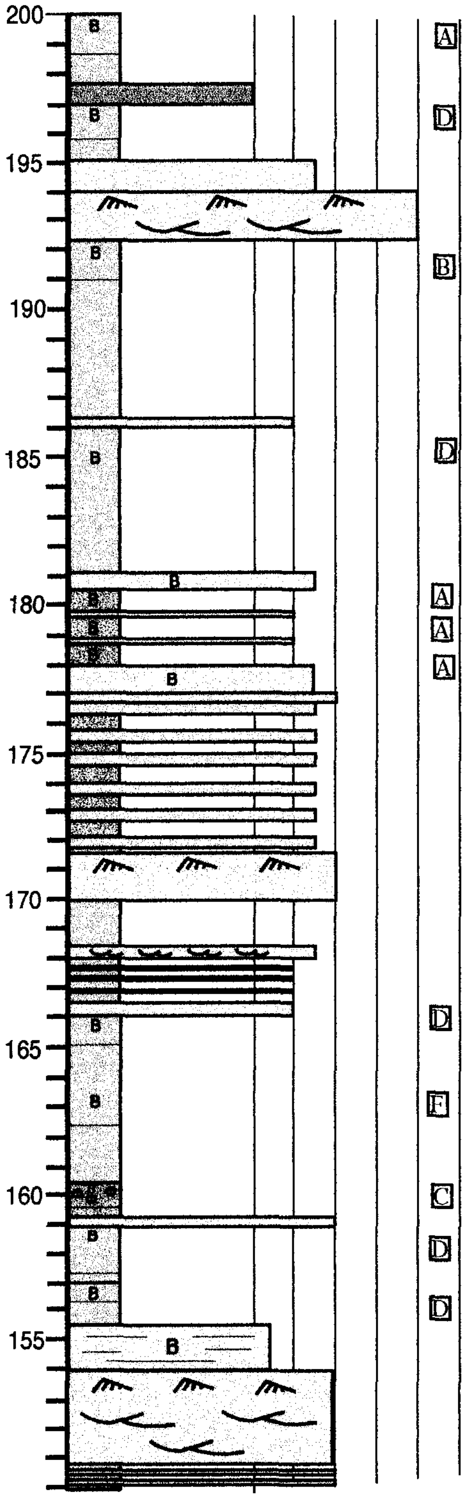
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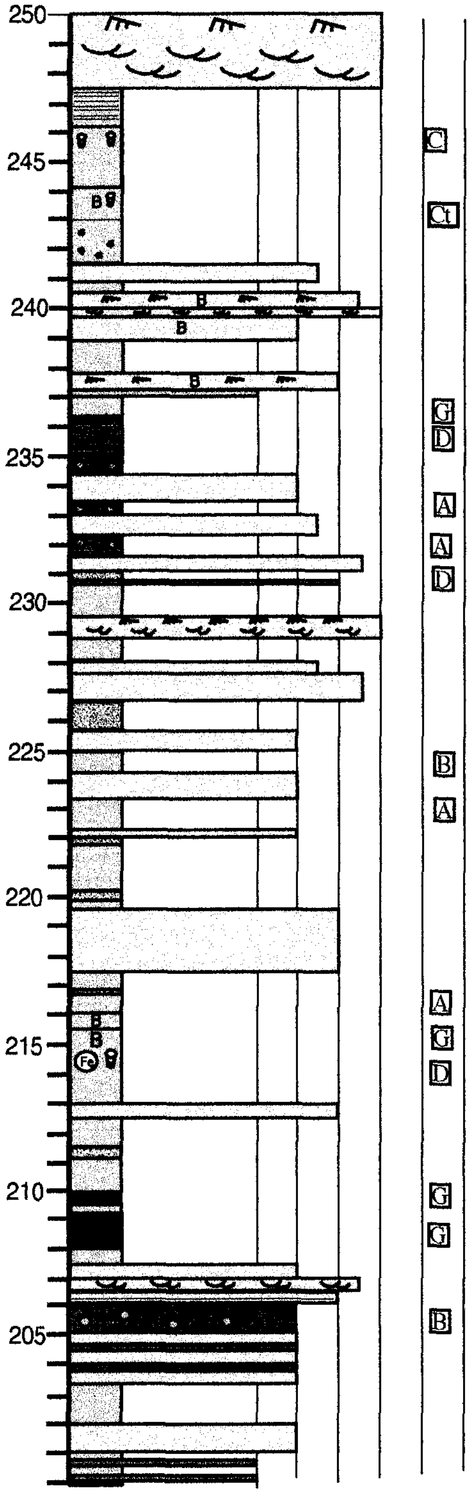

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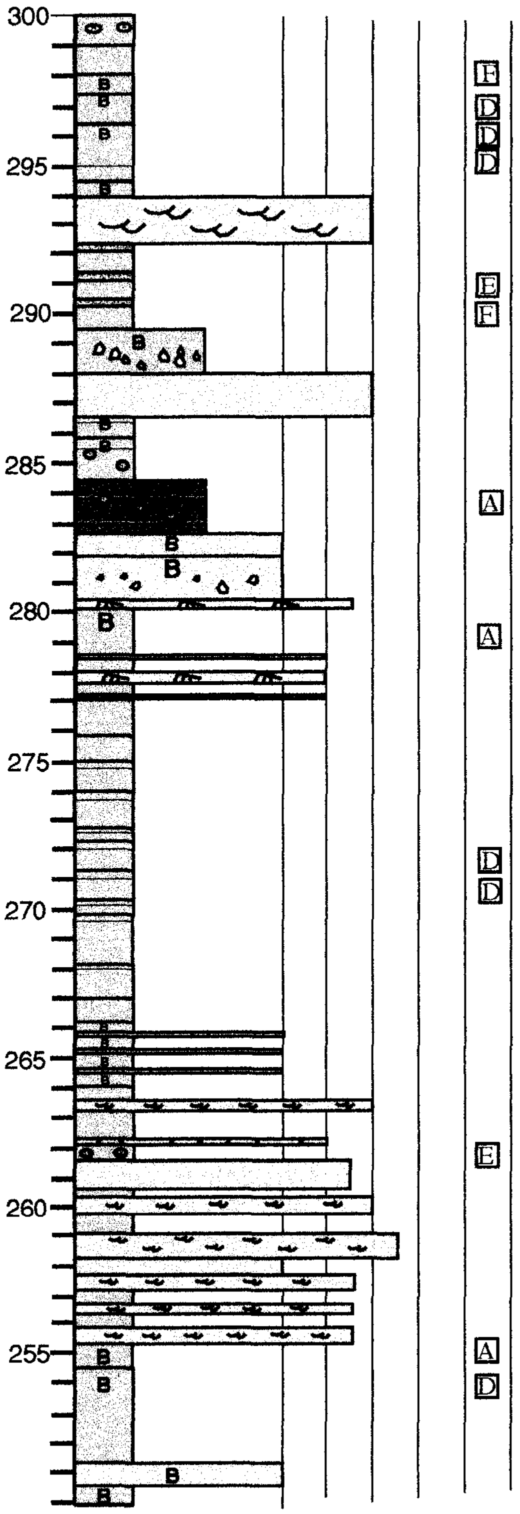
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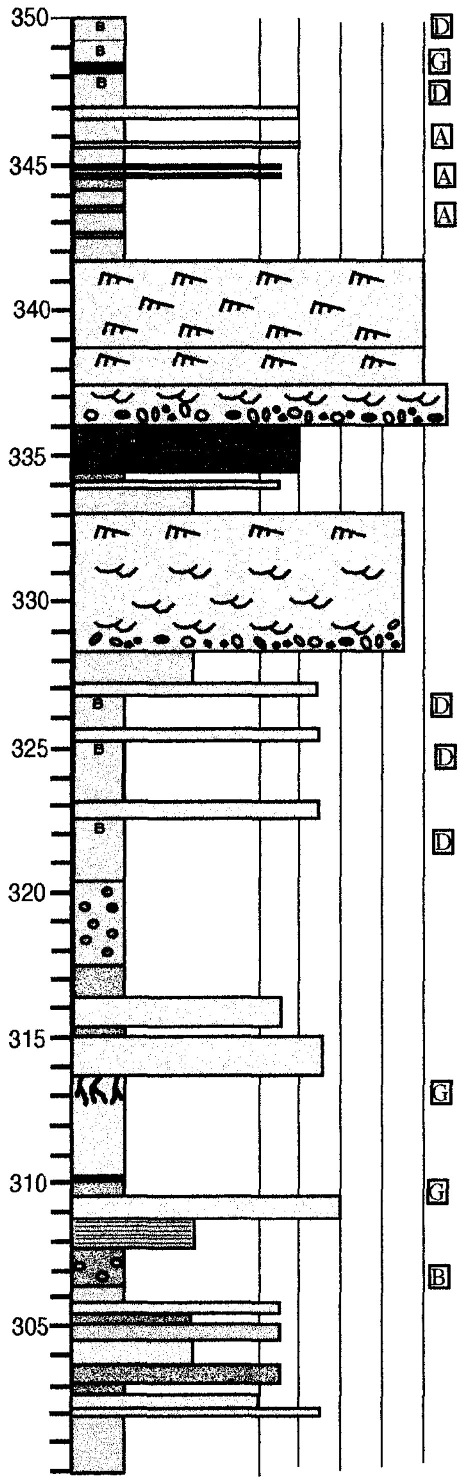
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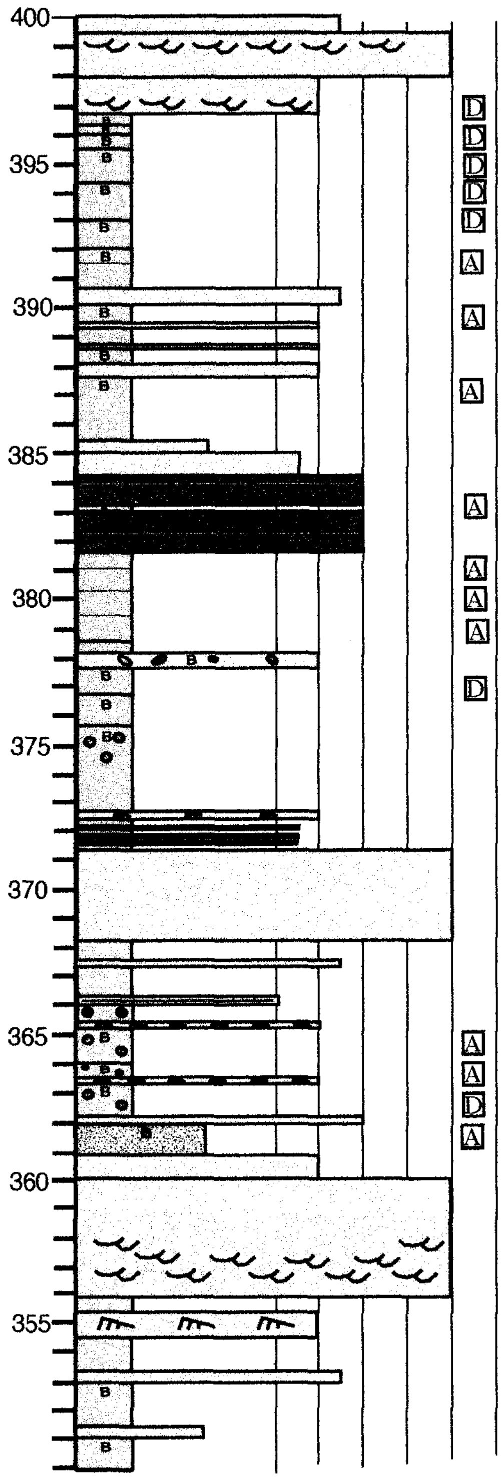
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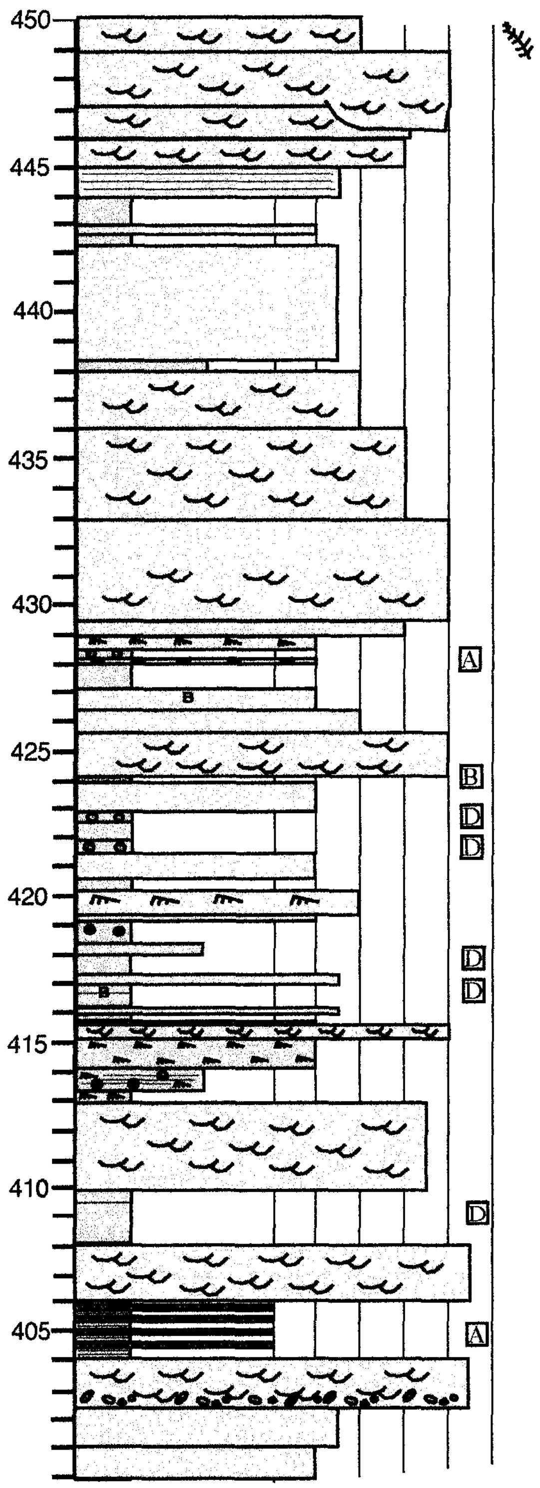
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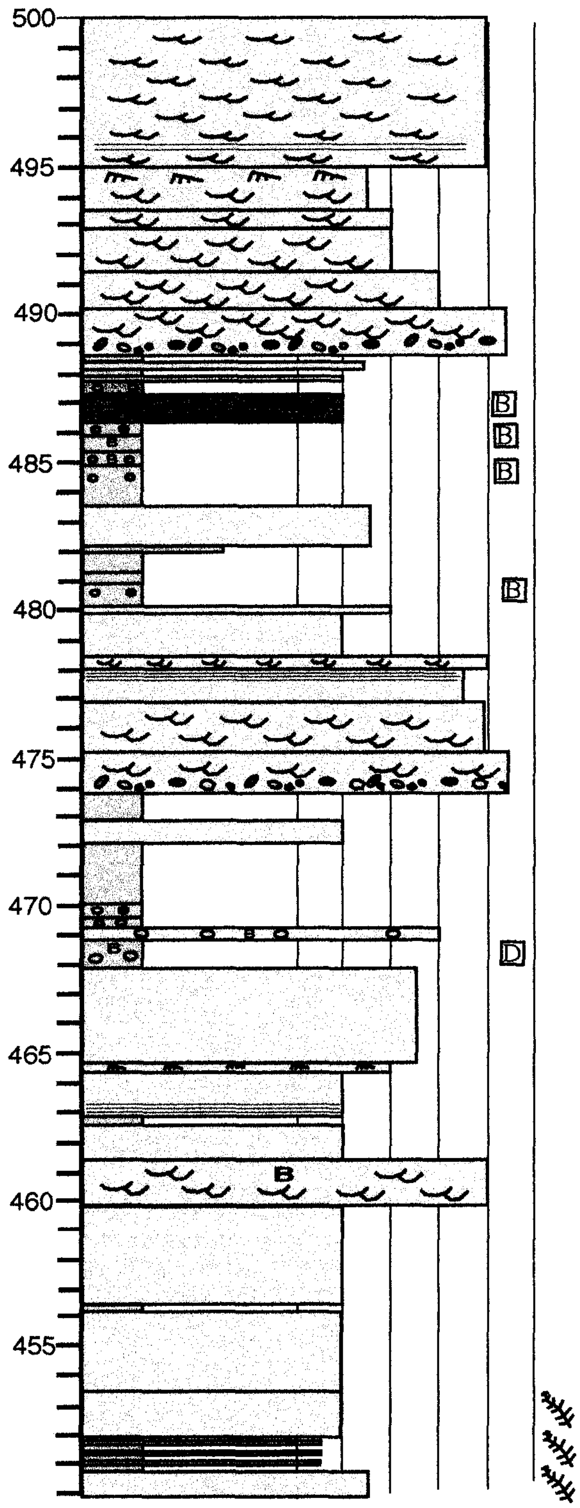
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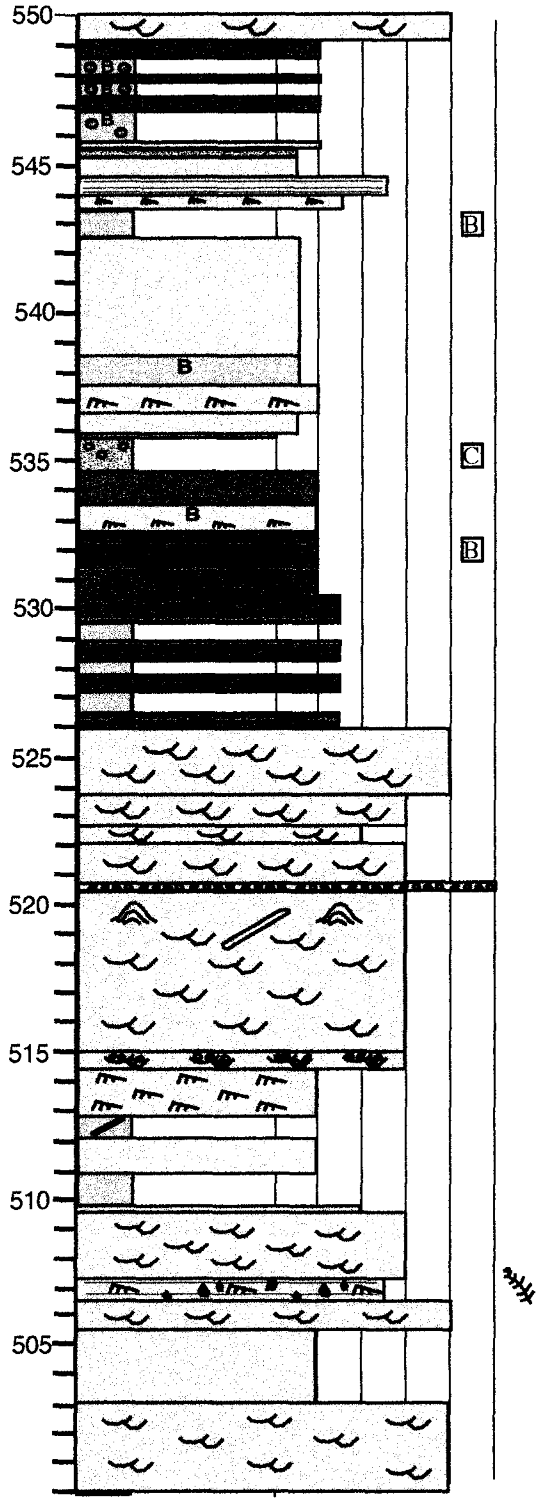
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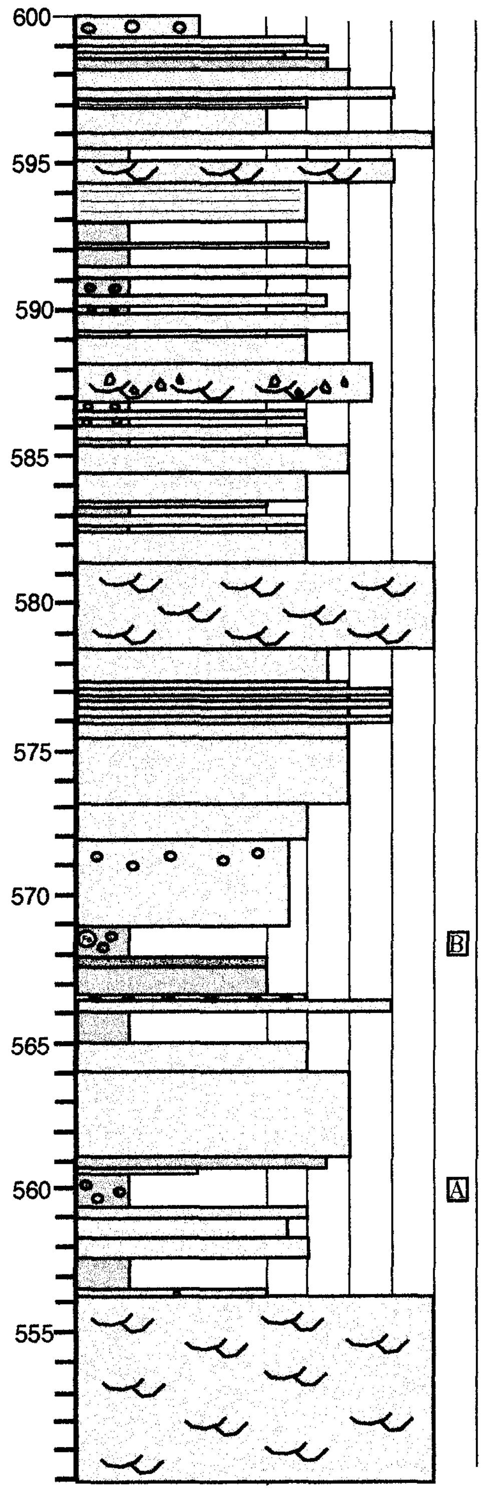
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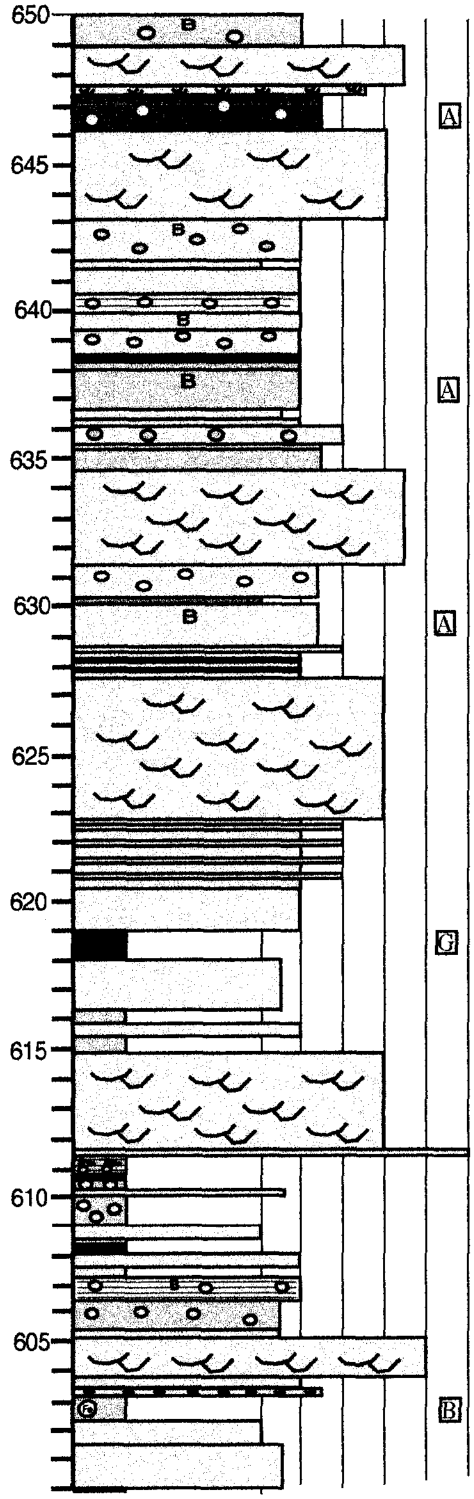
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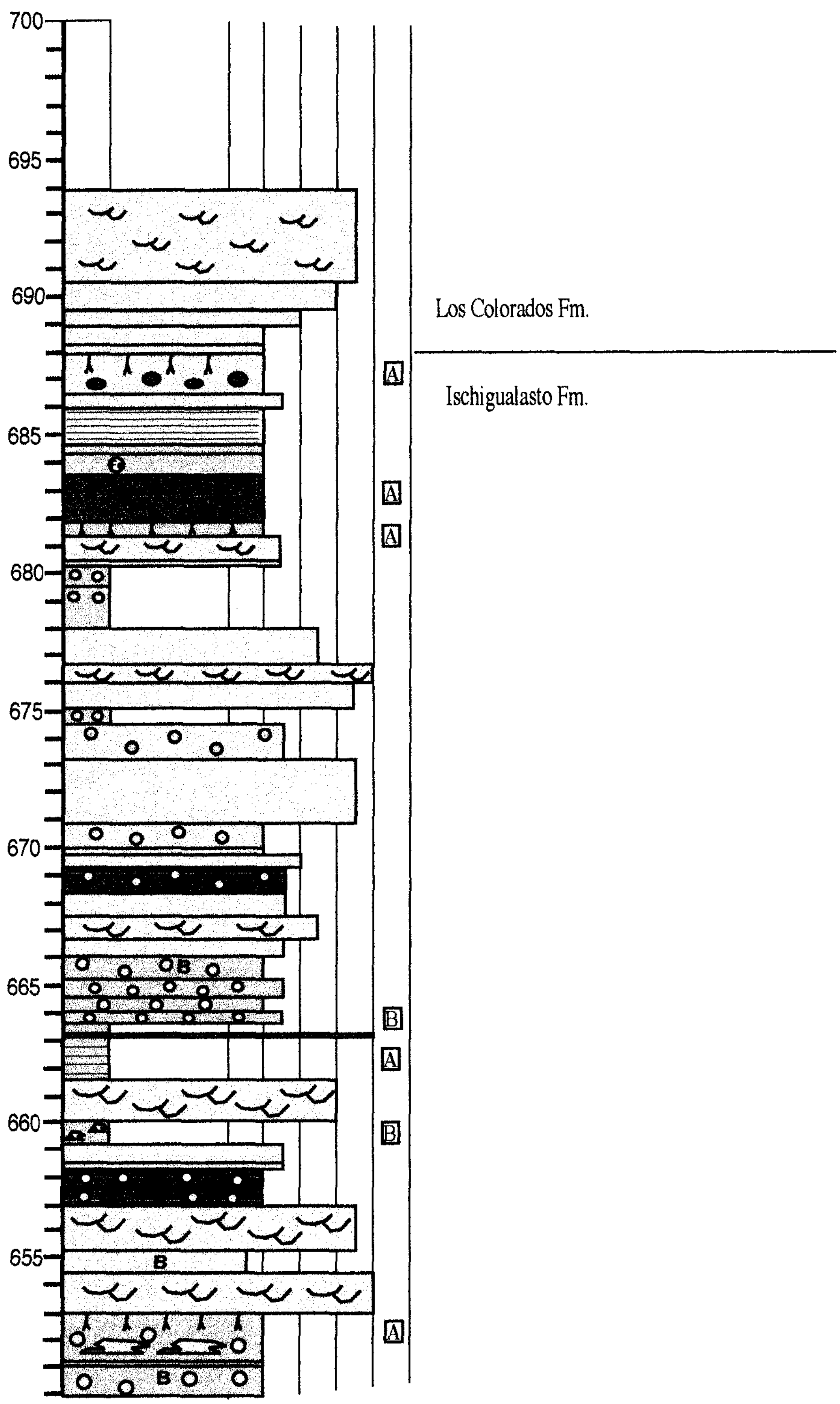
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Los Colorados Fm.
Ischigualasto Fm.

APPENDIX E

SECTION 2

Key to stratigraphic columns

Mottles

Pedotype

Sand pocket

Soft sediment deformation

Trough cross-stratified

Petrocalcic horizon

Ripple cross-laminated

Rip-up Clasts

Root trace

Clasts

Fe nodules

Mn nodules

Rhizocrete

Plant material

Bioturbation

Carbonate nodule

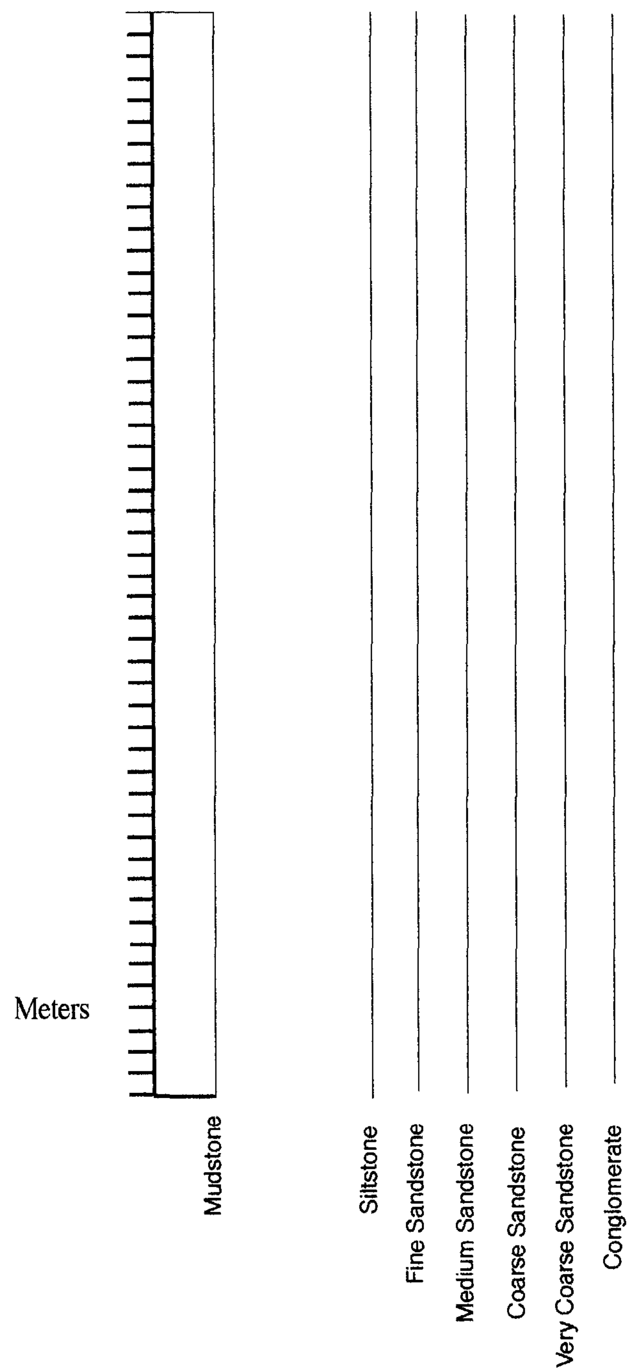
Clastic dike

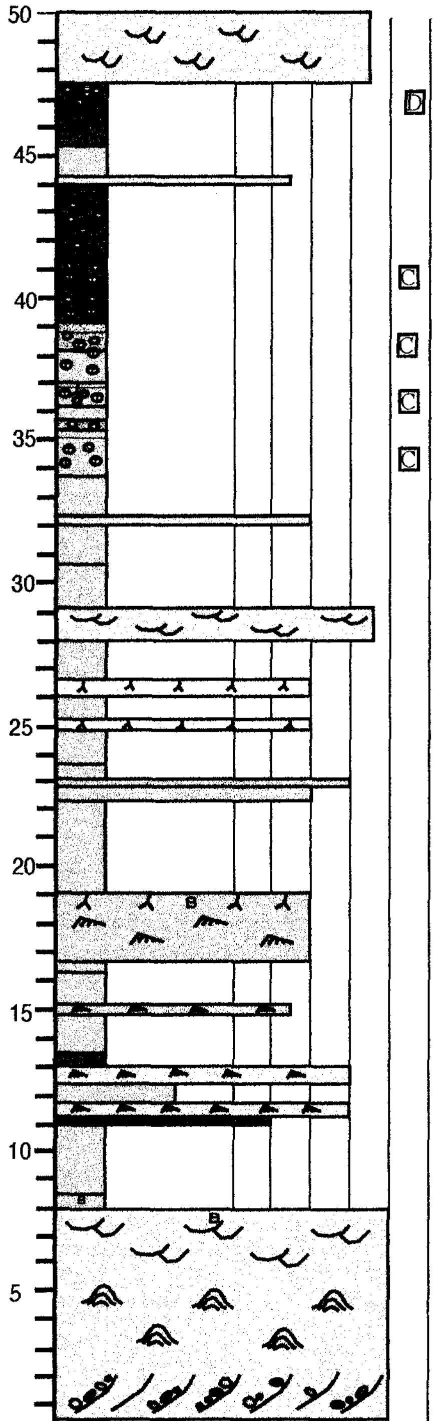
Basalt

Spheroidal-weathered basalt

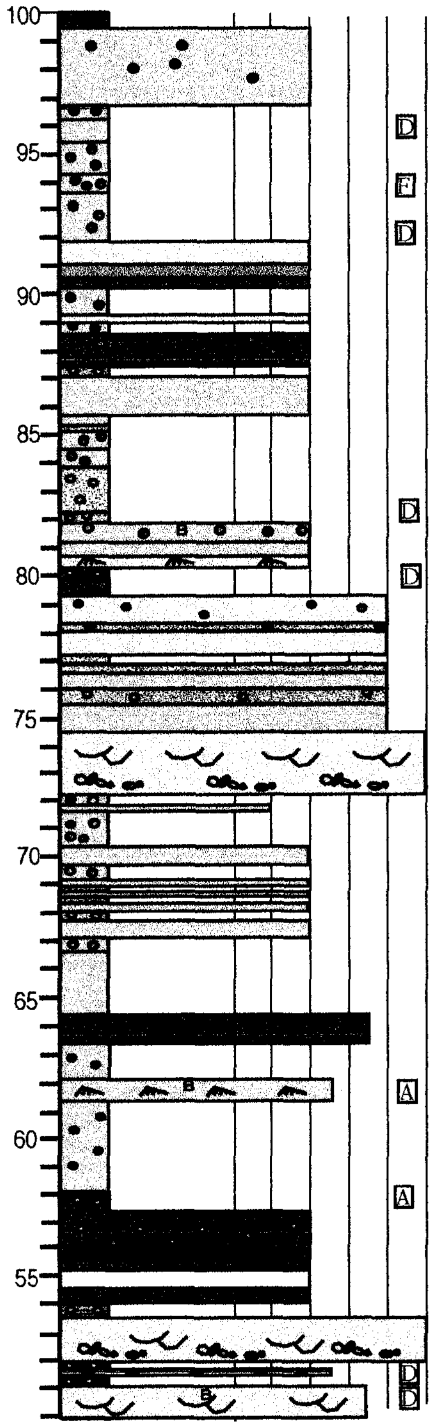
Planar beds

Fossil wood





Top of the Peña Conglomerate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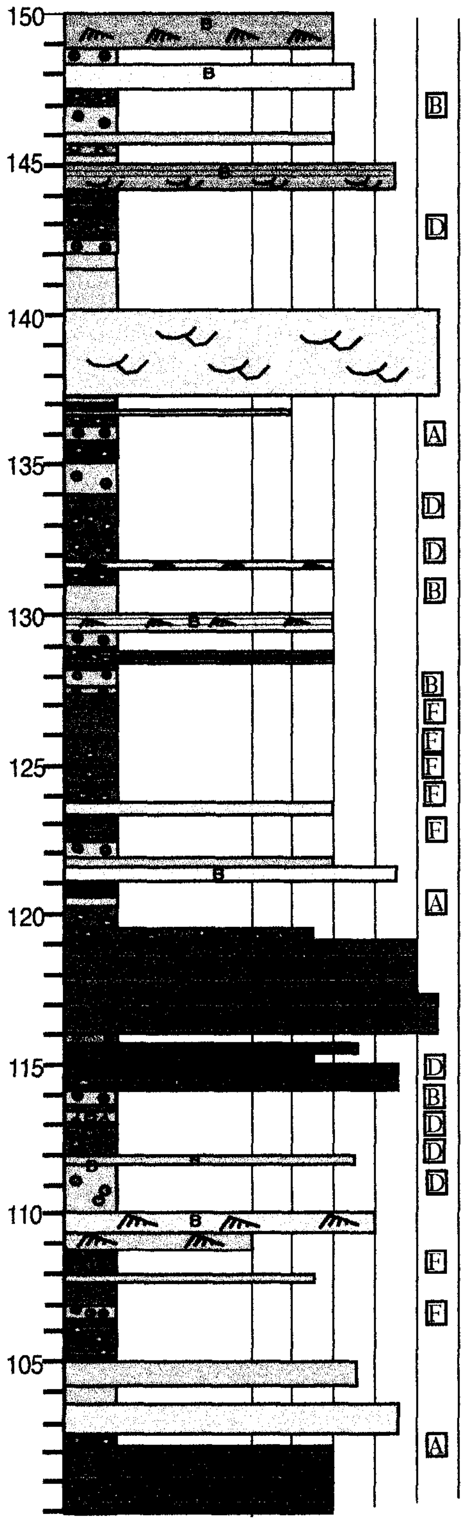
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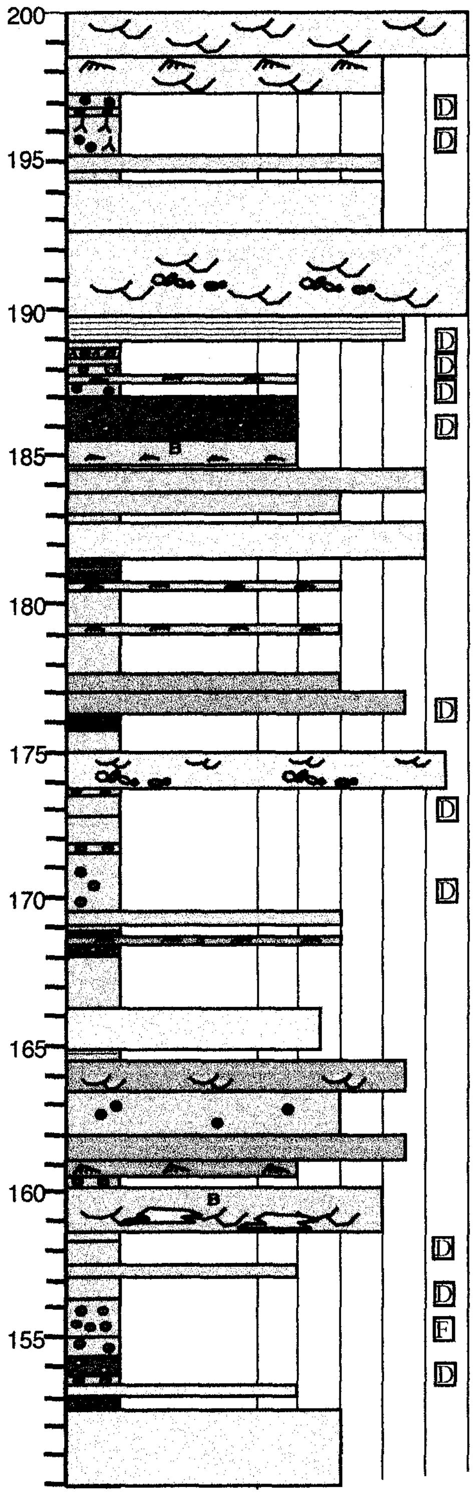
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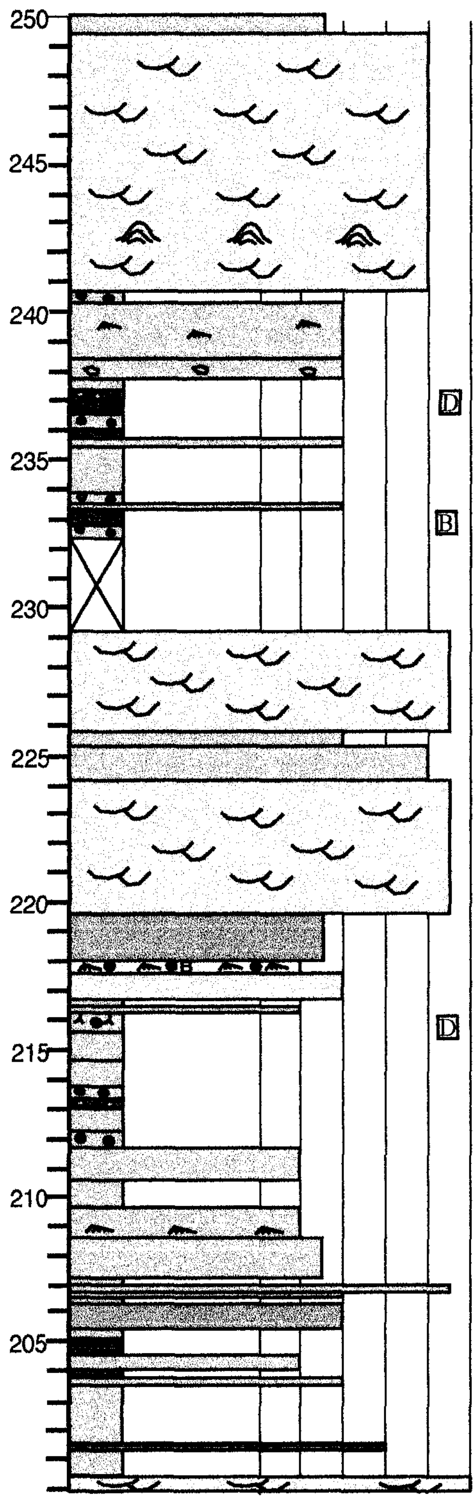
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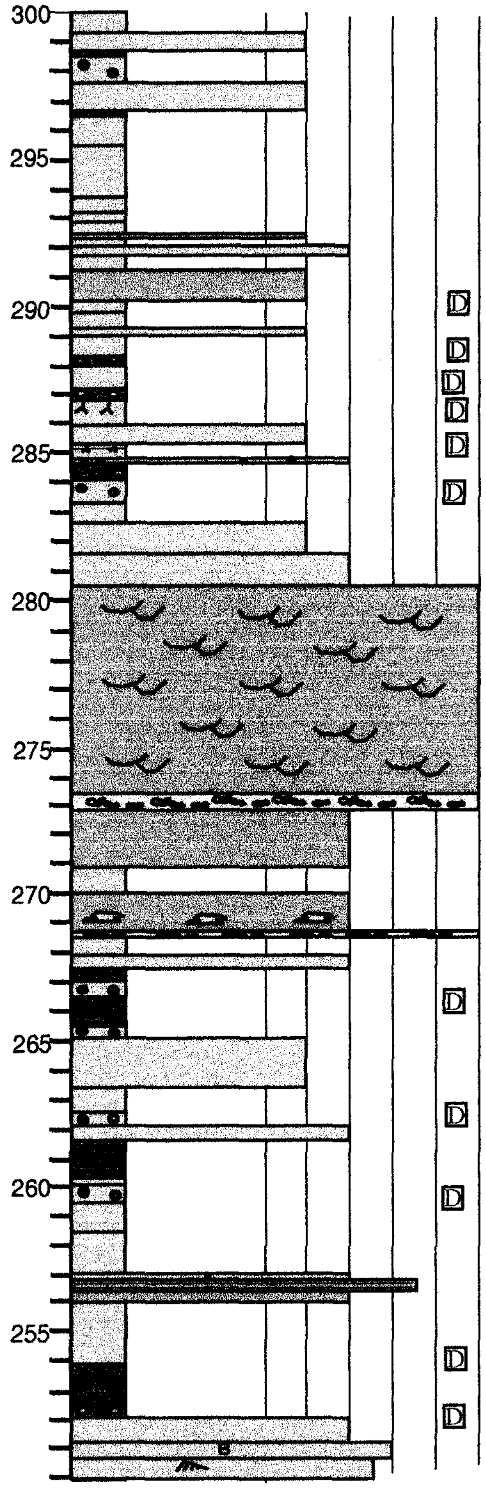
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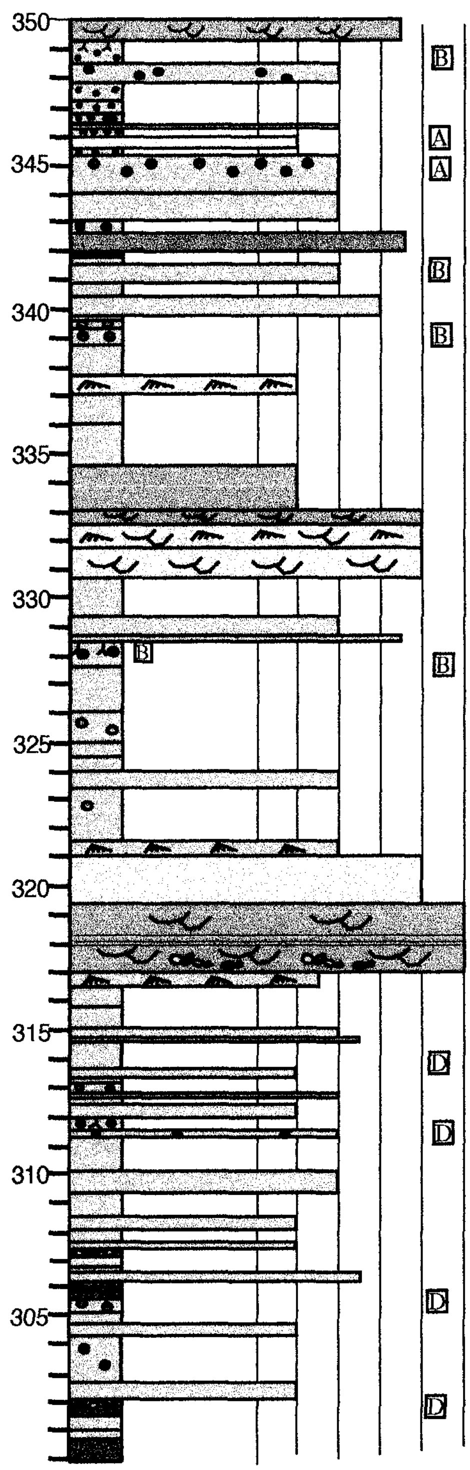
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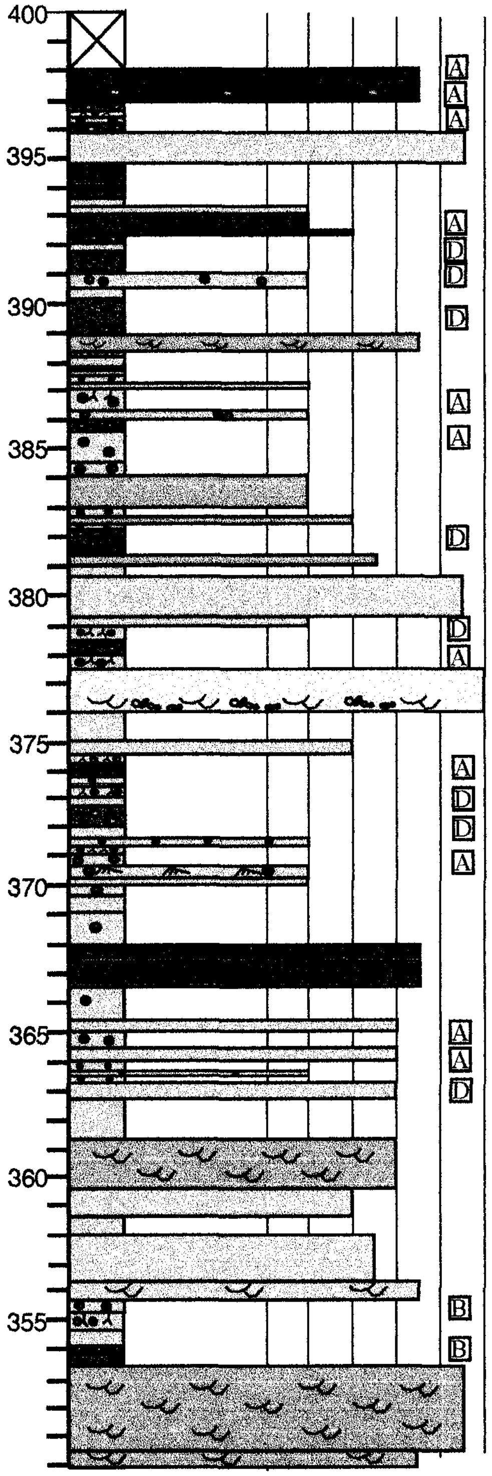
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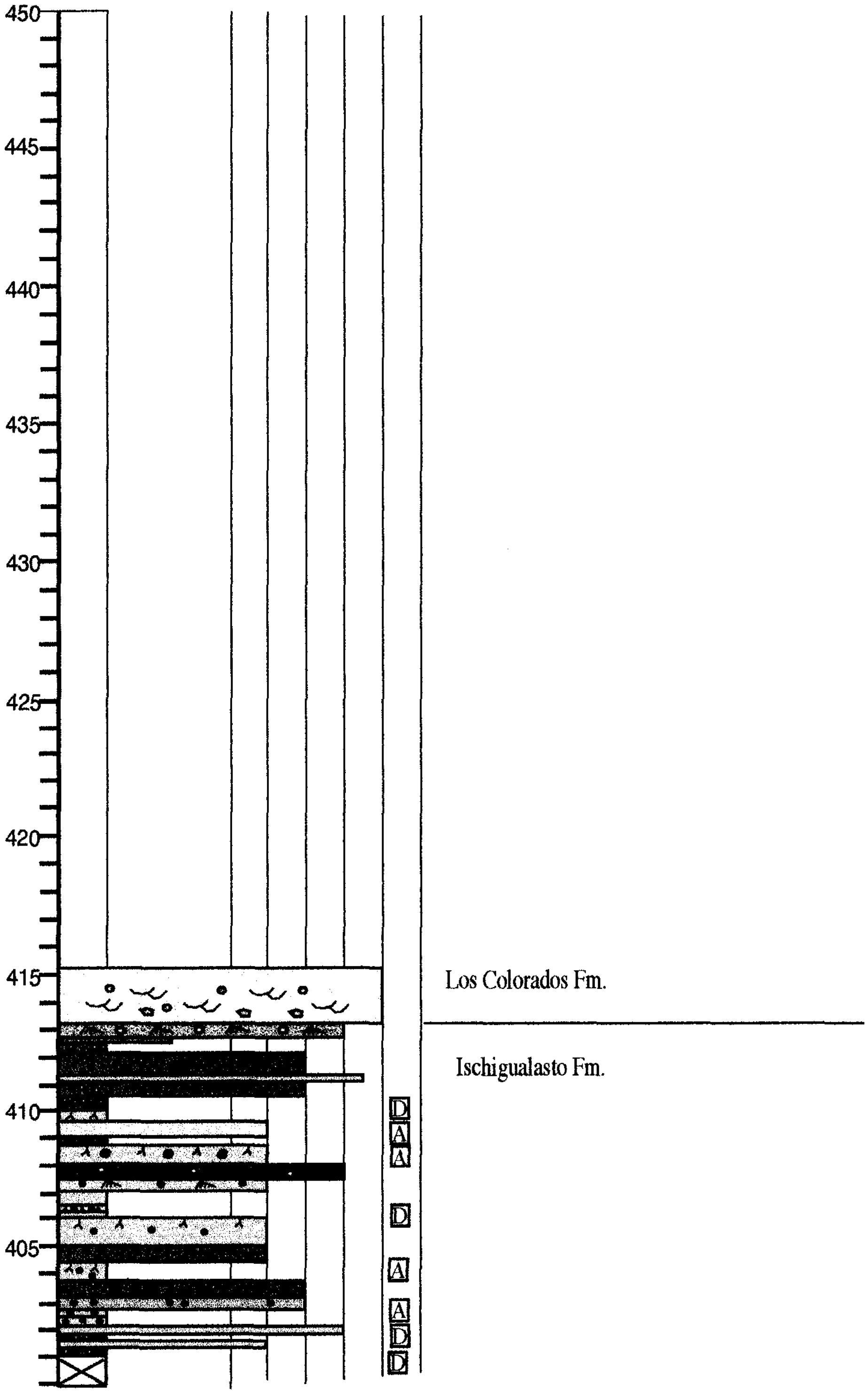
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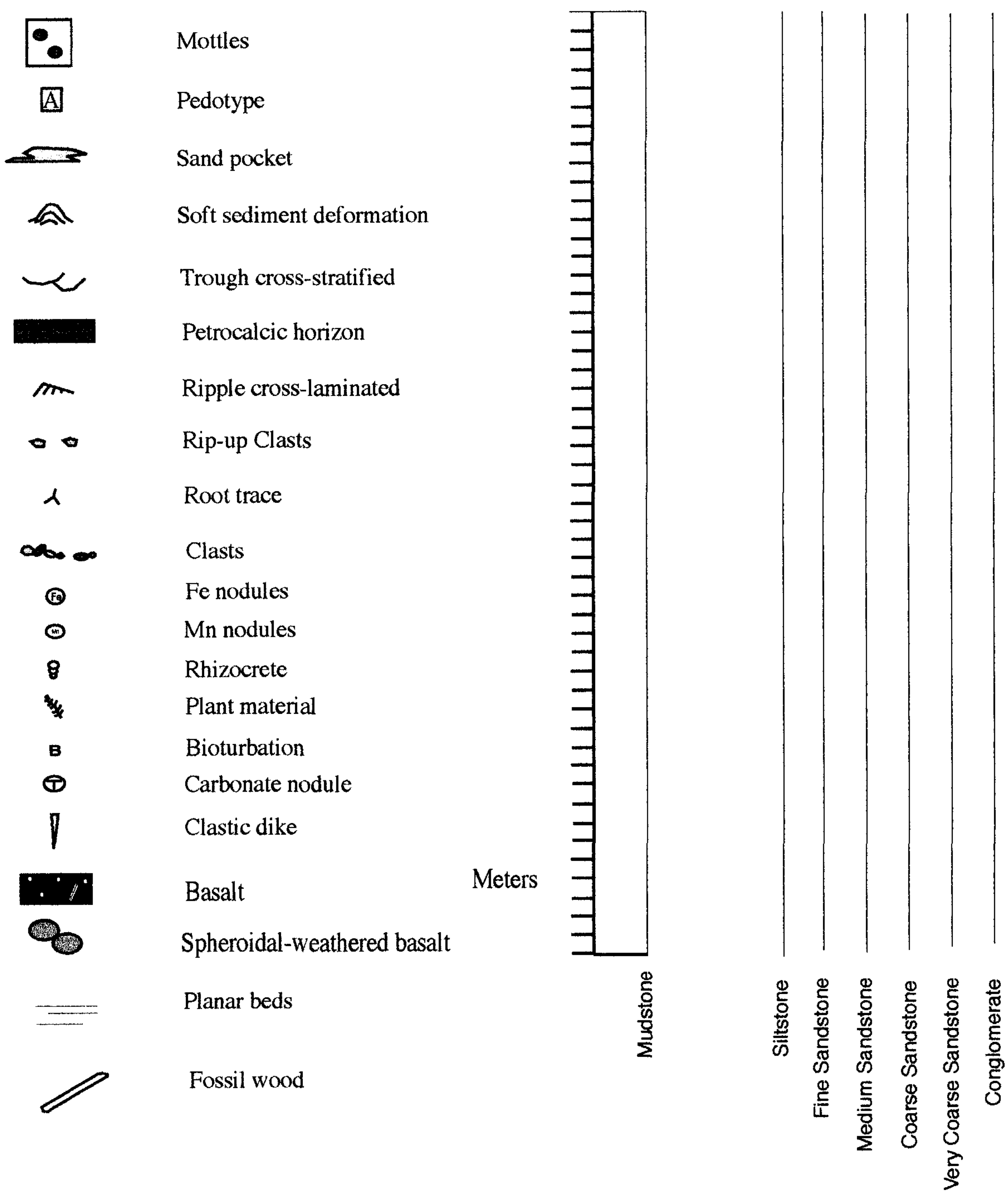
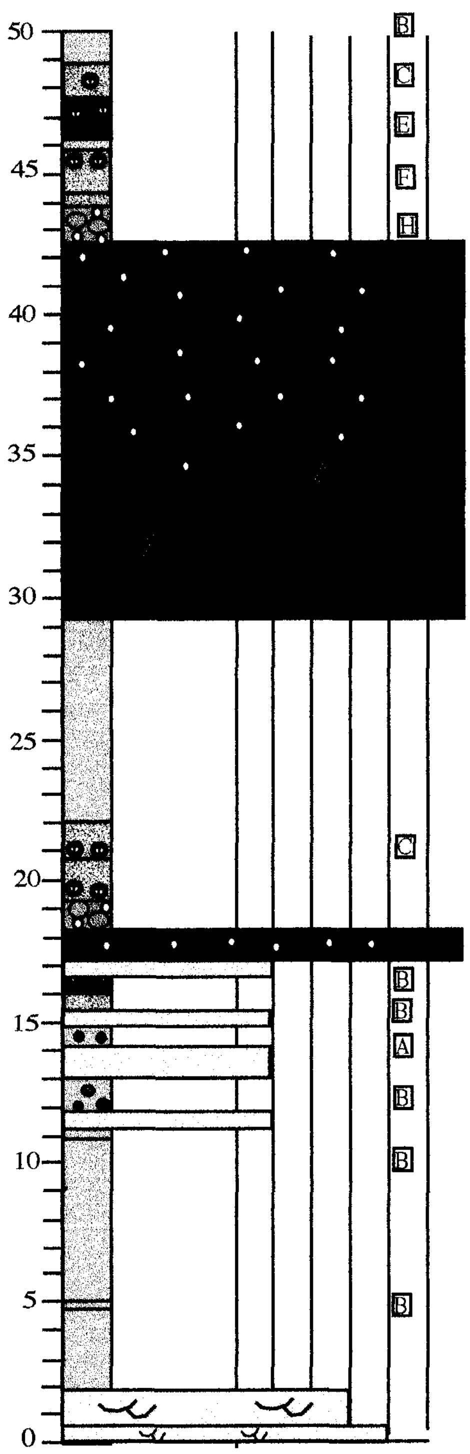
APPENDIX-F

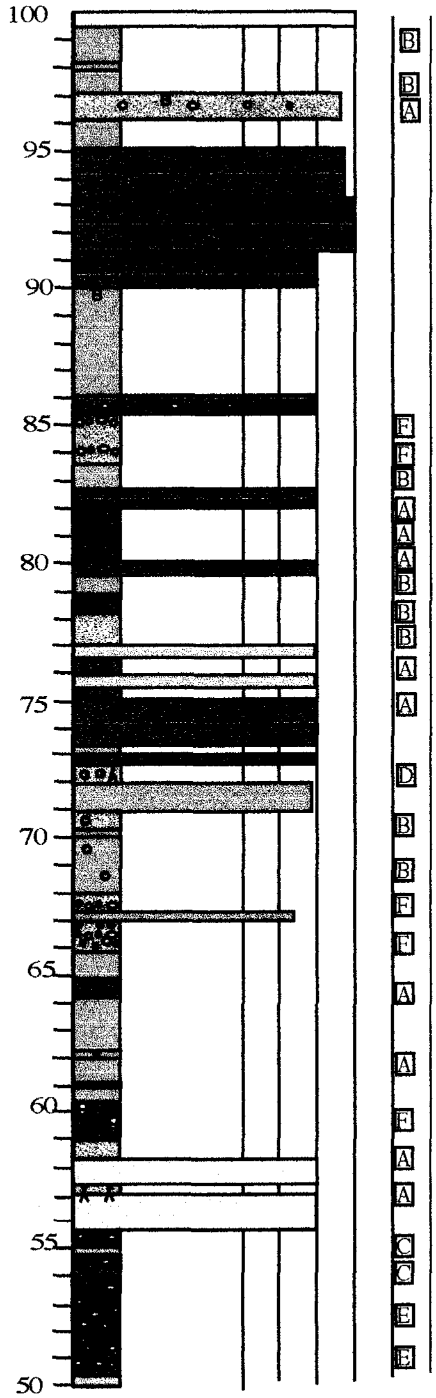
SECTION 3

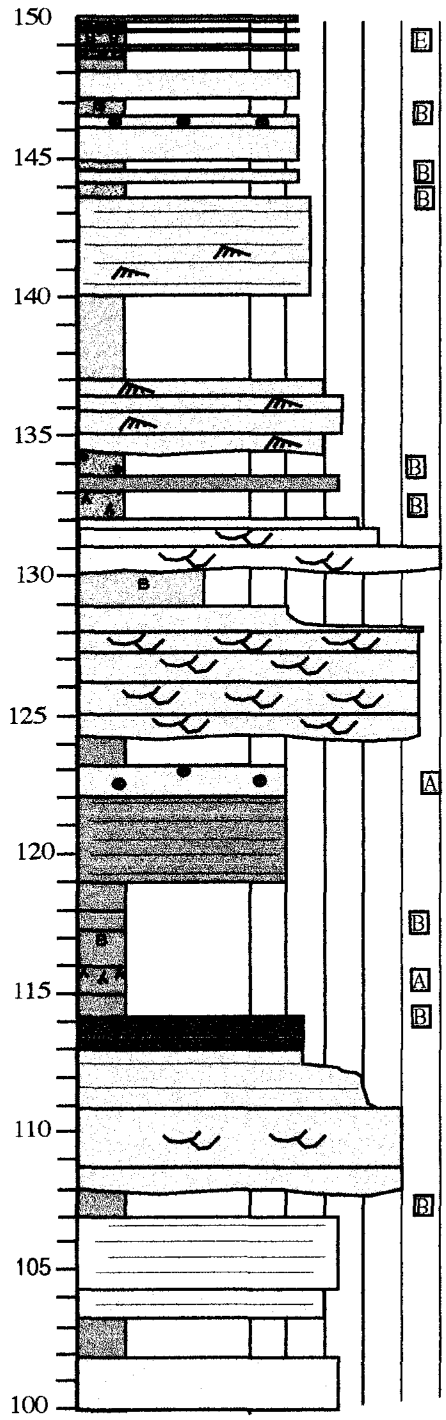
Key to stratigraphic columns

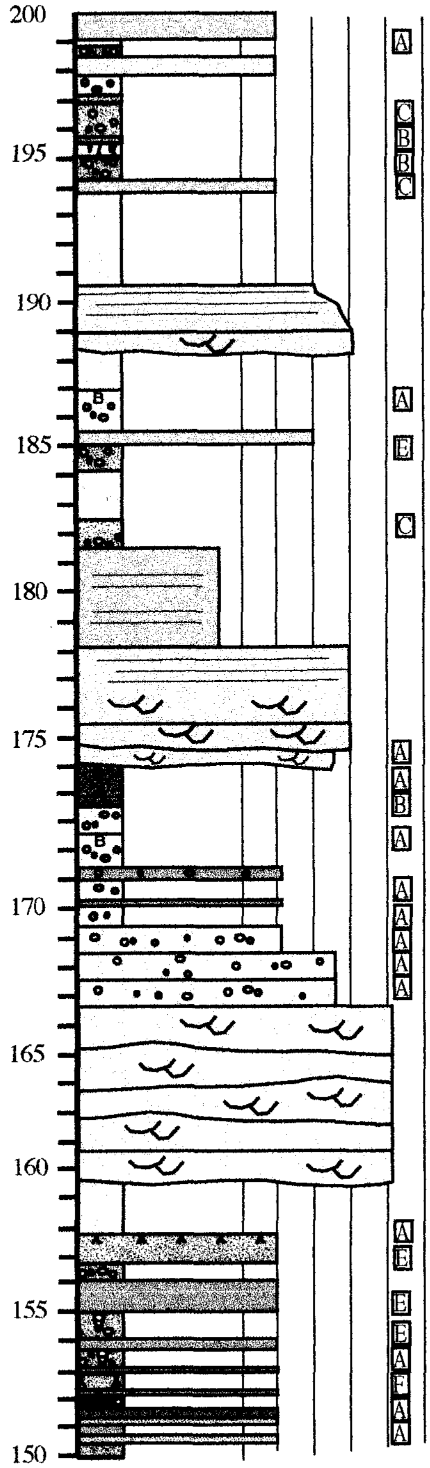


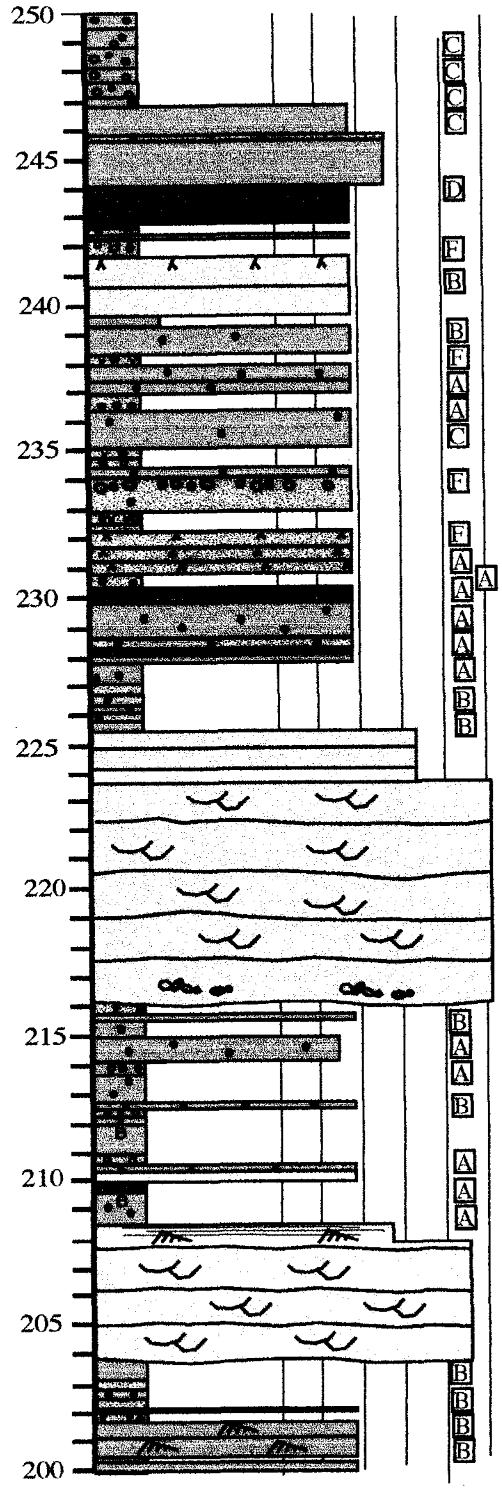


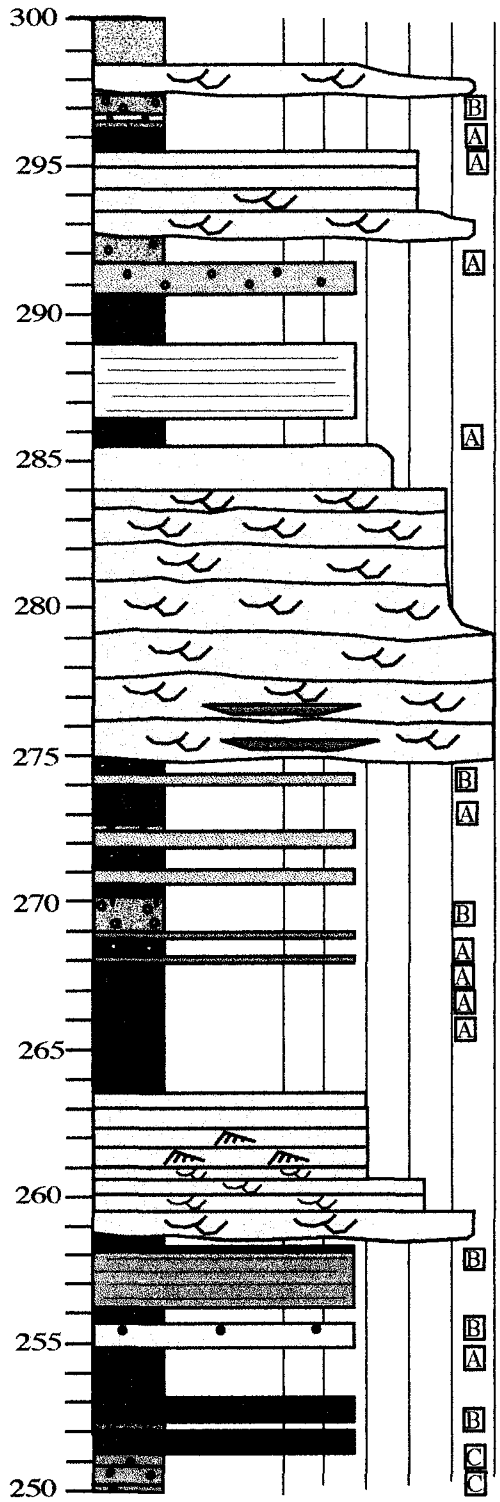
Top of the Peña Conglomerate

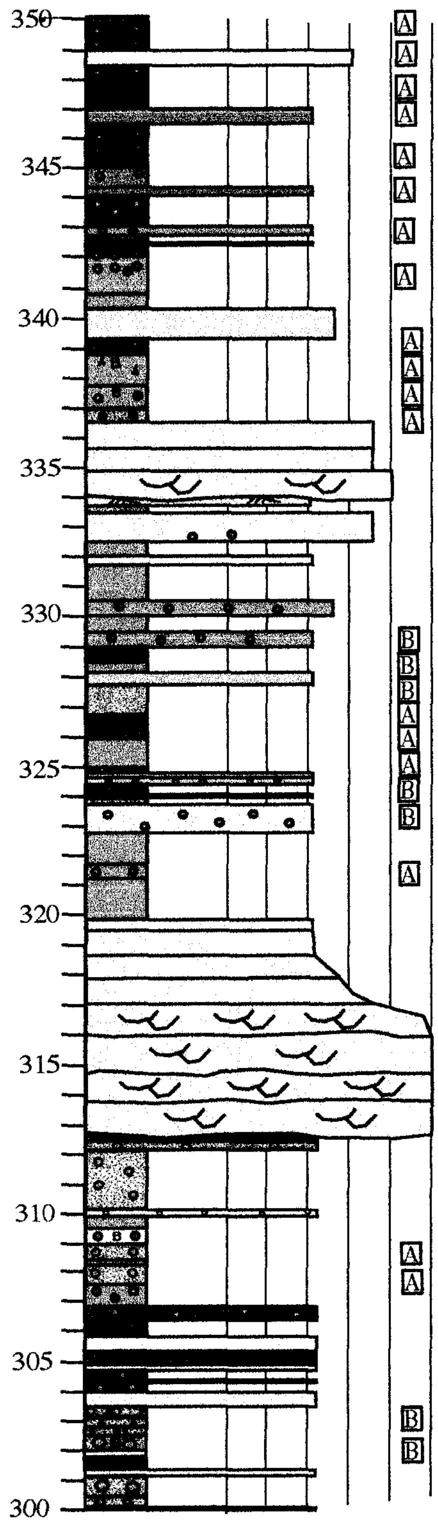

100
95
90
85
80
75
70
65
60
55
50
B
B
A
F
F
B
A
A
A
B
B
B
A
A
D
B
B
F
F
A
A
F
A
A
C
C
E
E

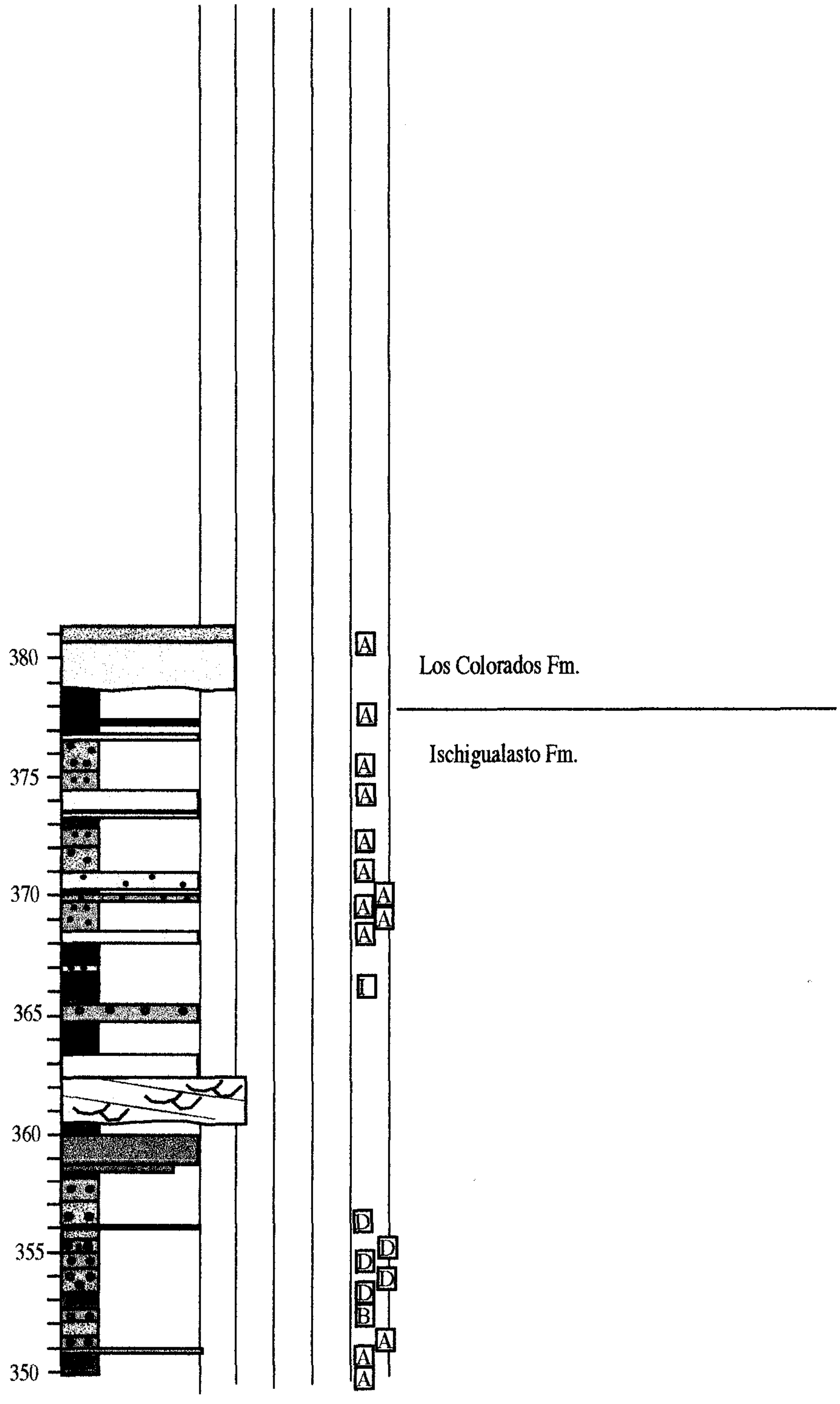

150
145
140
135
130
125
120
115
110
105
100
E
B
B
B
B
B
B
A
B
A
B
B
B
B


200
195
190
185
180
175
170
165
160
155
150
A
C
B
B
C
A
E
C
A
A
B
A
A
A
A
A
A
A
E
E
E
A
F
A
A


250
245
240
235
230
225
220
215
210
205
200
C
C
C
C
D
F
B
B
F
A
A
C
F
F
A
A
A
A
A
A
B
B
B
A
A
B
A
A
A
B
B
B
B


300
295
290
285
280
275
270
265
260
255
250
B
A
A
A
A
B
A
B
A
A
A
A
B
B
A
B
C
C


350
345
340
335
330
325
320
315
310
305
300
A
B



380
375
370
365
360
355
350
A
D
B
Los Colorados Fm.
Ischigualasto Fm.